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Measurement of the
differential single-top-quark t -channel
production cross section at $\sqrt{s} = 13$ TeV
with the ATLAS detector

Dissertation

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Abstract

In this dissertation, a measurement of differential production cross sections of single top quarks and top antiquarks produced via the t -channel exchange of a virtual W -boson is presented. The cross sections are measured as a function of the transverse momentum and absolute rapidity of the top quark and top antiquark. Absolute and normalised differential cross sections are measured as well as the differential ratio between the top-quark and top-antiquark cross sections. The analysed proton-proton collision data was collected by the ATLAS detector at the Large Hadron Collider in the years 2015–2018 at a centre-of-mass energy of 13 TeV and corresponds to an integrated luminosity of 140 fb^{-1} . The measured distributions are corrected for detector resolution and acceptance effects. Systematic and statistical uncertainties in the measurement are evaluated. The obtained differential cross sections are compared to theoretical predictions obtained from fixed-order calculations, various parton distribution functions and different event-generator and parton-shower programs. Overall, a good agreement within the measurement uncertainties is observed, where the measurement is limited by systematic uncertainties. The measurement results are interpreted in an effective field theory approach to constrain the Wilson-coefficient $C_{Qq}^{3,1}/\Lambda^2$ associated with a four-quark operator. The operator is found to have a significant impact on the acceptance of signal events, which is evaluated and taken into consideration for the interpretation.

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Introduction

In the beginning the Universe was created. This had made a lot of people very angry and been widely regarded as a bad move.

–Douglas Adams, *The Restaurant at the End of the Universe*

Nevertheless, it also sparked humanity’s curiosity and led countless generations of philosophers and scientists to search for answers to the big questions of how our universe came into existence, and how exactly it works. On the smallest spatial scales, the discipline of elementary particle physics studies the elementary building blocks of matter and the fundamental interactions governing the universe. The scientific endeavours of the past century led to the formulation of the Standard Model of particle physics, a theory that proved tremendously successful at describing experimental observations and even predicting the outcome of measurements. However, the Standard Model in its present form exhibits conceptual limitations, and there are some observed phenomena it cannot explain. The search for a complete description of the universe therefore continues.

A central tool of experimental particle physics are collision experiments, which enable the study of interactions between fundamental particles at short distances and high energies. The Large Hadron Collider is the largest particle collider built to date, reaching unprecedented collision energies of $\sqrt{s} = 13.6$ TeV. Several detectors, positioned along the collider ring, record particle collisions and enable a rich measurement programme, spanning from precision measurements to searches for new physics. Cross section measurements provide opportunities for both kinds of analyses, since the cross sections for physics processes are predicted by the Standard Model, and many theories for new physics anticipate deviations that would become visible in certain processes. Among the elementary particles, the top quark exhibits unique features due to its high mass. Precision measurements of its properties and interactions provide a valuable opportunity to study fundamental parameters of the Standard Model. Furthermore, the top quark is expected to provide a high sensitivity to new phenomena predicted at high energies.

In this thesis, a measurement of differential cross sections of singly produced top quarks is presented. Differential cross sections are measured as a function of some event observables, thereby providing the opportunity to test theoretical predictions for specific kinematic ranges. The analysis presented in this dissertation utilises proton-proton collision data collected with the ATLAS detector at the Large Hadron Collider at a centre-of-mass energy $\sqrt{s} = 13$ TeV in the years 2015–2018. The production of single top quarks via the exchange of a virtual W -boson is measured differentially at the parton level as a function of the transverse momentum p_T and the absolute rapidity



$|y|$ of the top quark. The production of top quarks and top antiquarks, referred to as tq and $\bar{t}q$ production, is measured separately, and the first differential measurement of the ratio of tq over $\bar{t}q$ production is presented. The $p_T(t)$ and $p_T(\bar{t})$ distributions are expected to provide sensitivity to differences among the predictions of different matrix-element and parton-shower programs. The proton PDFs impact the $|y(t)|$ and $|y(\bar{t})|$ distributions, which are therefore expected to be of interest for global PDF fits. The presented analysis is published in Ref. [1]. It builds upon the previous ATLAS measurement of the total tq and $\bar{t}q$ production cross sections at $\sqrt{s} = 13$ TeV [2].

The first chapters of this thesis introduce the theoretical and experimental groundwork for the analysis. An overview of the Standard Model is given in Chapter 1, where the successes and limitations of the theory as well as a possible extension through effective field theory are discussed in addition. The Large Hadron Collider and the ATLAS detector are introduced in Chapter 2, and a brief overview of the top-quark related measurement programme in ATLAS is presented in Chapter 3. In Chapter 4, the methods used to simulate proton-proton collision events are discussed, and details about the different theoretical predictions, which are later compared to the measured cross sections, are given. The technical details about the data and simulated samples used in this analysis are collected in Chapter 5, and the methods that are used to reconstruct physical objects from the raw detector measurements are introduced in Chapter 6.

The following chapters are dedicated to the analysis strategy, starting with a description of the applied event selection and the utilised top-quark-reconstruction algorithm in Chapter 7. The estimation of the normalisation of the background processes requires special attention and is described in Chapter 8. Iterative Bayesian Unfolding is employed to correct the measured distributions for detector effects. The mathematical background, required inputs and validation of the method are presented in Chapter 9. The numerous sources of uncertainties affecting the measurement are introduced in Chapter 10, and their impact on the measured cross sections is evaluated and discussed. Finally, the results of the measurement are presented in Chapter 11. The agreement between the theoretical predictions and the measured cross sections is evaluated, and some striking features of the distributions are discussed. Additionally, the measurement results are interpreted in the context of an effective field theory approach to search for physics beyond the Standard Model.

1. Standard Model of particle physics

The Standard Model of particle physics (SM) encapsulates our current understanding of the most fundamental building blocks of the universe. It is the result of decades of scientific progress in the field of elementary particle physics and stands in the context of scientific endeavours dating back even further.

The concept that matter consists of a limited number of smallest particles has been present in science since ancient times, where Greek philosophers discussed the idea of *atomos*, the “uncuttable”. As time progressed and physics and chemistry emerged as autonomous disciplines, a scientific basis for the theory of *atoms* as building blocks of matter was developed by Dalton [3] at the beginning of the 19th century and later refined by Mendeleev, laying the groundwork for the *periodic table of elements* [4]. Around the same time, a unified description of electricity and magnetism, termed *electromagnetism*, was developed by Maxwell [5], which proved to be a cornerstone for the development of modern physics. A further important breakthrough was made by Thomson in 1897 with the discovery of the *electron* [6] and his following attempt to describe the inner structure of atoms [7]. Rutherford successfully deduced the existence of the atomic core from scattering experiments [8], and the discovery of the *proton* and *neutron* [9, 10] lead to a consistent picture. Around the 1950s however, new experimental techniques lead to the discovery of such a large number of particles thought to be elementary at the time that the term *particle zoo* was coined. The *eightfold way* [11], postulated by Gell-Mann and Ne’eman in 1961, proved successful at organising the particles according to their properties. This eventually led to the insight that they were composed of even smaller particles, the *quarks*, and paved the way for the development of *quantum chromodynamics* (QCD). In the same decade, the theory of the *electroweak interaction*, which unifies electromagnetism and the weak force, was developed by Salam and Weinberg, building on work by Glashow. Additionally, the mechanism by which elementary particles acquire mass was proposed almost simultaneously by multiple groups [12–14] and is commonly named *Higgs mechanism* after one of its discoverers. These major breakthroughs, along with relentless progress in experimental and theoretical particle physics, led to the formulation of the SM, which today describes all known elementary particles and their interactions.

An overview of the elementary particles of the SM and their main characteristics is given in Figure 1.1. The particles are categorised according to their spin quantum number into *fermions* with spin $1/2$ and *bosons* with integer spin.

Fermions are the building blocks of matter. The SM contains twelve unique types of fermions which are further divided into quarks and *leptons*. Quarks carry a *color charge* and fractional electric charge, by which they are organised into *up-type* quarks

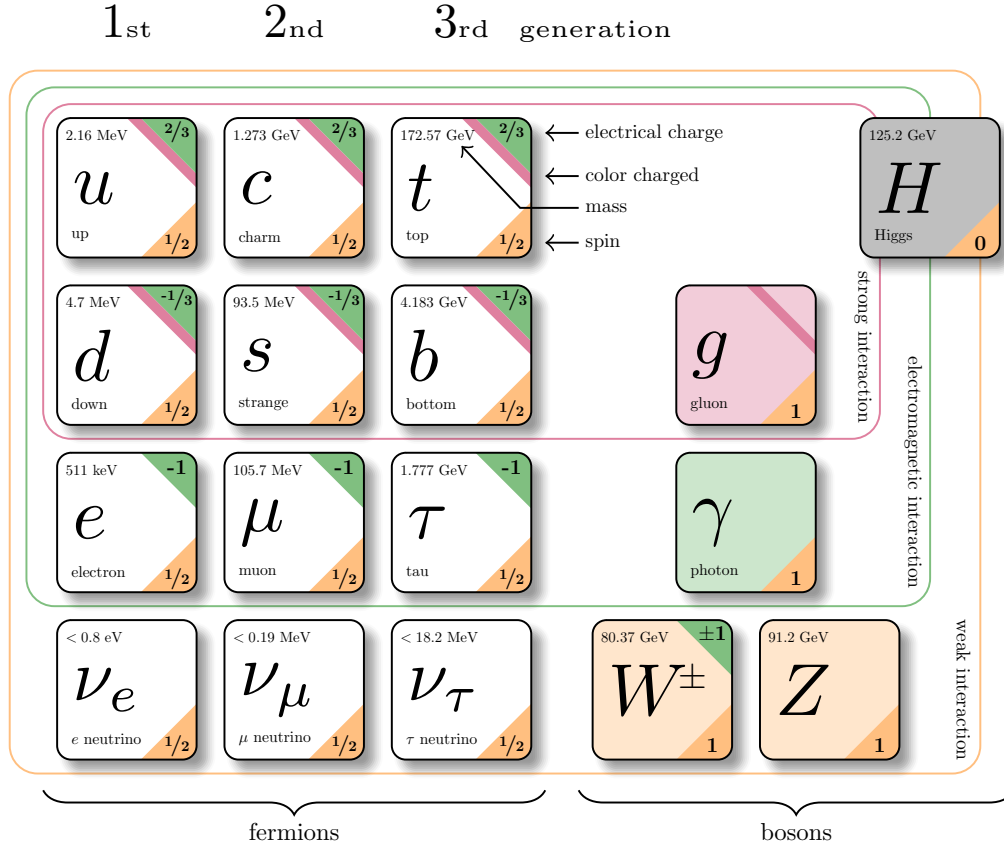


Figure 1.1: Overview of the particle content of the SM. Particle masses cannot be predicted from theory, therefore the given values are the world-leading measurement results taken from [15]. Figure adapted from [16].

with an electric charge of $2/3e$ and *down-type* quarks with an electric charge of $-1/3e$. Additionally, the quarks are sorted by their increasing mass into three generations, which contain one up-type quark and one down-type quark each. Overall, six different quark types exist, which are referred to by their *flavour* as up (u), down (d), charm (c), strange (s), top (t) and bottom (b).

Leptons comprise the three charged leptons named electron (e), muon (μ) and tau (τ) and their associated *neutrinos* (ν_e , ν_μ , ν_τ). Similarly to quarks, they form three generations that each contain one charged lepton and its associated neutrino. The generations are sorted by increasing mass of the charged leptons, as neutrinos are considered to be massless in the SM.

Only the quarks and leptons of the first generation are stable and constitute the everyday matter. Each fermion has a corresponding *antiparticle* possessing an identical mass but inverted charges.



1.1. Theoretical formulation

Table 1.1.: Overview of the fundamental interactions of the SM. The relative strengths are given at a distance of 1 fm [17].

Interaction	Relative strength	Range	Quantum number	Mediator
Strong	1	$\approx 10^{-15}$ m	color charge C	gluons
Electromagnetic	$\frac{1}{137}$	∞	electric charge Q	photon
Weak	10^{-16}	$\approx 10^{-18}$ m	weak isospin I_3	$W^\pm, Z$ bosons

The gauge bosons are particles with a spin equal to one that mediate the three fundamental interactions described by the SM. Their distinct characteristics are related to the different properties of the respective interactions, which are summarised in Table 1.1. The carriers of the strong force are the massless *gluons* (g) which couple to the color charge. Therefore, the strong force acts exclusively on quarks and the gluons themselves. The *photon* (γ) mediates the electromagnetic interaction which couples to the electric charge. As the photons themselves carry neither mass nor electric charge, the range of the electromagnetic interaction is unlimited. Lastly, the weak interaction is mediated by three massive gauge bosons; the neutral Z -boson and the W^+ and W^- bosons which carry an electric charge of $\pm 1e$ respectively. The weak force acts on the *weak isospin* which is non-zero for all fermions.

The boson content of the SM is completed by the *Higgs boson* (H), a massive particle with a spin of zero, making it the only scalar particle in the SM. It emerges from the Higgs mechanism by which the elementary particles acquire their masses. This chapter provides a brief overview of the mathematical foundations of the SM followed by a discussion of the fundamental interactions. Examples of experimental evidence supporting the SM are given and limitations of the theory and potential extensions are outlined.

1.1. Theoretical formulation

The SM is a *quantum field theory* (QFT) built on the laws of quantum mechanics and special relativity [18]. Particles are described as excitations of *fields* whose properties and interactions are encoded in the *Lagrangian*. The fundamental particles in the SM are fermions that are described by *Dirac fields*. In the absence of interactions, the corresponding Lagrangian takes the form

$$\mathcal{L}_0 = \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi, \quad (1.1)$$

where ψ denotes the four-component spinor describing the fermion field, γ^μ indicates the Dirac matrices, m the mass of the fermion and $\bar{\psi} = \psi^\dagger \gamma^0$ the *Dirac adjoint* of ψ .



In all formulas in this chapter, greek indices run from zero to three, latin indices run from one to three and Einstein's summation convention is applied.

The central principle by which the SM Lagrangian is built from Equation 1.1 is the invariance of the system under certain symmetry transformations. Mathematically, this means that the Lagrangian is required to be invariant under a local transformation of the fermion field $\psi \rightarrow \psi' = U(x)\psi$, where $U(x)$ constitutes an element of the symmetry group G . According to group theory, the transformation can be expressed as

$$U(x) = e^{-ig\alpha(x)_a T^a},$$

with a real parameter g , location-dependant phases $\alpha(x)_a$ and the generators of the symmetry group T^a . The generators obey the commutation relation $[T^a, T^b] = if^{abc}T^c$ with *structure constants* f^{abc} , which are zero for *abelian* theories. Under such transformations, $\mathcal{L}_0$ changes as terms depending on the derivative of $\alpha(x)_a$ emerge. In order to achieve *local gauge invariance*, these terms are counteracted by introducing the *gauge covariant derivative*

$$D_\mu = \partial_\mu + igA_\mu^a T^a,$$

which replaces the partial derivative in Equation 1.1. A *gauge field* $A_\mu(x)$ is introduced, which transforms under local gauge transformations as

$$A_\mu^a \rightarrow (A_\mu^a)' = A_\mu^a - \partial_\mu g\alpha(x)_a.$$

This approach ensures local gauge invariance of the Lagrangian by introducing a coupling between the initial fermion field and the gauge field. The strength of the coupling is encoded in the parameter g .

Now that the gauge field is introduced to the Lagrangian, a term that describes its free propagation needs to be added. Using the *field strength tensor* of A_μ :

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc}A_\mu^b A_\nu^c, \quad (1.2)$$

the simplest suitable addition for a source-free field reads

$$\mathcal{L}_{\text{dyn}} = -\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu a}. \quad (1.3)$$

The SM is invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$. With the recipe outlined above, this can be used to construct the fundamental interactions and properties of their mediators. Since this thesis has an experimental focus, the discussion of the mathematical details will be kept to a minimum for the remainder of this chapter.

Two interesting consequences of Equations 1.2 and 1.3 should be noted for the discussion of the fundamental interactions. For non-abelian gauge theories, the structure constants f^{abc} are non-zero, which gives rise to self-couplings of the gauge fields. Secondly, mass terms for the gauge fields analogous to those of the fermion field in Equation 1.1 would require terms of the order $A_\mu^a A^{a\mu}$. Such terms are not gauge invariant, and gauge theories formulated according to the recipe given above therefore only describe fermions interacting through the exchange of massless bosons.



1.2. Scattering amplitudes and Feynman diagrams

The framework of QFTs does not only provide an elegant way to define the properties of particles and interactions between them but also offers the means to make quantitative predictions about the production, interaction and decay of particles [19]. The central quantity needed to derive predictions is the *scattering amplitude*, or *matrix element*, $\mathcal{M}_{fi}$ for an initial state $|\Phi\rangle$ to evolve into a different final state $\langle\Psi|$,

$$\mathcal{M}_{fi} = \langle\Psi|M|\Phi\rangle.$$

The scattering amplitude in turn depends on the *interaction operator* M of the scattering process which can be calculated via the usage of *Feynman diagrams* [20]. These diagrams are associated with a set of *Feynman rules* and thereby provide a powerful tool to visualise QFT processes and calculate the associated matrix elements.

Example Feynman diagrams for a generic scattering process $\psi\bar{\psi} \rightarrow \psi\bar{\psi}$ mediated by a gauge boson A are presented in Figure 1.2. The convention that time flows from the left to the right is employed for all Feynman diagrams in this thesis. Each line represents a particle, where straight lines indicate fermions and different line styles are used for bosons. The arrow on fermion lines is used to distinguish particles from antiparticles, where the arrows of the latter point in the negative time direction. External lines denote the particles in the initial and final states and are associated with the four-momenta and quantum numbers of the respective particles. Internal lines, or *propagators*, identify *virtual particles* which have the peculiar property that their four-momentum q violates the relation $q^2 = m^2$, wherefore they are referred to as being *off-shell*. A connection between lines is termed *vertex*, and the definition of

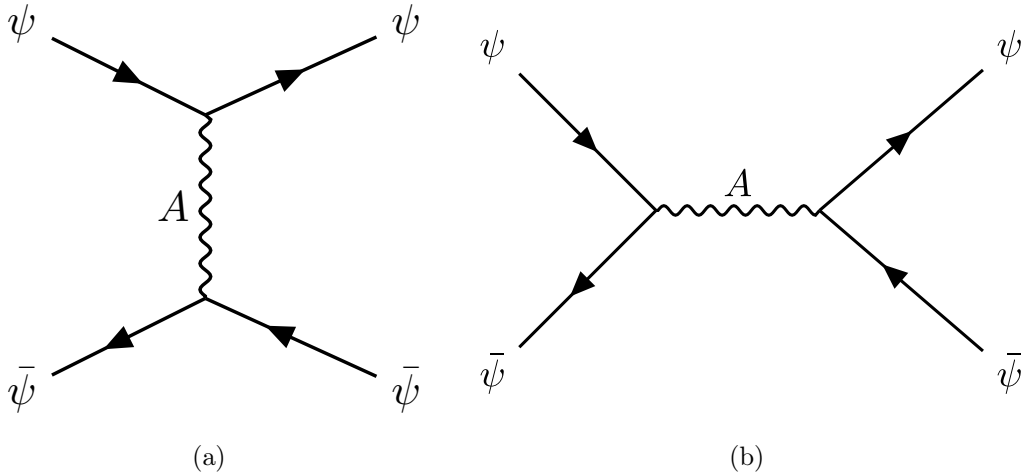


Figure 1.2: Example Feynman diagrams for a $\psi\bar{\psi} \rightarrow \psi\bar{\psi}$ scattering process mediated by (a) the exchange of a boson A and (b) the annihilation and pair-production of the fermions.



allowed vertices, i.e. which particles and how many may be connected to a single vertex, depends on the underlying theory. The Feynman rules for a given theory define the mathematical factors associated with vertices and propagators. Common rules for all theories include the conservation of four-momentum and quantum numbers at each vertex and the integration over internal four-momenta. A notable feature of vertices is that they contribute a factor proportional to g to the matrix element. The final scattering amplitude of any process is obtained by summing over all allowed and topologically unique diagrams.

For a $2 \rightarrow 2$ scattering process of a Hermitian scalar field yield, three different types of diagrams can contribute as shown in Figure 1.3. The respective matrix elements depend on the *Mandelstam variables* [18]

$$\begin{aligned} s &= (p_1 + p_2)^2, \\ t &= (p_1 - p_3)^2, \\ u &= (p_1 - p_4)^2, \end{aligned}$$

which correspond to the square of the four-momentum transfer. The variable s additionally equates to the square of the centre-of-mass energy of the process. Interactions whose Feynman diagrams share their topology with those in Figure 1.3 are commonly referred to as s -channel, t -channel and u -channel processes.

All Feynman diagrams discussed up to now represent *tree-level* diagrams that mediate the scattering process at the lowest possible order, or *leading order* (LO), of the coupling strength g . Examples for *next-to-leading order* (NLO) and *next-to-next-to-leading order* (NNLO) Feynman diagrams are given in Figure 1.4. The NLO process shown in Figure 1.4(a) contains an internal vertex, or *loop correction*, and the NNLO process in Figure 1.4(b) includes both a loop correction and an additional *real emission* of a boson. Diagrams of higher orders are built and labelled analogously.

The Feynman rules allow to add an arbitrary number of loop corrections and real

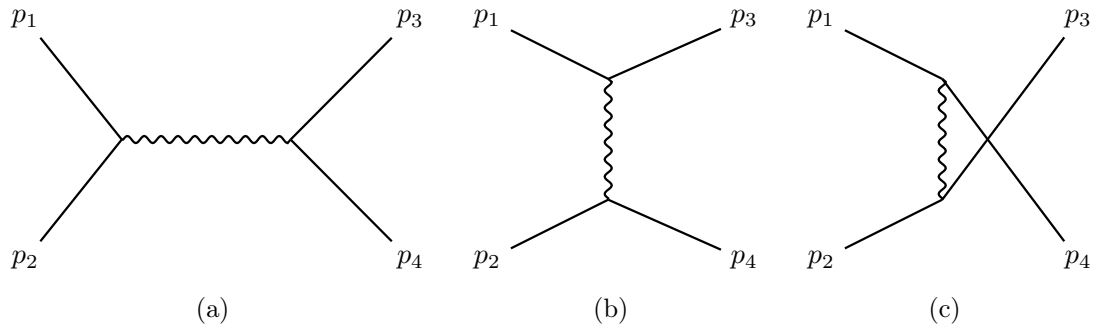


Figure 1.3: The three topologically distinct Feynman diagrams for a $2 \rightarrow 2$ scattering process referred to as (a) s -channel, (b) t -channel and (c) u -channel production. The p_i denote the four-momenta of the respective particles.

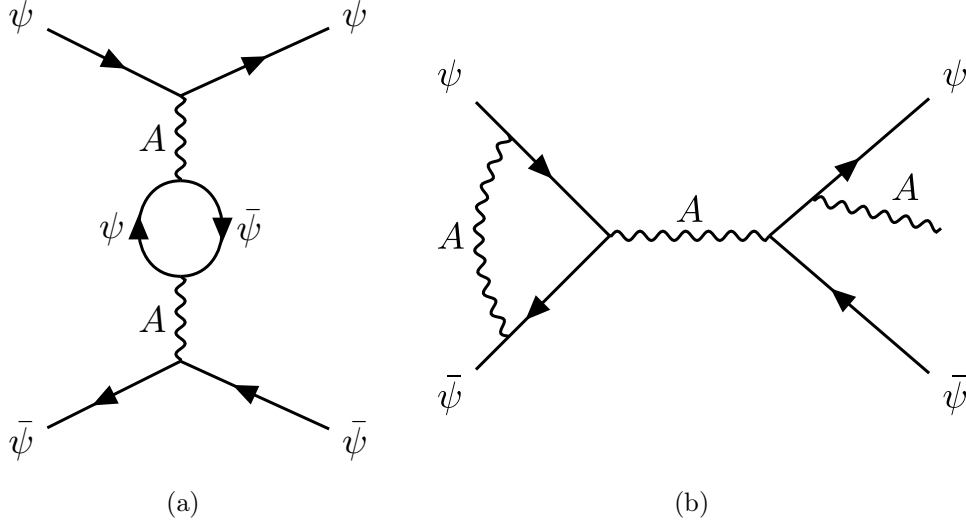


Figure 1.4: Examples for (a) NLO and (b) NNLO diagrams of the $\psi\bar{\psi} \rightarrow \psi\bar{\psi}$ scattering process.

emissions, which means that each scattering process is in principle mediated by an infinite number of diagrams. In practice, reasonable approximations of the scattering amplitude are obtained from *perturbative calculations* at a fixed order of g , which can be carried out when g is small. The contributions from higher-order diagrams are then suppressed by increasing powers of g and eventually become negligible.

However, effects from the lowest higher-order corrections need to be taken into account for precise predictions, which introduces an issue to the determination of matrix elements. As mentioned earlier, the calculation of matrix elements involves the integration over all internal four-momenta. For diagrams with loop corrections, these integrals diverge, leading to unphysical infinities. The solution lies in the application of *regularisation* and *renormalisation* techniques [18]. Regularisation introduces an upper scale Λ up to which the integration is performed. This yields finite results for the integrals, but it also causes the matrix element to depend on the artificial scale Λ . Renormalisation solves this issue by absorbing the divergent terms into observable quantities, which leads to a redefinition of the masses and couplings. The physical quantities m_{Phys} and g_{Phys} are measurable and finite; it is therefore assumed that the bare quantities m and g cancel out the infinities. The SM is a *renormalisable theory*, which means that all occurring divergencies can be absorbed by the redefinition of measurable quantities. An important property of all SM interactions follows from the renormalisation; the strength of the couplings depends on the momentum scale Q^2 of the process. The renormalised couplings are denoted as

$$\alpha(Q^2) = \frac{g(Q^2)^2}{4\pi}.$$



As another consequence, the masses of particles and the coupling strengths of the interactions cannot be predicted but are instead free parameters of the SM that have to be determined from measurements.

Taking all considerations outlined above into account, scattering amplitudes $\mathcal{M}_{fi}$ can be calculated and consequently used to derive predictions for scattering processes that can be tested experimentally [19]. A useful observable is the probability for a state transition $i \rightarrow f$ which is described by the *cross section* σ . It is proportional to the square of the magnitude of the scattering amplitude

$$\sigma_{i \rightarrow f} \propto |\mathcal{M}_{fi}|^2, \quad (1.4)$$

and usually calculated up to a certain order in perturbation theory. An NLO cross section is for example calculated from all contributing LO and NLO diagrams. It follows from Equation 1.4 that cross sections are sensitive to interference effects between diagrams. The cross section for a process with two contributing diagrams would for instance be proportional to

$$|\mathcal{M}|^2 = |\mathcal{M}_1 + \mathcal{M}_2|^2 = |\mathcal{M}_1|^2 + |\mathcal{M}_2|^2 + \underbrace{\mathcal{M}_1^* \mathcal{M}_2 + \mathcal{M}_1 \mathcal{M}_2^*}_{\text{interference}}.$$

A cross section has the dimension of an area and the unit commonly used in particle physics is the *barn*, where $1 \text{ b} = 10^{-28} \text{ m}^2$.

1.3. Quantum chromodynamics

The theoretical formulation of the strong force is based on the $SU(3)_C$ symmetry group and known as QCD. Three additional degrees of freedom are introduced, which are referred to as *color charges* and can take the values red, blue and green (r, b, g). The corresponding anticharges are denoted as $\bar{r}$, $\bar{b}$ and $\bar{g}$. Quarks are the only fermions that carry color charge and partake in the strong interaction. Unlike the quantum numbers associated with the electroweak interaction, the color charges are not connected to the quark flavour. Each quark therefore exists in one of three distinct color states, and the Lagrangian is constructed as the sum over all flavours f and color charges c ,

$$\begin{aligned} \mathcal{L}_{\text{QCD},q} &= \sum_{f,c} \bar{\psi}_{f,c} i \gamma^\mu D_\mu \psi_{f,c} \\ &= \sum_{f,c} \bar{\psi}_{f,c} i \gamma^\mu \left(\partial_\mu - i g_S \frac{\lambda^a}{2} G_\mu^a \right) \psi_{f,c}. \end{aligned}$$

Here, g_S denotes the strong coupling constant, G^a are the *gluon fields* and $\lambda^a \in \mathbb{C}^{3 \times 3}$ represent the eight generators of the $SU(3)_C$ symmetry group known as *Gell-Mann*



1.3. Quantum chromodynamics

matrices [19]. The Lagrangian of the free gluon field takes the form

$$\mathcal{L}_{\text{QCD,g}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu},$$

in accordance with Equation 1.3.

QCD is a non-abelian gauge theory and therefore includes self-couplings among gluons. The eight gluons associated with the Gell-Mann matrices form a *color octet*:

$$r\bar{g}, \bar{r}g, r\bar{b}, \bar{r}b, b\bar{g}, \bar{b}g, \frac{1}{\sqrt{2}}(r\bar{r} - g\bar{g}), \frac{1}{\sqrt{6}}(r\bar{r} + g\bar{g} - 2b\bar{b}).$$

As the different color states cannot be observed experimentally, no distinction is made in the technical language, and the strong interaction is commonly said to be mediated by a single gluon. Nevertheless, self-couplings between gluons are an important aspect of the strong interaction, which gives rise to the unique feature of the strong coupling constant that it increases with distance.

As outlined in Section 1.2, the couplings α of both the electroweak and the strong interaction depend on the energy scale at which the interaction takes place. The absolute value of a coupling strength cannot be calculated in QFT, but if the coupling is known at some energy scale μ^2 , a perturbative interpolation to a different scale Q^2 can be performed. For the strong interaction, the *running* of the strong coupling constant can be expressed at leading order as

$$\alpha_S(Q^2) = \frac{\alpha_S(\mu^2)}{1 + \alpha_S(\mu^2) \frac{11n_c - 2n_f}{12\pi} \ln\left(\frac{Q^2}{\mu^2}\right)}, \quad (1.5)$$

where n_c denotes the number of color charges and n_f the number of active quark flavours with $m_f^2 < Q^2$. This approximation is only valid up to the infrared cutoff scale Λ_{QCD} at which the denominator becomes zero. For energies below Λ_{QCD} , the perturbative approach is no longer applicable, since α_S becomes large.

The running of α_S is depicted schematically in Figure 1.5. For large energies, or short distances, the coupling strength approaches zero and allows for a perturbative description of QCD processes. This phenomenon is known as *asymptotic freedom*. On the other hand, the strong coupling increases for low energies and large distances which leads to *confinement*. When two quarks are spatially separated, the QCD potential between them increases until it is energetically preferable to produce a new quark-antiquark pair. Therefore, quarks cannot be observed individually and only occur in color-neutral bound states known as *hadrons*. The two common types of hadrons are *baryons*, composed out of three quarks with three different color charges, and *mesons*, which are built from a quark-antiquark pair with opposing color charges.

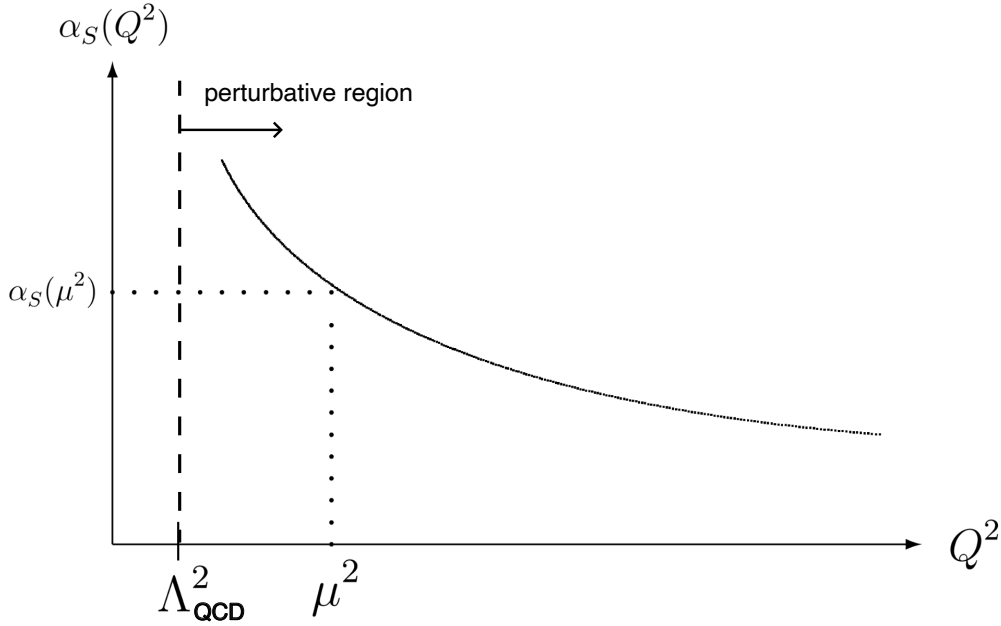


Figure 1.5: Dependence of the strong coupling constant α_S on the square of the momentum scale Q^2 shown with the infrared cutoff scale Λ_{QCD} and some arbitrary scale μ . Figure adapted from [21].

1.4. The electroweak interaction

The electroweak interaction unifies the theories of the weak interaction and *quantum electro dynamics* (QED), which constitutes the extension of electromagnetism into a QFT. Its underlying symmetry group is $SU(2)_L \times U(1)_Y$. The associated quantum numbers are the third component I_3 of the weak isospin I and the *weak hypercharge* Y . The generators of $SU(2)_L$ can be expressed via the three *Pauli matrices* $\sigma_i \in \mathbb{C}^{2 \times 2}$, giving rise to three non-abelian gauge bosons W_μ^i . The $U(1)_Y$ group has only one generator, and the associated gauge boson coupling to the weak hypercharge is denoted as B_μ . The $U(1)$ symmetry group is of abelian nature and allows no self-couplings of B_μ .

The electroweak interaction has the unique property to differentiate between particles according to their *chirality*. Defined as the eigenvalues of the matrix $\gamma^5 = \gamma^0 \gamma^1 \gamma^2 \gamma^3$, chirality can take the values $+1$ and -1 . Fermion fields can be split into a *right-handed* part ψ_R associated with a chirality of $+1$ and a *left-handed* part ψ_L for the chirality of -1 . The gauge bosons W_μ^i only couple to left-handed fermions, which form doublets under the weak isospin. The isospin doublets consist of either an up-type and a down-type quark of the same generation or a lepton with its associated neut-



rino:

$$\psi_L \in \begin{pmatrix} q^{\text{u-type}} \\ q^{\text{d-type}} \end{pmatrix}_L, \begin{pmatrix} \ell \\ \nu_\ell \end{pmatrix}_L. \quad (1.6)$$

Right-handed fermions are represented as singlets,

$$\psi_R \in q_R^{\text{u-type}}, q_R^{\text{d-type}}, \ell_R, \quad (1.7)$$

where it should be stressed that right-handed neutrinos are not included in the SM. The electroweak Lagrangian then takes the form

$$\begin{aligned} \mathcal{L}_{\text{EW}} = & -\frac{1}{4}W_{\mu\nu}^j W^{j\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} && \text{(gauge fields)} \\ & + i\bar{\psi}\gamma^\nu\partial_\nu\psi && \text{(fermion fields)} \\ & + (\bar{\psi}_L \quad \bar{\psi}'_L) \left(g\gamma^\mu W_\mu^i \frac{\sigma_i}{2} + g'\gamma^\mu B_\mu \frac{Y}{2} \right) \begin{pmatrix} \psi_L \\ \psi'_L \end{pmatrix} && \text{(left-handed interactions)} \\ & + \bar{\psi}_R g'\gamma^\mu B_\mu \frac{Y}{2} \psi_R && \text{(right-handed interactions)} \\ & + \text{hermitian conjugate,} \end{aligned}$$

where g and g' denote the respective coupling strengths of the bosons W_μ^i and B_μ . However, the gauge bosons W_μ^i cannot be identified with the force carriers of the weak interaction for two striking reasons. Firstly, the Z -boson couples to both left-handed and right-handed fermions [17], and secondly, the observed W and Z bosons are massive particles. The solution to both issues is described in the following.

1.5. The Higgs mechanism

The theoretical foundation of the SM presented up to now cannot accommodate massive bosons without breaking the underlying symmetries of the theory. This issue is addressed by the Higgs mechanism. It relies on the concept of *spontaneous symmetry breaking*, where the Lagrangian of a theory is invariant under a given symmetry, but the ground state is not.

A complex scalar field, the *Higgs field*, which possesses a weak hypercharge $Y = +1$ and constitutes a weak-isospin doublet is introduced,

$$\Phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}.$$

The field is subject to the *Higgs potential*

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2,$$

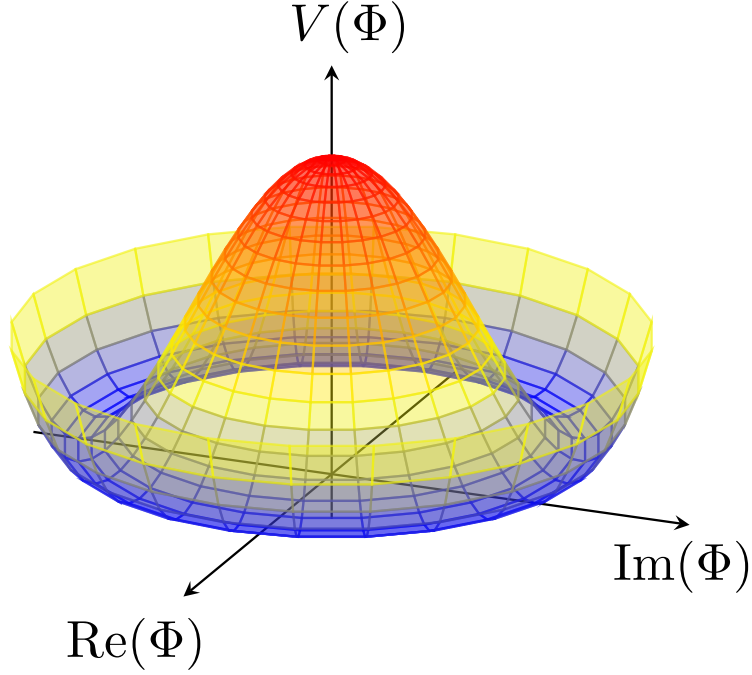


Figure 1.6: Representation of the Higgs potential as a function of the real and imaginary parts of a scalar field Φ for $\mu^2 < 0$ [22].

with the parameters $\mu^2 < 0$ and $\lambda > 0$. The potential is shown in Figure 1.6 as a function of the real and imaginary parts of a single scalar field. Due to its iconic shape, it is often referred to as *mexican hat potential*. Its characteristic features are an unstable maximum at $\Phi = 0$ and a set of stable but degenerate minima that form a circle with radius $\Phi^\dagger \Phi = \nu = -\mu^2/\lambda$ around the origin. The field thereby gains a non-zero ground state with a *vacuum expectation value* (VEV) ν and can be expressed in the *unitary gauge* [18] as

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H(x) \end{pmatrix},$$

where $H(x)$ is the Higgs boson emerging as an excitation of the field. The Higgs part of the SM Lagrangian reads

$$\mathcal{L}_\Phi = (D^\mu \Phi) D_\mu \Phi - V(\Phi), \quad (1.8)$$

where D^μ denotes the covariant derivative of the electroweak interaction. By plugging the full terms for D^μ and $\Phi(x)$ into Equation 1.8, it becomes apparent that the VEV of the Higgs field gives rise to four vector bosons that can be expressed as mixtures of the W_μ^i and B_μ bosons:



$$\begin{aligned}
W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2) && \text{with } m_W = \frac{gv}{2}, \\
Z_\mu &= (\cos(\theta_W)W_\mu^3 - \sin(\theta_W)B_\mu) && \text{with } m_Z = \frac{gv}{2\cos(\theta_W)}, \\
A_\mu &= (\sin(\theta_W)W_\mu^3 + \cos(\theta_W)B_\mu) && \text{with } m_A = 0.
\end{aligned}$$

The *weak mixing angle* θ_W is defined as $\tan(\theta_W) = \frac{g'}{g}$ from the coupling strengths g and g' associated with the W_μ^i and B_μ bosons. The Lagrangian $\mathcal{L}_\Phi$ contains terms of the form $W_\mu W^\mu$ and $Z_\mu Z^\mu$ from which the masses of the W and Z bosons are determined. The *photon field* A_μ remains massless and couples to the electric charge Q , which is related to the quantum numbers of the electroweak interaction through the relation

$$Q = I_3 + \frac{Y}{2}.$$

The Higgs boson itself obtains the mass $m_H = \sqrt{2\lambda}\nu$. Additionally, fermion masses can be generated through couplings to the Higgs field, allowing for a uniform picture of the origin of particle masses. The coupling between a Dirac field and a scalar field is termed *Yukawa coupling* [21]. The Yukawa part of the SM Lagrangian takes the general form

$$\mathcal{L}_{\text{Yukawa}} = y_f \bar{\phi}_L \Phi \phi_R + \text{hermitian conjugate},$$

where y_f denotes the coupling strength, Φ represents the Higgs field and $\phi_{L/R}$ are the left-handed doublets and right-handed singlets of the fermion fields introduced in Equations 1.6 and 1.7. By writing out the terms of $\mathcal{L}_{\text{Yukawa}}$, it can again be shown that mass terms of the form $y_f \frac{\nu}{\sqrt{2}} \bar{\phi} \phi$ arise. Fermions thereby acquire a mass proportional to their respective coupling strength to the Higgs field, $m_f = y_f \frac{\nu}{\sqrt{2}}$. Neutrinos however remain massless as the SM does not include right-handed neutrino fields.

Quark mixing

The fermion fields that acquire mass through the Yukawa coupling as outlined above are known as the *mass eigenstates*. For quarks, these states do not coincide with the *weak eigenstates* taking part in the weak interaction. If the mass eigenstates and weak eigenstates of up-type quarks are set to agree, the weak eigenstates of down-type quarks d' , s' and b' can be expressed as linear combinations of the mass eigenstates d , s and b via the *Cabibbo-Kobayashi-Maskawa* (CKM) *matrix* [23]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$



The matrix elements are not independent but can be expressed in terms of four free parameters of the SM; one CP-violating phase and three mixing angles. The most precise measurements of the matrix elements to date [15] yield

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix}. \quad (1.9)$$

As the probability for a transition of quark flavour $i \rightarrow j$ is proportional to $|V_{ij}|^2$, flavour changes between different generations are suppressed.

Only the charged-current interaction mediated by the W -boson causes quark flavour transitions in the SM. Flavour changes mediated by the Z -boson are forbidden at tree level and heavily suppressed at higher orders by the *GIM mechanism* [18]. For leptons, the weak eigenstates are identical with the mass eigenstates, therefore flavour transitions are forbidden.

1.6. Experimental validation

In the decades since its formulation, the SM has been tested meticulously by various experiments that probed its predictions over a broad spectrum of energy scales. The vast majority of experiments found excellent agreement with the SM predictions. Up to the time of writing this thesis, this finding persists even as advancements in both theoretical calculations and experiments allow for comparisons with unprecedented precision. This section provides some examples of experimental results supporting the SM.

Prediction of elementary particles

A very strong backing for the credibility of any theory in physics is the capability of predicting the outcome of measurements. The SM has been up to this challenge multiple times, as numerous elementary particles have been postulated since the 1960s and subsequently observed in measurements. The latest example is the discovery of the Higgs boson in 2012 [24, 25] which concluded the search for particles predicted by the SM. An overview of all elementary particles predicted and discovered after 1960 is given in Figure 1.7.

Cross-section measurements

An important tool to test predictions from theoretical calculations are cross-section measurements. The predictions of the SM for the cross sections of various processes

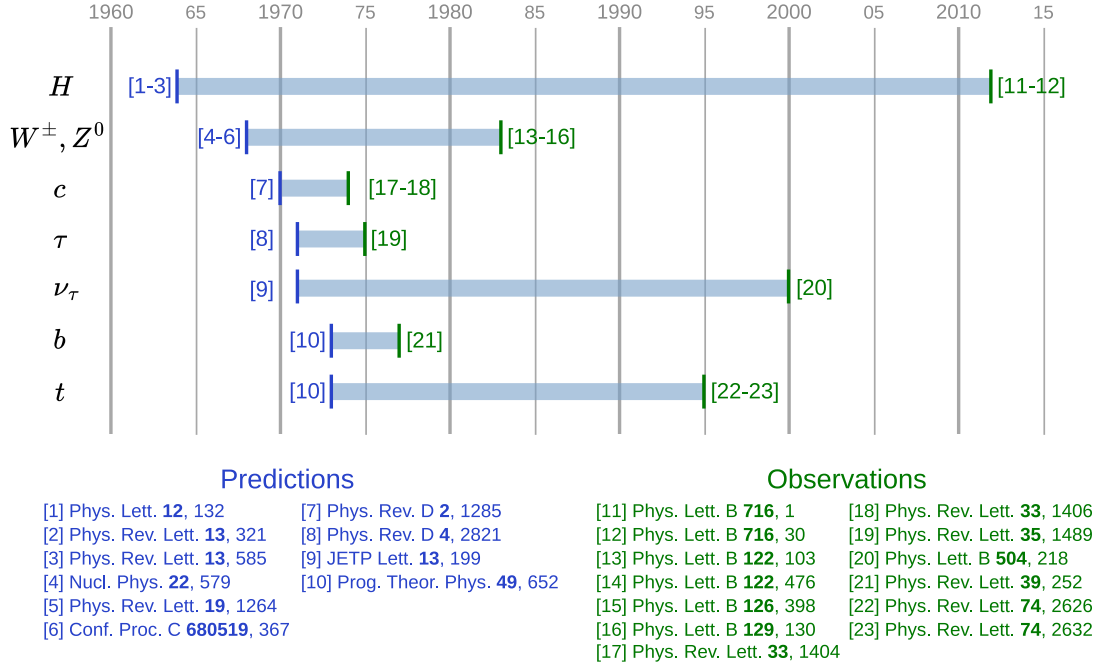


Figure 1.7: Overview of elementary particles that were predicted and observed after 1960.

have been tested extensively over the years by many different experiments. Figure 1.8 exemplarily shows the measurement results obtained by the ATLAS experiment for the cross sections of numerous interactions at different centre-of-mass energies. The figure includes total and fiducial cross sections, where the latter are measured in a limited phase space. The shown results cover electroweak and strong interaction processes with cross sections that are spread over several orders of magnitude. Over the whole probed spectrum, the SM predictions exhibit an excellent agreement with the measurement results.

Consistency in the free parameters

While the SM offers no prediction for its 19 free parameters, their interdependence can be used to probe the consistency of the theory. For instance, the masses of the top quark and Higgs boson affect the W -boson mass through loop corrections, which was used successfully to set constraints on the Higgs-boson mass prior to its discovery [27]. Precision data from the electroweak sector is routinely used to perform a global fit of the SM to data. With measurements available for all free parameters, the global fit can evaluate the agreement between the individual measurements and the constraints set by the other parameters according to the SM. The latest fit found full compatibility between the precision data and the SM predictions, with no tension outside of expected statistical fluctuations [28].

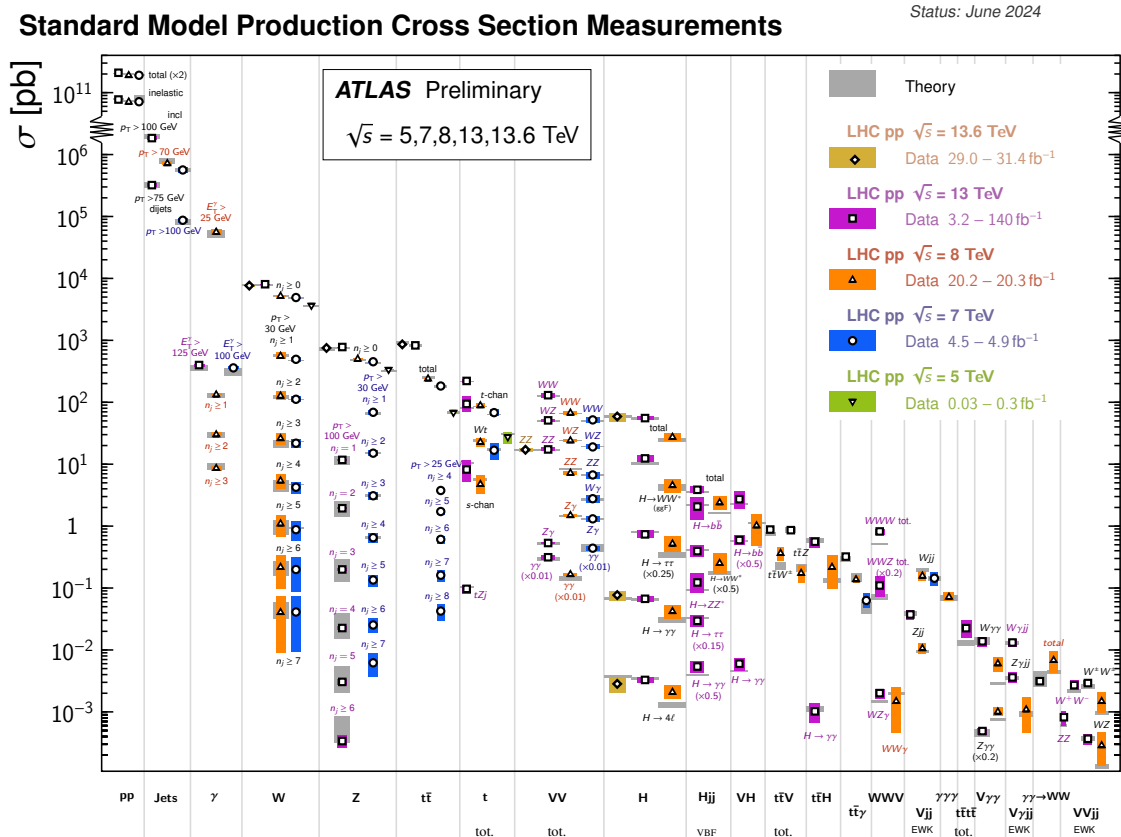


Figure 1.8: Summary of cross-section measurements performed by the ATLAS experiment with a comparison to the SM predictions [26].

1.7. Limitations

The SM has proven to be a tremendously successful theory, able to describe most observations to date. However, some open questions remain. There are some experimental findings the SM in its current form cannot explain, and conceptual issues hint at the need for a more fundamental theory. A selection of unexplained phenomena is discussed in the following.

Neutrino oscillations

As outlined in Section 1.5, neutrinos are considered to be massless in the SM. This however stands in contradiction with the well-established phenomenon of neutrino oscillations, i.e. the observation that neutrinos can change their flavour as they propagate [29]. The theoretical description of neutrino oscillation requires the flavour eigenstates to be linear combinations of the mass eigenstates, determined by a mixing



matrix similar to the CKM matrix. With different masses for each neutrino and a non-vanishing mixing, the probability for a neutrino to undergo flavour oscillation depends on its energy and the travelled distance.

In principle, the SM can be extended to account for neutrino masses, but mutually exclusive models exist for the mechanism by which neutrinos acquire mass [30]. In some models, neutrinos are Dirac fermions that are coupled very weakly to the Higgs field. Other theories predict neutrinos to be Majorana fermions, which means that neutrinos and antineutrinos are described by the same field, whose mass is a consequence of new high-energy phenomena. As long as the nature of neutrinos remains unclear, the SM remains incomplete.

The standard model of cosmology

The SM of particle physics describes the fundamental interactions at small interaction lengths and high energies with unmatched precision. On the other end of the spectrum, the nature of the universe is successfully described by the standard model of cosmology, which is also called the Λ -CDM model after its two central concepts [31]. The cosmological constant Λ represents the *dark energy* which manifests as a constant energy density and is responsible for the accelerated expansion of the universe. The *cold dark matter* (CDM) on the other hand provides an explanation for gravitational lensing effects and the measured rotation curves of spiral galaxies [32, 33]. The Λ -CDM model has also proven successful in modelling the anisotropy spectrum of the *cosmic microwave background* [31]. Related measurements suggest a composition of 68 % dark energy, 27 % dark matter and only 5 % common matter in our universe. The SM of particle physics offers no dark matter candidates and predicts a vacuum energy density, a potential source of the dark energy, that lies 120 orders of magnitude above the the measured values [34]. Reducing the tension between the two models and finding a dark matter candidate compatible with both models would pose an important breakthrough towards a holistic understanding of the universe.

Conceptual limitations

From a conceptual point of view, the SM exhibits some features begging for explanation by a more complete theory. For instance, no evidence for CP violation in QCD interactions has been found to date, which puts very tight constraints on the CP violating phase in QCD, one of the free parameters of the SM [35]. There is however no theoretical explanation why this parameter should have such a low value, and this puzzle is known as the *strong CP problem*. On a similar note, there is no compelling reason for the existence of exactly three generations of both leptons and quarks.

Another striking feature of the SM is that it describes only three of the four fundamental interactions observed in nature. Gravity is described by Einstein's theory of *general relativity* [36] in terms of bending of space-time, and the unification with the

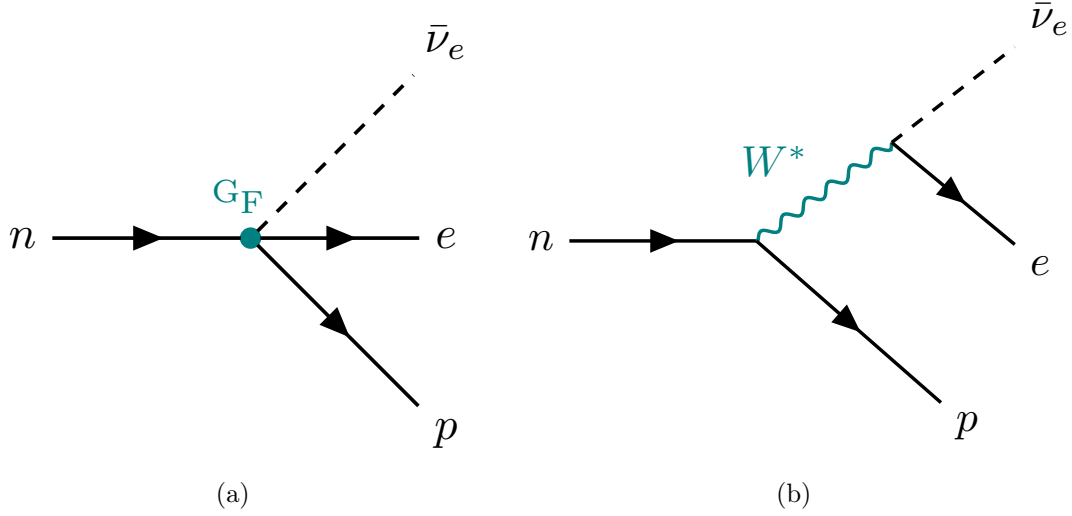


Figure 1.9: Feynman diagrams of the β decay at low energies according to (a) the Fermi theory and (b) the SM.

SM remains an open issue. Additionally, the large discrepancy between the strengths of the fundamental forces is known as the *hierarchy problem* since it is not understood why the strength of the gravitational interaction is 24 orders of magnitude below the weak interaction.

1.8. Extension through effective field theory

As open questions about the nature of the universe at the smallest scales remain, searches for physics beyond the SM (BSM) constitute an important sector of particle physics. A model-agnostic approach to search for new particles or interactions at higher energy scales is provided by *effective field theory* (EFT) frameworks, which operate under the assumption that high-energy phenomena have an effective impact on experiments carried out at lower energies. This approach was successfully used in the past by Enrico Fermi to describe the weak interaction [37]. His description of observed β decays of the sort $n \rightarrow p + e^- + \bar{\nu}_e$ took the form of a four-fermion contact interaction as shown in Figure 1.9(a). The strength of the interaction is denoted by the Fermi constant G_F , and the theory accurately describes the interaction at the energy scales that were accessible at that time. However, the predicted cross section diverges at high energies as it grows proportional to $G_F^2 E^2$. This was an early indicator that the theory would break down at some energy scale. This scale turned out to be the mass-scale of the weak gauge bosons, as Fermi's interaction constitutes a low-energy EFT description of the weak interaction which mediates the β decay via the exchange of a W -boson as shown in Figure 1.9(b).



The idea of treating the SM as a low-energy approximation of a more complete theory is therefore an obvious approach to search for effects of new high-energy phenomena. In *Standard Model effective field theory* (SMEFT), the SM is described as an effective theory that is applicable up to the energy scale of new interactions Λ . The field theory above that scale is required to be invariant under the SM gauge symmetries $SU(3)_C \times SU(2)_L \times U(1)_Y$ and incorporate all degrees of freedom of the SM, either as fundamental or composite fields.

The SM Lagrangian then becomes the first term in an effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda} \mathcal{L}^{(5)} + \frac{1}{\Lambda^2} \mathcal{L}^{(6)} + \dots,$$

where the upper index denotes the dimension of the individual terms. The terms of higher dimensions take the form

$$\mathcal{L}^{(d)} = \sum_k C_k^{(d)} O_k^{(d)},$$

where the $O_k^{(d)}$ denote the operators of dimension d with a corresponding dimensionless coupling constant, or *Wilson coefficient*, $C_k^{(d)}$. In this way, the low-energy effects of new phenomena are described without restricting the theory to a specific model.

At dimension five, only one independent operator exists that satisfies the SM gauge symmetry constraints. It violates lepton-number conservation and generates neutrino masses in accordance with the theory of neutrinos being Majorana fermions [38]. At dimension six, 59 independent operators remain when minimal flavour violation and baryon-number conservation are assumed. The SMEFT approach remains useful for searches despite the sizeable amount of operators, since only a subset of them contribute to any given process. Operators of higher dimensions are suppressed by further factors of Λ and increase drastically in numbers [39], which complicates their assessment from both the experimental and theoretical side.

2. The ATLAS detector at the Large Hadron Collider

On the experimental side of particle physics, huge progress has been made in the past decades. A major driver of the progress is the steady improvement in the instrumentation available to study elementary particles, which has come a long way from the cloud chambers used in the 1930s.

Nowadays, particle accelerators in combination with dedicated detectors are central tools to study the interactions between elementary particles. The accelerator and detector that produced and collected the data analysed in this thesis are introduced in the following.

2.1. The Large Hadron Collider

The *Large Hadron Collider* (LHC) [40] is a particle accelerator and collider situated at CERN, within the territories of Switzerland and France. With a circumference of 26.7 km, the LHC is the largest and most powerful particle accelerator built to date. Protons, or in special runs heavy ions, are accelerated and brought to collision at four dedicated interaction points, where the detectors of the four main experiments are situated. The two largest experiments *A Toroidal LHC ApparatuS* (ATLAS) [41] and *Compact Muon Solenoid* (CMS) [42] use general-purpose detectors to perform a broad range of measurements, spanning from precision measurements of SM parameters to searches for BSM physics. *A Large Ion Collider Experiment* (ALICE) [43] is dedicated to measurements of heavy ion collisions to study the quark-gluon plasma and the *Large Hadron Collider beauty* (LHCb) [44] experiment focuses on the decays of hadrons containing b -quarks.

In the current data taking period, a centre-of-mass energy $\sqrt{s} = 13.6$ TeV is reached in proton-proton collisions. The measurement presented in this thesis analyses the proton-proton collision data taken during the so-called Run 2 in the years 2015–2018 at $\sqrt{s} = 13$ TeV.

To reach such high energies, several pre-accelerators are needed. A schematic representation of the accelerator complex at the end of Run 2 is shown in Figure 2.1. At the beginning of the acceleration process, an electric field is used to strip hydrogen atoms off their electrons. The remaining protons are accelerated to an energy of 50 MeV by the linear accelerator LINAC 2 and injected into the *Proton Synchrotron Booster*, where an energy of 1.6 GeV is reached. The Booster injects into the *Proton Synchrotron* (PS) which further accelerates the protons to 26 GeV. From there, the

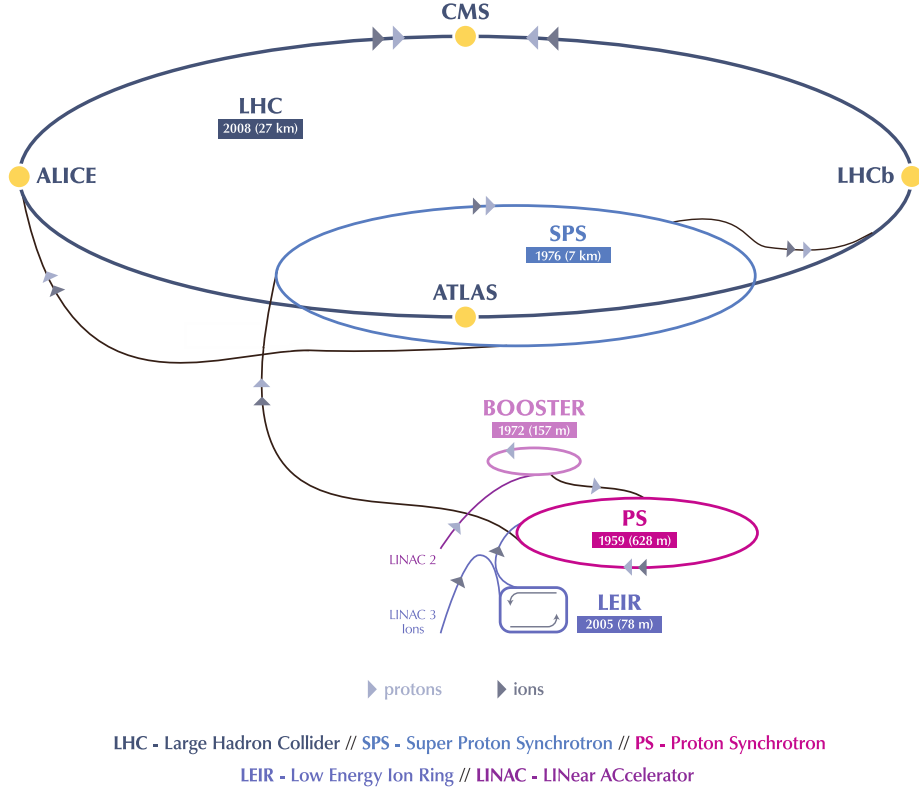


Figure 2.1: Schematic representation of the part of CERN’s accelerator complex relevant for the LHC operation. The state of the accelerator complex at the end of Run 2 is shown. Figure adapted from [45].

protons are passed to the *Super Proton Synchrotron* (SPS) where they are accelerated to 450 GeV and finally injected into the LHC in the form of *bunches* which are spaced at 25 ns [46]. Two counter-rotating beams are incrementally filled this way. Each beam can contain up to 2556 bunches, which in turn contain about 10^{11} protons each.

The beam properties determine how many collisions will occur when the beams are crossed at the interaction points. A measure for the number of interactions within a given area and time is the *instantaneous luminosity* $\mathcal{L}$. For a Gaussian beam profile, the luminosity is determined as

$$\mathcal{L} = \frac{N_b n_p^2 f_R \gamma_r}{4\pi \epsilon_n \beta^*} F. \quad (2.1)$$

N_b denotes the number of bunches per beam, n_p the number of protons per bunch, f_R the revolution frequency and γ_r the relativistic gamma factor. The ϵ_n indicates the



normalised transverse beam emittance, the beta function β^* determines the transverse beam size at the interaction point and the *geometric luminosity reduction factor* F accounts for the reduction in luminosity due to the non-zero crossing angle between the beams.

The *integrated luminosity* $\mathcal{L}_{\text{int}}$ connects the cross section σ of a given process with the expected number of produced events N

$$N = \sigma \int \mathcal{L} dt = \sigma \mathcal{L}_{\text{int}}. \quad (2.2)$$

Therefore, a precise measurement of $\mathcal{L}_{\text{int}}$ is important for cross-section measurements. A high luminosity is generally favourable as it leads to a large number of events, which is especially important for the measurement of rare processes, i.e. processes with a low cross section. However, a high instantaneous luminosity comes at the price of additional proton-proton interactions per bunch crossing. The mean number of interactions per bunch crossing is referred to as the *pileup* μ . For Run 2, the average pileup in ATLAS was $\langle \mu \rangle = 33.7$ [47].

2.2. The ATLAS detector

The ATLAS detector is the largest detector at the LHC with a length of 46 m and a diameter of 25 m. An overview of the detector layout is presented in Figure 2.2. Cylindrical in shape, the detector comprises various sub-detectors which are arranged in layers around the interaction point to identify particles and measure their properties. The detector is forward-backward symmetric with respect to the interaction point and divided into a *barrel* region, where the sub-detectors are arranged concentrically around the beam pipe, and two *end-caps* at either side of the barrel, oriented perpendicularly to the beam pipe.

ATLAS uses a right-handed coordinate system with the nominal interaction point as its origin. The x -axis points towards the centre of the LHC, the y -axis points upwards and the z -axis is oriented along the beam pipe. To describe the direction of particles, polar coordinates are commonly used. The azimuthal angle ϕ is defined in the xy -plane with respect to the x -axis, and the polar angle θ defines the opening angle with respect to the z -axis. The *pseudorapidity*

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right) \quad (2.3)$$

is commonly used instead of the polar angle. In cases where the mass of a particle is negligible, η approximates the particles *rapidity*

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right). \quad (2.4)$$

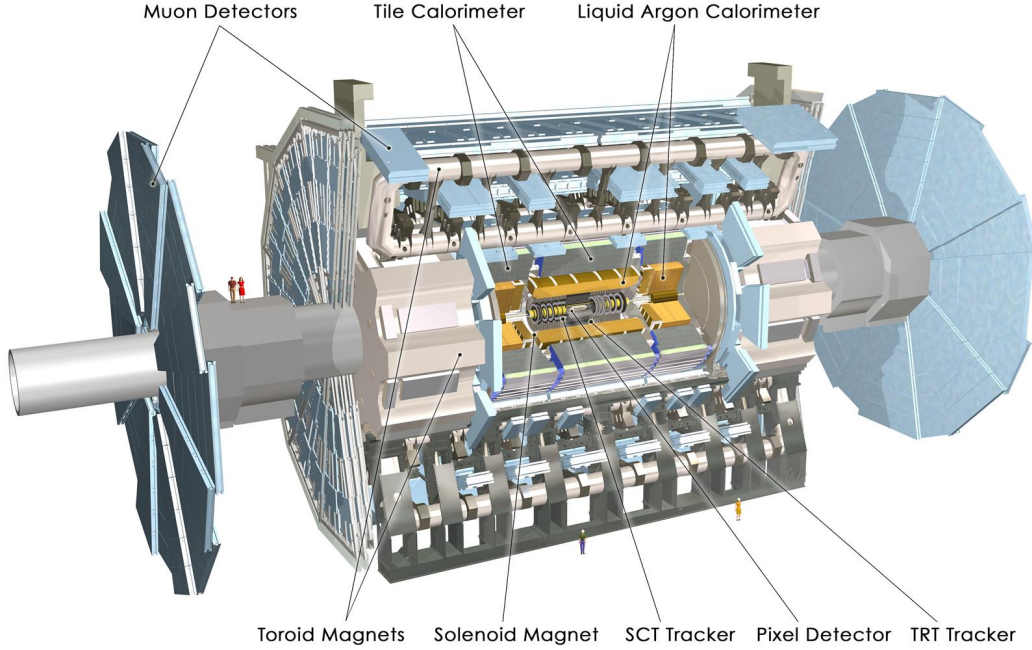


Figure 2.2: Schematic representation of the ATLAS detector [48].

The angular distance between two particles $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is commonly calculated using the pseudorapidity.

2.2.1. The Inner Detector

The *Inner Detector* (ID) [49, 50] is a tracking detector and the closest layer to the beam pipe. It contains three sub detectors, the *Pixel Detector*, the *Semiconductor Tracker* (SCT) and the *Transition Radiation Tracker* (TRT), and is submerged in a 2 T solenoidal magnetic field oriented along the z -axis. The ID measures the trajectory of electrically charged particles with a high spatial resolution in the pseudorapidity range $|\eta| < 2.5$. The particles are deflected by the magnetic field, which allows for the reconstruction of a particle's momentum. The resolution of the ID in the *transverse momentum* $p_T = \sqrt{p_x^2 + p_y^2}$ is

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% \cdot p_T \oplus 1\%,$$

where the p_T is given in GeV and $\oplus$ denotes the quadratic addition of the uncertainty components. The layout of the ID is shown in Figure 2.3.

The innermost subsystem of the ID is the Pixel Detector. It utilises silicon pixel sensors to detect charged particles passing through the semiconductor by applying an external electric field to separate the electron-hole pairs created by the traversing

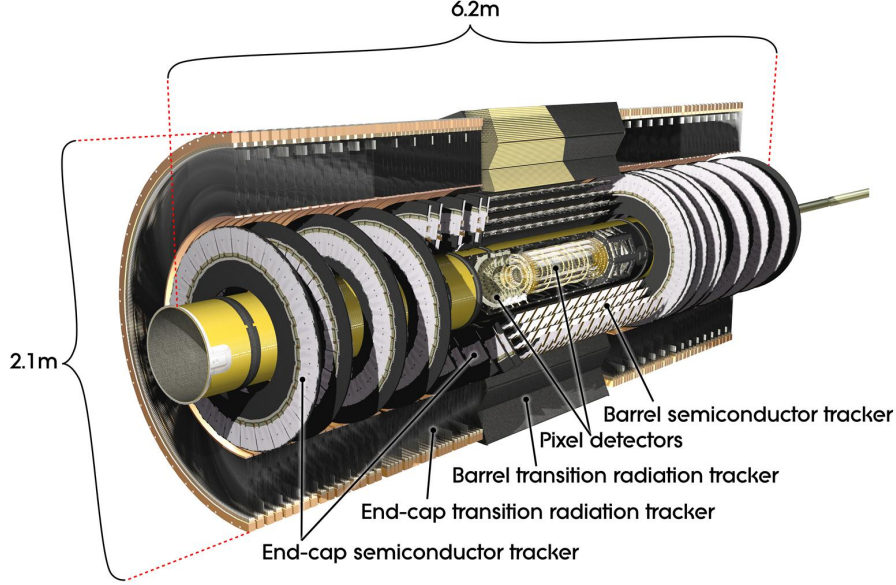


Figure 2.3: Schematic representation of the ATLAS ID in its original state from 2008 [51].

particle. The original detector contained three pixel layers to guarantee at least three space points for the reconstruction of tracks, reaching a spatial resolution of $10\mu\text{m}$ in the xy -plane and $115\mu\text{m}$ in z -direction. An additional fourth layer, the *Insertable B-Layer* (IBL) [52], was installed as new innermost layer prior to Run 2 to maintain the ID tracking performance under the increased pileup conditions and the anticipated radiation damage of the innermost layer. The IBL enhances the spatial resolution in z -direction to approximately $70\mu\text{m}$ and improves the reconstruction of the origin of tracks, which is crucial for many aspects of a precise event reconstruction, such as the distinction between the primary vertex of the hard scattering event and secondary decay vertices of long-lived interaction products.

The Pixel Detector is surrounded by the SCT, a silicon micro-strip detector that adds four layers of sensors in the barrel region and nine layers in the end-cap. The sensors are based on the same detection principle as the silicon pixel sensors, but have a coarser resolution of $17\mu\text{m}$ in the xy -plane and $580\mu\text{m}$ in z -direction.

The TRT constitutes the outermost layer of the ID and offers a continuous tracking, complementary to the silicon based detectors. It consists of more than 70 layers of drift tubes, each 4mm in diameter, oriented parallel to the beam pipe in the barrel region and perpendicularly in the end-cap regions. The drift tubes are filled with an $\text{Ar:CO}_2\text{:O}_2$ or $\text{Xe:CO}_2\text{:O}_2$ gas mixture in the barrel and end-cap regions respectively. The gas mixture is ionised by traversing charged particles. The resulting electrons are collected at the central anode wire, producing a signal to be read out. The drift tubes are interleaved with radiator materials, where traversing charged particles emit transition radiation with an energy proportional to their Lorentz factor $\gamma = E/m$.

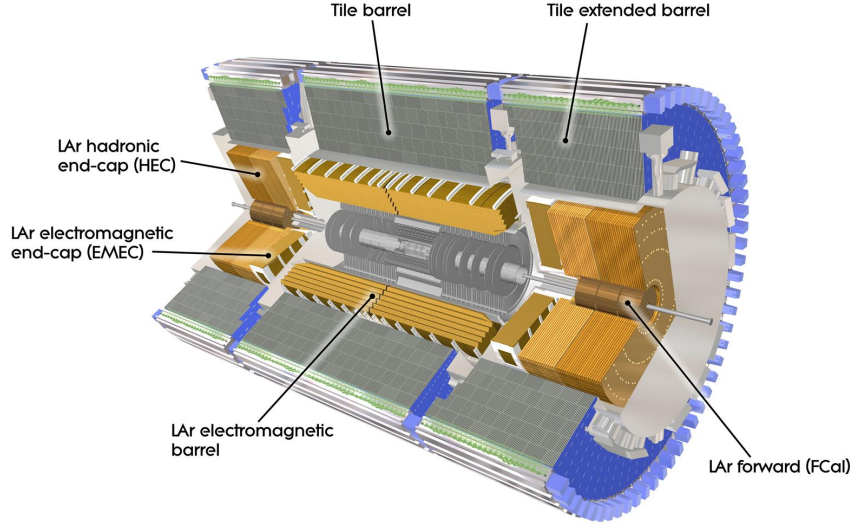


Figure 2.4: Schematic representation of the ATLAS calorimetry system [56].

Therefore, the TRT provides electron identification complementary to that of the calorimetry system.

2.2.2. The calorimeters

The calorimetry system is positioned around the ID and measures the energy of particles. It consists of three calorimeters, the *Electromagnetic Calorimeter* (ECal), the *Hadronic Calorimeter* (HCal) and the *Forward Calorimeter* (FCal) [53–55]. All three subsystems consist of sampling detectors, which employ alternating layers of high-density absorber materials to induce and contain particle showers and active material to measure the deposited energy. An overview of the calorimeter system is shown in Figure 2.4.

The ECal comprises the innermost calorimeter layer, dedicated to measuring the energy of electrons and photons. The initial electron or photon induces an electromagnetic shower via bremsstrahlung or electron-positron pair-production, losing some of its energy in the process. The energy of an initial electron is decreased to $1/e$ of its starting energy after travelling one *radiation length* X_0 , where X_0 depends on the chosen absorber material. The ECal uses lead as absorber and liquid Argon (LAr) as active material, covers a region up to $|\eta| = 3.2$ and reaches a full coverage in ϕ due to its accordion geometry. The active layers are segmented in η and ϕ to provide spatial resolution of the energy deposition. The thickness of the calorimeter varies with $|\eta|$, between $22\text{--}33 X_0$ in the barrel region and $24\text{--}38 X_0$ in the end-cap regions, to fully contain the electromagnetic showers. In the transition region between barrel and



end-cap, $1.37 < |\eta| < 1.52$, the energy resolution is diminished by structural material. Outside this region, the energy resolution is given by

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%,$$

where the energy is given in GeV. Hadrons only deposit a small fraction of their energy in the ECal and are fully absorbed in the HCal. Hadronic showers are induced by inelastic interactions with nuclei of the absorber. Their spatial expansion is characterised by the *hadronic interaction length* λ . It is defined analogously to X_0 but takes on larger values since hadronic interactions have lower cross sections than electromagnetic interactions. The HCal therefore utilises thicker absorption layers than the ECal. In the barrel region up to $|\eta| = 1.7$, the calorimeter uses steel as an absorber, a scintillator as active material and has a thickness of approximately 7.4λ . The end-cap regions up to $|\eta| = 3.2$ utilise copper and LAr.

Hadronic showers exhibit large fluctuations in the energy fraction that cannot be measured, which comprises for example nuclear binding energy. Therefore, the HCal provides a lower energy resolution than the ECal,

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%.$$

The FCal measures particle energies in the forward direction $3.1 < |\eta| < 4.9$ to enhance the solid-angle coverage. Its innermost module uses copper as absorber material to optimise the resolution, and subsequent layers consist of tungsten to fully contain hadronic showers. The active layers again consist of LAr but are thinner as the FCal is exposed to higher particle fluxes. The FCal provides an energy resolution of

$$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%.$$

2.2.3. The Muon Spectrometer

The outermost part of the ATLAS detector is the *Muon Spectrometer* (MS) [57]. Due to their high mass, muons lose very little energy via bremsstrahlung in the calorimeters and pass through the whole detector. The MS provides precise measurements of their trajectories and momenta. A schematic representation of the MS is shown in Figure 2.5. The muon trajectories are deflected in the field of the toroidal magnets, which reach integrated field strengths of up to 3 Tm in the barrel and 6 Tm in the end-cap regions.

Three layers of *Monitored Drift Tube* (MDT) chambers measure the muon trajectories in the region $|\eta| < 2.7$. Each chamber comprises multiple layers of drift tubes that are filled with an Ar:CO₂ gas mixture and employ the same measurement method as

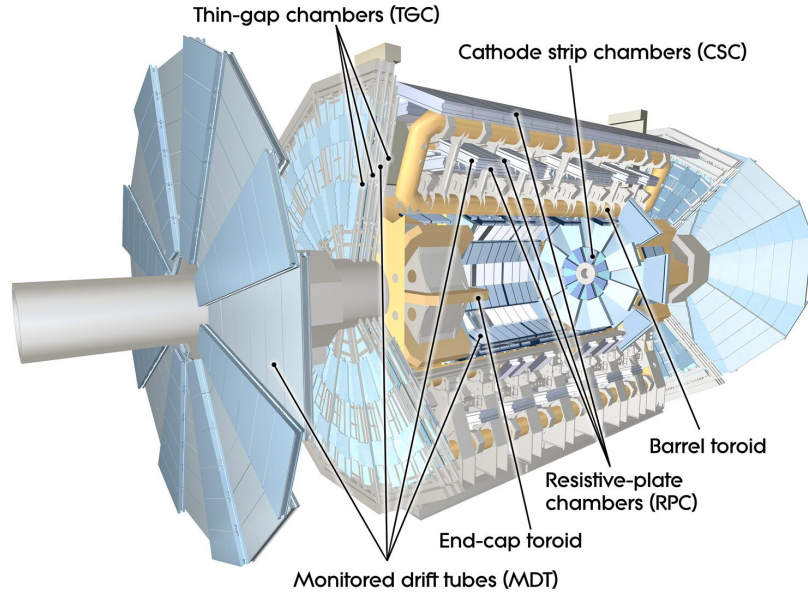


Figure 2.5: Schematic representation of the ATLAS MS [59].

the TRT tubes. They measure tracks of charged particles with an alignment accuracy of $30-40\ \mu\text{m}$ and a single-hit resolution of $80-90\ \mu\text{m}$ [58]. In the forward region $2.0 < |\eta| < 2.7$, *Cathode Strip Chambers* (CSCs) are used instead of MDTs in the innermost layer. These multiwire proportional chambers are better suited for the high background rates expected in this region while providing the required spatial resolution.

The high spatial resolution translates into a momentum resolution $\Delta p_T/p_T < 4\%$ over a large range of muon momenta, increasing to about $\Delta p_T/p_T = 10\%$ for tracks with high momenta $p_T \geq 1\ \text{TeV}$. This high momentum resolution comes at the price of long drift times of up to $720\ \text{ns}$, which are much higher than the LHC bunch spacing. Therefore, the MDTs are complemented with *Resistive Plate Chambers* (RPCs) in the barrel region and *Thin Gap Chambers* (TGCs) in the end-cap regions up to $|\eta| < 2.4$. They provide a high timing resolution of about $2\ \text{ns}$ and comprise the basis for the muon trigger system.

2.2.4. The trigger system

The LHC bunch-crossing rate of $40\ \text{MHz}$ leads to an enormous amount of collision events that can be neither read out nor stored entirely. However, only a fraction of the events contain hard-scattering processes that are of interest for the physics analyses. ATLAS therefore employs a two-level trigger system [60, 61] to identify interesting collisions at runtime and decrease the amount of recorded data to a manageable level. The *Level-1* (L1) trigger is a hardware-based system that uses information from the



Table 2.1.: Requirements imposed by the triggers used in this analysis. If all criteria of any one row are met, an event is accepted. The *var* prefix to an isolation criterion implies that the size of the isolation cone varies with the p_T of the lepton.

Trigger type	Year	L1 p_T min [GeV]	HLT p_T min [GeV]	HLT identification	HLT isolation
Single electron	2015	20	24	medium	-
		22	60	medium	-
		22	120	loose	-
	2016, 2017, 2018	22	26	tight	var-loose
		22	60	medium	-
		22	140	loose	-
Single muon	2015	20	26	-	loose
		20	50	-	-
	2016, 2017, 2018	21	26	-	medium
		21	50	-	-

calorimeters and the MS to bring the event rate down to the maximal detector read-out rate of 100 kHz. It also identifies *Regions of Interest* (ROIs) in the $\eta - \phi$ plane which are to be investigated by the second trigger stage, the software-based *High-Level Trigger* (HLT).

The HLT additionally uses tracking information from the ID and performs an event reconstruction similar to the ones used for physics analyses in the ROIs to make the final decision whether the event is recorded or discarded. Events that pass the HLT are sent to permanent storage units, with an output rate of approximately 1.2 kHz.

A variety of triggers are employed simultaneously, which require different physics objects to be present in a collision. The analysis presented in this thesis uses single-lepton triggers, the details of which are listed in Table 2.1. The L1 single-muon triggers require a muon candidate with p_T over the given threshold and at least three hits in the RPCs or TGCs. If an isolation criterion is specified, the p_T deposited in a cone of radius ΔR around the muon candidate has to be below a certain threshold.

The L1 single-electron triggers search for spatially restricted and isolated energy deposits in the EM calorimeter. The HLT additionally uses information from the ID to perform a likelihood-based identification of electrons, providing three working points to identify signal electrons and reject background electrons, which do not originate from the primary interaction but for example from photon conversions. The isolation criterion follows the same principle as for the single-muon triggers.



2.2.5. Luminosity measurement

A precise knowledge of the luminosity delivered to ATLAS is crucial for the accuracy of physical analyses of the collected data. The luminosity produced by a single pair of colliding bunches can be written as

$$\mathcal{L}_b = \frac{\mu_{\text{vis}} f_r}{\sigma_{\text{vis}}}.$$

Here, f_r denotes the bunch revolution frequency, μ_{vis} the visible interaction rate, i.e. the number of collisions measured by the detector in a single bunch crossing, and σ_{vis} the visible cross section. For each data-taking year, σ_{vis} is determined in dedicated calibration runs using *van der Meer* scans, where the beam positions in the transverse plane are varied with respect to each other. The μ_{vis} changes over time and therefore needs to be measured in parallel to the recording of collision data. This is done by the upgraded *Luminosity Cherenkov Integrating Detector* (LUCID-2) [62], which consists of two modules equipped with photomultipliers situated at $z = \pm 17$ m along the beam pipe.

The full dataset recorded in Run 2 by ATLAS that meets certain quality standards [63] and is therefore suitable for physics analyses corresponds to an integrated luminosity of $(140.1 \pm 1.2) \text{ fb}^{-1}$ [64].

3. The top quark at the LHC

The top quark is the heaviest known elementary particle, with a mass measured as $(172.57 \pm 0.29) \text{ GeV}$ [15]. Originally discovered in 1995 by the CDF and D0 collaborations at the proton-antiproton collider Tevatron at Fermilab [65, 66], the top quark possesses unique features related to its large mass that make it the subject of a wide-ranging measurement programme at the LHC.

At hadron colliders, top quarks are produced via strong and weak interaction processes. The dominating process at the LHC is the production of top quark-antiquark pairs ($t\bar{t}$) via the strong force. The $t\bar{t}$ production is in turn dominated by gluon-gluon fusion; the other relevant production mode is quark-antiquark annihilation. Representative Feynman diagrams of $t\bar{t}$ production at LO in QCD are shown in Figure 3.1 for both relevant production modes.

Single top quarks are produced in weak interaction processes. The three main production modes are distinguished by the virtuality of the involved W -boson and referred to as t -channel (tq and $\bar{t}q$), tW and s -channel ($t\bar{b}$ and $\bar{t}b$) production. Exemplary Feynman diagrams for all three processes at LO are shown in Figure 3.2, where b -quarks are explicitly shown at the tWq vertices, as the coupling of the top quark to d -quarks and s -quarks is suppressed by the associated CKM-matrix elements (cf. Equation 1.9). On a similar note, the Feynman diagram for the t -channel production explicitly shows a u -quark in the initial state, since the most probable scattering partner for the b -quark is a valence u -quark from the other proton.

The top quark decays almost exclusively into a b -quark and a W -boson. Depending on the decay channel of the W -boson, the top-quark decay is referred to as hadronic or semileptonic decay. A $t\bar{t}$ pair decays semileptonically when only one of the two W -bosons decays leptonically.

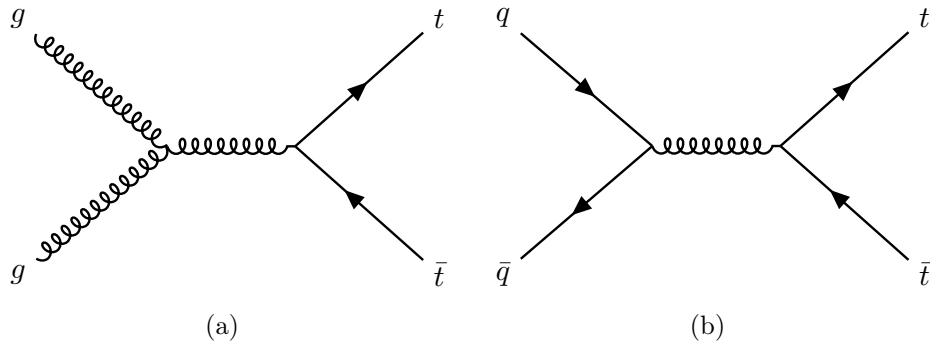


Figure 3.1: Exemplary Feynman diagrams of $t\bar{t}$ production at LO in QCD via (a) gluon-gluon fusion and (b) quark-antiquark annihilation.

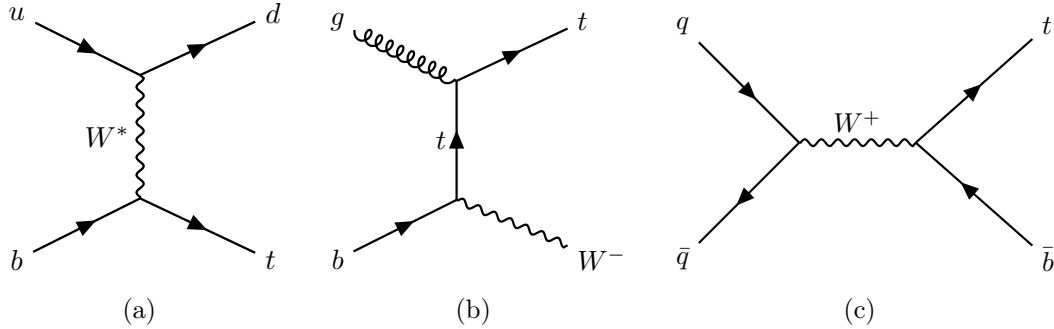


Figure 3.2: Exemplary LO Feynman diagrams of the three main production channels for single top quarks at the LHC, the (a) t -channel, (b) tW and (c) s -channel production.

A large variety of measurements related to the top quark is performed at the ATLAS experiment [67]. A unique feature of the top quark, related to its high mass, is a decay width $\Gamma_t = 1.4 \text{ GeV}$ larger than the hadronisation scale $\Lambda_{\text{QCD}} = 250 \text{ MeV}$. The top quark therefore decays before it can form bound states, and its properties can be studied through the decay products. A recent example is the measurement of spin correlation in $t\bar{t}$ pairs [68] which provides the highest-energy observation of quantum entanglement to date.

The mass of the top quark m_t is directly linked to the vacuum stability of the universe [69] and has a significant impact on the masses of the Higgs and the W -boson through loop corrections, thereby providing an opportunity for precision tests of the consistency of the SM. The most precise result for m_t to date stems from a combination of fifteen individual measurements performed by ATLAS and CMS [70].

A variety of BSM theories predict effects that would be predominantly visible in top-quark-related measurements. New elementary particles at energy scales inaccessible to the LHC could alter the coupling of the top quark to the Higgs and W -boson through loop corrections. Several proposed SM extensions predict an enhancement of *flavour changing neutral current* (FCNC) interactions involving top quarks, which are heavily suppressed in the SM [18]. Measurements of associated $t\bar{t}$ production, e.g. $t\bar{t}W$ [71], and searches for FCNC couplings of the top quark [72] provide opportunities to search for BSM physics. A common approach is to embed the searches in a SMEFT approach, as several Wilson-Coefficients can be constrained from top-quark property and cross-section measurements [67].

Cross-section measurements provide an excellent opportunity to test SM predictions and search for BSM effects. Measurements of single top-quark production are especially suited to study the coupling at the tWb vertex, which occurs in all three production modes. Furthermore, the production channels can provide sensitivity to different BSM effects. A SMEFT operator modifying the top-gluon vertex predominantly affects the tW channel, while an operator characterising a four-quark contact interaction only affects the t -channel and s -channel production modes. It is therefore

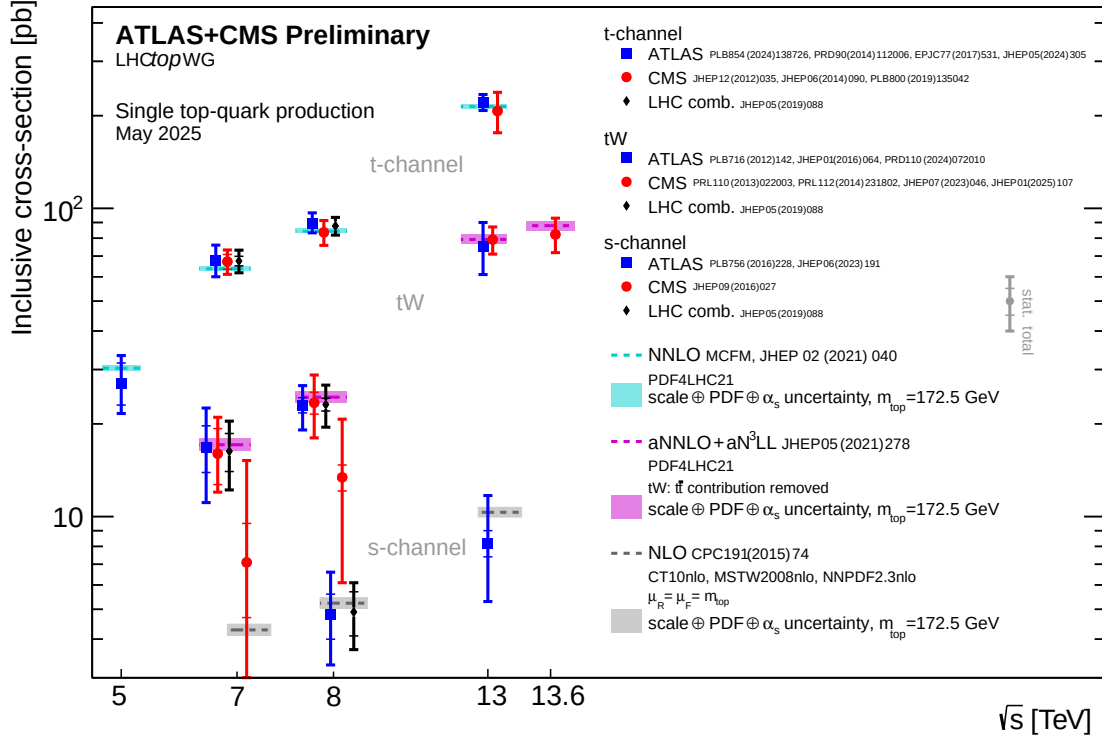


Figure 3.3: Summary of ATLAS and CMS measurements of the total single-top-quark production cross sections for all three main production modes as a function of the centre-of-mass energy [76].

useful to take advantage of the distinct final states of the different production channels and measure them separately.

Measurements of the total production cross sections for all three production modes were performed by ATLAS and CMS at different centre-of-mass energies. The results of the measurements are summarised in Figure 3.3, showing a good agreement with the SM predictions.

Measurements of differential production cross sections are especially suited to test the SM predictions obtained from theoretical calculations and phenomenological models, which necessarily depend on certain assumptions. Differential t -channel production cross sections were measured by ATLAS at 7 TeV [73] and 8 TeV [74]. At 13 TeV, CMS performed a measurement using a partial Run 2 data sample with an integrated luminosity of 35.9 fb^{-1} [75], which provides only limited statistical power. The analysis presented in this thesis is the first measurement with the full Run 2 dataset, utilising 140 fb^{-1} of collision data to measure differential distributions over a wide kinematic range with good accuracy.

4. Simulation of proton-proton collisions

In the modern age of particle physics, theoretical predictions of the involved processes play an important role in physics analyses. The predictions are compared to measurement results, either to refine the theoretical models or to search for discrepancies hinting at BSM physics. Most techniques employed to analyse collision data also rely on predictions, which model for instance the contribution from different processes in a given phase space or the expected shape of a kinematic distribution.

The modelling of proton-proton collisions is a challenging task involving phenomena at both high and low energy scales. The latter cannot be calculated perturbatively due to confinement (cf. Section 1.3), therefore phenomenological methods are employed. In the following, the various steps needed to simulate collision events are described. All steps in the simulation utilise *Monte Carlo* (MC) methods, which rely on repeated random sampling to perform for instance numerical integrations.

4.1. Modelling of the proton substructure

At the high collision energies reached at the LHC, single constituents of the colliding protons interact with each other. A precise knowledge of the proton substructure is therefore crucial to properly model collision events. The proton consists of three *valence quarks*, two up quarks and one down quark, which determine the proton's quantum numbers. The valence quarks are bound together by the strong force mediated by gluons, which can split into quark-antiquark ($q\bar{q}$) pairs. These *sea quarks* are short lived as they annihilate into gluons again, but they can be of any flavour except top, since the top-quark mass is too large. The valence quarks, sea quarks and gluons are the *partons* of the proton. The total momentum of an accelerated proton is distributed among its partons, where each parton carries a momentum fraction given by the *Bjorken scaling variable* x .

The probability to find a parton a with momentum fraction x_a when the proton is probed at the energy scale Q^2 is described by the *parton distribution function* (PDF) $f_a(x_a, Q^2)$. PDFs cannot be derived from first principles and are therefore determined phenomenologically. Once extracted at a specific Q^2 , PDFs can be perturbatively extrapolated to other energy scales using the *DGLAP evolution equations*. Figure 4.1 exemplarily shows the NNPDF3.1 PDF set [77] at NNLO evaluated at two different energy scales $\mu^2 = 10 \text{ GeV}^2$ and $\mu^2 = 10^4 \text{ GeV}^2$. It can be seen for both energy scales that the valence quarks peak in the high- x regime, while gluons dominate for low momentum fractions. The importance of the gluon and, to a lesser extent, the sea-quark

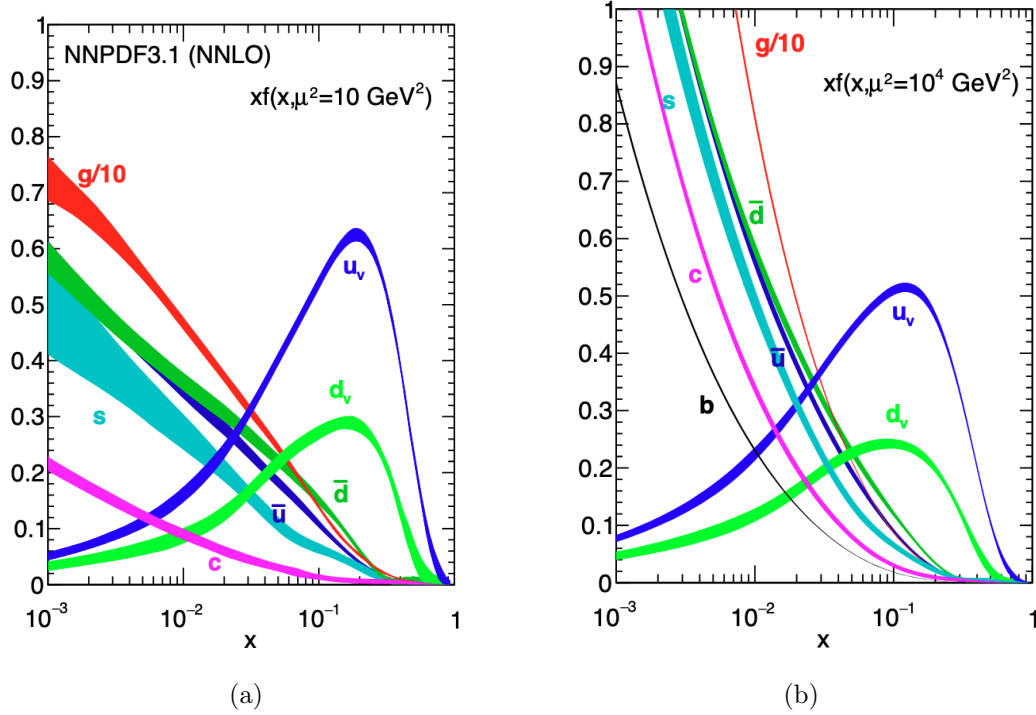


Figure 4.1: Proton PDFs obtained from the NNPDF3.1 PDF set [77] at NNLO evaluated at the energy scales (a) $\mu^2 = 10 \text{ GeV}^2$ and (b) $\mu^2 = 10^4 \text{ GeV}^2$. The valence-quark PDFs are denoted by the subscript v .

PDFs increases with the energy scale. At LHC energies, gluons are the predominating partons in collision events. A more detailed discussion of proton PDFs is provided in Section 4.4.

4.2. Hard scattering and parton shower

Most physics analyses target collision events in which two high-momentum partons from the colliding protons interact with each other. A schematic representation of such an event is shown in Figure 4.2. Two partons a and b interact in the high-energetic *hard-scattering* process, which may involve the production and decay of heavy elementary particles X . The radiation of additional gluons and photons off a and b is referred to as *initial state radiation* (ISR), and radiation off X and its decay products is described by *final state radiation* (FSR). The combination of ISR and FSR is commonly referred to as *parton shower*, as more and more particles are produced through gluon splittings and secondary contributions from electromagnetic radiation. A characteristic property of this process is the formation of collimated sprays of hadrons called *jets*. Finally, the remnants of the initial protons can interact with each other in *multiple*

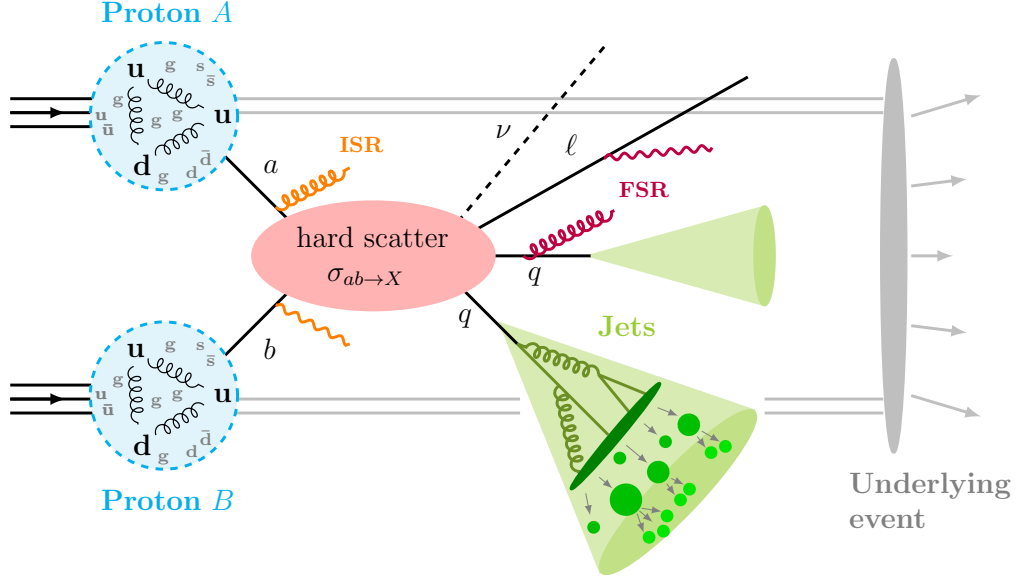


Figure 4.2: Schematic representation of a proton-proton collision event. The lines a and b represent arbitrary proton partons and the decay of the hard-scatter products X is exemplarily chosen as $X \rightarrow qq\ell\nu$. The structure of a jet modelled from parton shower and hadronisation is indicated for one of the jets. Figure adapted from [78].

parton interactions. These processes are connected to the hard scattering through the color fields and are summarised as the *underlying event*. The simulation of collision events is split into several steps that are outlined in the following.

Fixed-order cross section

The calculation of the cross section $\sigma_{AB \rightarrow X}$ involves both the proton PDFs and the high-energetic hard scattering. As described by the *factorisation theorem* [79], the perturbative and non-perturbative parts of the calculation can be separated at some *factorisation scale* μ_f :

$$\sigma_{AB \rightarrow X} = \sum_{a,b} \int dx_a dx_b f_a(x_a, \mu_f^2) f_b(x_b, \mu_f^2) \sigma_{ab \rightarrow X}(x_a x_b s, \mu_r^2, \mu_f^2). \quad (4.1)$$

Here, the partonic cross section $\sigma_{ab \rightarrow X}$ additionally depends on the centre-of-mass energy s and the *renormalisation scale* μ_r , at which higher-order QCD loop corrections are evaluated. Both μ_r and μ_f are usually set to a typical energy scale of the considered process, as this minimises the dependence of $\sigma_{AB \rightarrow X}$ on the scale choice. The partonic cross section can be calculated perturbatively up to a *fixed order* n in $\alpha_S(\mu_r)$



as

$$\sigma_{ab \rightarrow X}^n = \frac{1}{x_a x_b s} \sum_{k=0}^n \int d\phi_{X+k} \left| \sum_{l=0}^{n-k} \mathcal{M}_{X+k}^{(l)}(\phi_{X+k}, \mu_r^2, \mu_f^2) \right|^2,$$

where ϕ denotes the phase space and $\mathcal{M}$ the matrix element. Calculating a cross section at order n means that terms up to α_s^n are considered in the integration, and the summation includes all matrix elements with $k + l \leq n$, where k denotes the number of additional real emissions in the final state and l indicates the number of loop corrections. Matrix-element generators implement MC methods to perform the integration. A large number of MC events sampling the phase space of the hard scattering is generated, and each event is assigned an *event weight* proportional to its probability.

Parton shower

The parton shower models higher-order real emissions originating from ISR and FSR, which can result in $\mathcal{O}(100)$ particles in the final state. Matrix-element calculations at this order are technically infeasible, and as an additional complication, the shower includes frequent soft and collinear radiation characterised by low energies and small angles, both of which lead to divergences in the integrals. Parton-shower algorithms therefore model the shower evolution via splitting probabilities. The probability for a final-state particle f starting at some energy scale Q_0 to decay at a scale $Q_1 < Q_0$ is defined as

$$P_f(Q_1|Q_0) = P_{f \rightarrow gh}(Q_1) \cdot \Pi(Q_1, Q_0). \quad (4.2)$$

Here, $P_{f \rightarrow gh}(Q_1)$ is the probability for a splitting to occur at Q_1 and $\Pi(Q_1, Q_0)$ denotes the probability for f to survive up to this point [80]. The splittings are dominated by the QCD processes $q \rightarrow gq$, $g \rightarrow qq$ and $g \rightarrow gg$. The shower evolution continues until the non-perturbative scale $Q_h \approx 1$ GeV is reached.

The ISR is modelled in a similar way, with the important difference that the evolution is simulated in reverse. The parton a taking part in the hard scattering is taken as starting point, and the probability that a originated from a splitting $c \rightarrow ad$ is evaluated. In each step, d is radiated as additional particle and the scale for further radiations is decreased. The evolution continues until either Q_h is reached or the total energy of the mother particle c exceeds the energy of the original proton.

The underlying event takes place at low-energy scales and is therefore modelled phenomenologically and usually simulated by the parton-shower program. The optimal combination of generator settings to model the underlying event as well as ISR and FSR is extracted from comparisons to data and summarised in a *tune*.

The combination of matrix-element calculations and parton-shower simulations is a successful approach that provides accurate descriptions of collision events. The interfacing between the two components however requires careful consideration to avoid the

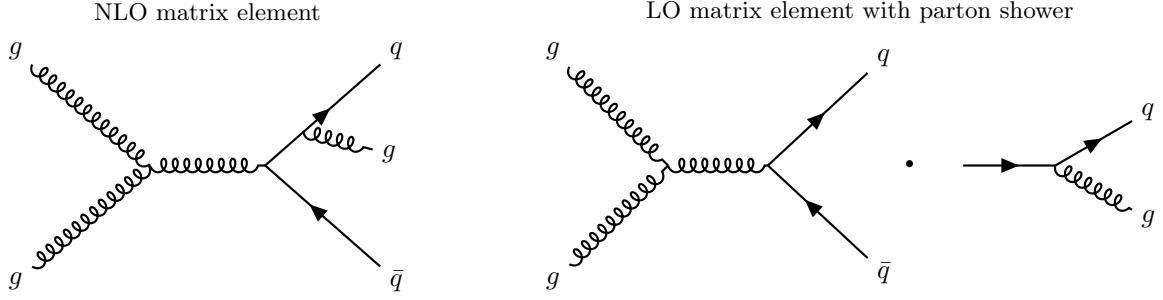


Figure 4.3: Feynman diagrams for a gluon-gluon fusion process illustrating the potential overlap between NLO diagrams and LO diagrams with consecutive hard emissions in the parton shower.

double-counting of certain diagrams. As visualised in Figure 4.3, a LO diagram with a hard emission simulated in the parton shower can overlap with an NLO diagram from the matrix-element calculation. Various techniques to perform *NLO matching* and mitigate the double-counting exist, and some of them can be applied simultaneously to improve the result [81]. A common approach is the *subtraction scheme* where the relevant NLO corrections from the parton shower are subtracted from the matrix-element calculations. Another possibility is to use the *vetoed power shower scheme*, where the hardest emission is defined by the matrix-element calculation. Emissions in the parton shower above this scale are then vetoed.

Hadronisation

Once the shower evolution of both ISR and FSR is completed, the formation of color-neutral hadrons from the produced partons and the subsequent decay of unstable hadrons are simulated. Hadronisation is generally a non-perturbative process and therefore modelled phenomenologically, usually by one of the two well-established approaches.

The *Lund string model* [82] assumes $q\bar{q}$ pairs connected via massless relativistic strings with a potential energy proportional to the string length. Gluons are represented by energy and momentum carrying kinks on the strings. When the potential energy of a string is high enough to produce an on-shell $q\bar{q}$ pair, it may break. The probability for the splitting is proportional to the string's phase space and its probability to have survived without splitting up to this point. Newly produced $q\bar{q}$ pairs are incorporated in the hadronisation process that continues until all remaining strings are of sufficiently short length. The second approach called *cluster hadronisation model* [83] begins by grouping all quarks into color-neutral clusters. Gluons in the final state of the parton shower are decayed into $q\bar{q}$ pairs, which are also considered in the clustering. The clusters are then broken down into hadrons or smaller clusters, depending on their invariant mass. The process continues until only hadrons remain.



4.3. Detector simulation and pileup overlay

The last step in the event-generation chain simulates the response of the ATLAS detector to the particles produced in an event. The GEANT4 toolkit [84] with an integrated detector model [85] is used to model the energy deposition of traversing particles in the detector subsystems as accurately as possible. The ATLAS model therefore contains a detailed description of the detector geometry and materials and allows to include known misalignments. The simulation of the detector response requires large computational resources, most of which are spent on the calorimeter systems. A fast simulation algorithm, referred to as Atfast-II [86], reduces the complexity of the simulation while providing reasonably accurate results by employing a parameterisation of the calorimeter response.

Pileup interactions originating from additional proton-proton interactions in a bunch crossing (cf. Section 2.1) are dominated by soft QCD processes. They are accounted for by using *minimum-bias* events, which utilise loose trigger requirements to record inelastic collision events with low-momentum particles. Minimum-bias events are simulated and overlaid on each MC event at the level of energy depositions in the detector. Dedicated tunes for pileup simulation are extracted from comparisons to data, and the mean number of pileup interactions per event is additionally reweighted to match the distribution seen in data.

The output format of the MC samples after the detector simulation resembles the data format such that all consecutive steps required for analyses, e.g. HLT selection and event reconstruction, can be applied to the simulated samples analogously to the recorded data samples.

4.4. Proton PDF sets

A precise knowledge of the proton substructure, encoded in the PDFs, is crucial for the theoretical interpretation of ATLAS measurements. The determination of proton PDFs from global QCD analyses is a challenging task taken up by multiple groups worldwide, like the ABM [88], CTEQ [90], MSHT [91] and NNPDF [77, 92, 93] collaborations. The PDF sets provided by these groups can differ for example in the included data, the treatment of heavy-quark PDFs, the fitting methodology and the values of SM parameters like α_S and heavy quark masses. A detailed discussion of PDF extractions is beyond the scope of this thesis. Therefore, only a brief overview of some key aspects is given in the following.

A compact overview of the PDF sets used to model tq and $\bar{t}q$ production is given in Table 4.1. Most PDF fits utilise a variety of different measurements as input data to reach a broad coverage in both Q^2 and x . Deep-inelastic scattering measurements in $e^\pm p$ collisions at the HERA accelerator [95] provide unique insight into the low Q^2 and



4.4. Proton PDF sets

Table 4.1.: Comparison of all PDF sets used to extract theoretical predictions for differential tq and $\bar{t}q$ cross sections. The listed properties provide a non-exhaustive overview of specifications required to extract PDFs. For the sake of brevity, the used input data is summarised under the collider or LHC experiment at which the data was taken. Differences in the choices of included measurements are not reflected. For the LHC experiments, the centre-of-mass energies of included measurements are given in brackets. The masses of the c -quark and b -quark, m_c and m_b , are needed regardless of the FS for the evolution of the PDFs [87].

PDF	Precision	FS	Input data	$\alpha_S(m_Z)$	m_c [GeV]	m_b [GeV]
ABMP16 [88]	NLO	4FS	Tevatron, HERA, Fixed-target experiments, ATLAS, CMS, LHCb (7,8 TeV)	0.11905	1.175	4.488
ATLASPDF21 [89]	NNLO	5FS	HERA, ATLAS (7,8,13 TeV)	0.118	1.41	4.2
CT18 [90]	NLO	5FS	Tevatron, HERA, ATLAS, CMS, LHCb (7,8 TeV)	0.118	1.3	4.75
MSHT20 [91]	NLO	4FS	Tevatron, HERA, ATLAS, CMS, LHCb (7,8 TeV)	0.118	1.4	4.75
NNPDF3.0 [92]	NLO	4FS	Tevatron, HERA, Fixed-target experiments, ATLAS, CMS, LHCb (7,8 TeV)	0.118	1.275	4.18
NNPDF4.0 [93]	NLO	4FS	Tevatron, HERA, Fixed-target experiments, ATLAS, CMS, LHCb (7,8,13 TeV)	0.118	1.51	4.92
PDF4LHC21 [94]	NLO	4FS	MC replicas of CT18, MSHT20 and NNPDF3.0 global fits	0.118	1.4	4.75

low x regime. ATLAS, CMS and LHCb measure many different processes, like dijet events or the production of gauge bosons or top-quark-antiquark pairs, that provide sensitivity to different quark flavours and kinematic regions. W -boson production measurements at the proton-antiproton collider Tevatron provide valuable insight on quark-flavour composition and in some PDF fits, fixed-target experiments with deuterium and nuclear targets are included to heighten the sensitivity to sea-quark PDFs. Another important aspect is the treatment of heavy-quark masses, or, more specifically tailored to this analysis, the treatment of b -quarks. When the hard scale of a process is much larger than the b -quark mass, $Q^2 \gg m_b$, the b -quark can be considered massless in the calculations. In the five-flavour scheme (5FS), the b -quark enters the running of α_S (cf. Equation 1.5) and is treated as a massless parton. In the four-flavour scheme (4FS), b -quarks are not treated as proton constituents. For hard-scattering processes with b -quarks in the initial state, the gluon splitting $g \rightarrow b\bar{b}$ is then included in the matrix-element calculation, which uses massive b -quarks. This leads to a better



modelling of the *spectator* b -quark that does not participate in the hard-scattering process [96]. Therefore, the 4FS is used when it is available.

4.5. Event generators and fixed-order calculations

Matrix-element calculations and parton-shower simulations are provided by various event generators that differ in the choice of used algorithms and models. Common choices for matrix-element calculations are the MADGRAPH5_AMC@NLO (abbreviated as MG_AMC@NLO) [97], POWHEG BOX [98–101] and SHERPA [102, 103] generators, all of which provide calculations at NLO in QCD for many different processes. For NLO matching, MG_AMC@NLO and SHERPA employ a subtraction scheme according to the MC@NLO prescription [104], while POWHEG BOX employs a vetoed power shower scheme [105].

The two main parton-shower programs used in this analysis are PYTHIA [106] and HERWIG [107, 108]. In PYTHIA, the default shower model orders emissions by their transverse momentum, starting with the hardest emission, and the Lund string model is utilised for hadronisation. HERWIG in contrast implements an angular shower ordering, where the shower moves from particles emitted at large angles to collinear emissions, and employs the cluster hadronisation model. The SHERPA generator includes a parton-shower simulation ordered by the transverse momentum of emissions and models hadronisation based on the cluster hadronisation model.

The matrix-element and parton-shower generator combinations used to extract predictions for the differential tq and $\bar{t}q$ cross sections are listed in Table 4.2. In principle, matrix-element generators are sufficient to obtain the predictions, but the parton-shower simulation contributes corrections to the FSR that can affect the kinematics of the top quark. The flavour scheme dictates whether the b -quark in the initial state is treated

Table 4.2.: Comparison of all generator combinations used to extract theoretical predictions for differential tq and $\bar{t}q$ cross sections. In all cases, the NNPDF3.0 PDF set is used in the FS that matches the one employed in the matrix-element calculation.

Generators	FS	μ_r and μ_f choice
POWHEG BOX v2 + PYTHIA 8.230	4FS	$4\sqrt{m_b^2 + p_T^2(b)}$
POWHEG BOX v2 + HERWIG 7.3	4FS	$4\sqrt{m_b^2 + p_T^2(b)}$
MG_AMC@NLO [2.7.3] + PYTHIA 8.230	4FS	$4\sqrt{m_b^2 + p_T^2(b)}$
MG_AMC@NLO [2.7.3] + PYTHIA 8.230	5FS	$H_T/2$
MG_AMC@NLO [2.7.3] + PYTHIA 8.230	5FS	$m_t = 172.5 \text{ GeV}$



as massless, and the corresponding version of the NNPDF3.0 PDF set is employed. The choice of the renormalisation and factorisation scales is not straightforward, as the dominating heavy-quark line ($b \rightarrow t$) contains two very different scales, namely the masses of the b -quark and of the top quark. Studies have shown that the overall scale dependence of the process is dominated by the transverse momentum of the b -quark in the initial state [96], therefore the renormalisation and factorisation scales are set to $\mu_r = \mu_f = 4 \sqrt{m_b^2 + p_T^2(b)}$ for all 4FS calculations, where m_b denotes the b -quark mass and $p_T(b)$ refers to the transverse momentum of the b -quark originating from the initial $g \rightarrow b\bar{b}$ splitting. Two different scales are chosen for the 5FS calculations; a dynamic setting $\mu_r = \mu_f = H_T/2$, where H_T denotes the sum over the transverse masses of all particles in the final state, and a static approach where the scales are fixed to the top-quark mass $\mu_r = \mu_f = 172.5 \text{ GeV}$. Compared to calculations in the 5FS, the 4FS has a stronger scale dependence, simply because the initial $g \rightarrow b\bar{b}$ splitting adds an additional factor of a_S .

Complementary to the various NLO calculations outlined above, predictions from calculations at different orders are extracted with MCFM [109, 110], an MC generator program within which the tq and $\bar{t}q$ production and decay can be calculated at up to NNLO in QCD. The NNLO calculation includes all effects of radiation in top-quark production and decay at this order and therefore yields state-of-the-art predictions for both total and differential tq and $\bar{t}q$ production cross sections. Calculations at all orders utilise the 5FS and the recommended *double deep inelastic scattering scale* [111]. The momentum transfer along the W -boson $\mu_r^{\text{light}} = \mu_f^{\text{light}} = Q_W^2$ is used to evaluate QCD corrections on the light-quark line ($u \rightarrow d$), and for the heavy-quark line, the scales are set to $\mu_r^{\text{heavy}} = \mu_f^{\text{heavy}} = Q_W^2 + m_t^2$. This separation is possible because the exchange of a virtual W -boson allows for a factorisation of the process into two deep inelastic scattering processes that holds under QCD radiation up to NNLO, except for small interference and off-shell effects. The values chosen for some

Table 4.3.: Values of particle masses and the Fermi constant G_F used for the fixed-order calculations with MCFM [112].

Parameter	Value
m_W	80.385 GeV
m_Z	91.1876 GeV
m_t	172.5 GeV
m_b	0 GeV
m_c	0 GeV
G_F	$0.116639 \cdot 10^{-4}$



of the most important parameters for the fixed-order calculations are summarised in Table 4.3.

5. Data and simulated samples

The data analysed in this thesis was collected by the ATLAS detector in the years 2015–2018 at a centre-of-mass energy $\sqrt{s} = 13\text{ TeV}$. Recorded events that are affected by issues in the detector hardware or readout chain are removed, and the remaining dataset corresponds to an integrated luminosity of $(140.1 \pm 1.2)\text{ fb}^{-1}$ [64]. Single-lepton triggers are used to select events for the analysis as described in Section 2.2.4.

MC methods are used to simulate the production of the signal process and of processes that can lead to similar final states and therefore contribute to the events selected for the measurement. As outlined in Chapter 4, different event generator and parton-shower programs are available, and the simulations depend on various parameters. Technical details about the nominal samples used in this analysis are given in the following. For some processes, systematically varied samples are produced by changing one parameter or employing a different parton-shower program. These variations are described in Section 10.1.

For all samples, the response of the ATLAS detector is modelled with the GEANT4 toolkit [84]. The nominal samples use a full detector model [85], while systematically varied samples employ the Atlfast-II fast simulation [86]. The minimum-bias events that are overlaid on the hard-scattering events to simulate energy depositions from pileup events are simulated in PYTHIA 8.186 [113] with the A3 [114] tune and the NNPDF2.3LO PDF set [115].

5.1. Signal samples

The signal tq and $\bar{t}q$ processes are simulated with POWHEG BOX v2 [96, 98–101, 116, 117] at NLO in QCD using the NNPDF3.0NLO_NF4 PDF set [92]. The 4FS is used as it leads to a more reliable modelling of the spectator b -quark (cf. Section 4.4). The top-quark mass is set to $m_t = 172.5\text{ GeV}$ for the signal sample and for all other simulations involving top quarks. The parton shower, hadronisation and underlying event are modelled with PYTHIA 8.230, using the NNPDF2.3LO PDF set and the A14 tune [118], which was optimised from comparisons to data and provides a configuration suitable for high- p_T processes. The default PYTHIA choices of a p_T -ordered parton shower and the Lund string model for hadronisation are employed. The renormalisation and factorisation scales μ_r and μ_f are set dynamically per event to $\mu_r = \mu_f = 4\sqrt{m_b^2 + p_T^2(b)}$. The top-quark decay is modelled with MADSPIN [119, 120] at LO to preserve spin correlations, and thereby the angular correlations between particles in the initial and final state. The narrow width approximation, confining the calculations to on-shell quarks, is employed. Finite-width



effects are accounted for afterwards by smearing the top-quark mass to agree with a Breit-Wigner distribution. The decays of b -hadrons and c -hadrons that are products of the hadronisation simulation are handled by the EVTGEN 1.6.0 program [121]. The samples are normalised to the theoretical predictions for the total cross sections calculated with MCFM 10.1 [110] at NNLO in QCD, $\sigma(tq) = (134.2 \pm 2.2)$ pb and $\sigma(\bar{t}q) = (80.0 \pm 1.6)$ pb [112].

The analysis includes an interpretation of the results in the SMEFT framework to constrain the Wilson-coefficient $C_{Qq}^{3,1}/\Lambda^2$ (cf. Section 11.2). Dedicated MC samples are generated with MADGRAPH5_AMC@NLO 2.7.3 in the 5FS with the NNPDF3.0NLO PDF set using the SMEFTatNLO-NLO model [122]. Separate samples are generated for $C_{Qq}^{3,1}/\Lambda^2 \in \{-0.6, -0.2, 0.0, 0.4, 1.0\} \text{ TeV}^{-2}$, which include both t -channel and s -channel production. The parton shower is simulated with PYTHIA 8.244 using the A14 tune and the NNPDF2.3LO PDF set. The detector response is modelled using AtIfast-II. The single-top-quark production cross sections are altered by $C_{Qq}^{3,1}/\Lambda^2$ and calculated with MADGRAPH5_AMC@NLO 2.7.3; the values are given in Appendix A.

5.2. Top-quark background samples

The production of $t\bar{t}$ pairs and single top quarks via the s -channel or tW process contribute as background processes. The samples for all processes are generated at NLO in QCD with POWHEG BOX v2 in the 5FS using the NNPDF3.0NLO PDF set. The parton shower, hadronisation and underlying event are modelled with PYTHIA 8.230 using the A14 tune and the NNPDF2.3LO PDF set. The top-quark decay is modelled by POWHEG BOX, and EVTGEN 1.6.0 is employed for the decay of b - and c -hadrons. For $t\bar{t}$ and tW events, the h_{damp} parameter plays an important role in the parton-shower matching, as it controls the p_T of the first beyond-LO gluon emission in the parton shower [123]. The samples are generated with $h_{\text{damp}} = 1.5 m_t$.

For the $t\bar{t}$ sample, μ_r and μ_f are chosen dynamically as a function of the top-quark mass and transverse momentum $\mu_r = \mu_f = \sqrt{m_t^2 + p_T^2(t)}$. The sample is normalised to a cross section of $\sigma(t\bar{t}) = (834 \pm 33)$ pb obtained from NNLO calculations with the TOP++ 2.0 program [124], which includes the resummation of next-to-next-to-leading logarithmic soft-gluon terms.

The generation of tW events employs dynamic scales $\mu_r = \mu_f = H_T/2$, where H_T denotes the sum over the transverse masses of all particles in the final state. The diagram removal [125] approach is used to account for the interference between higher-order diagrams of tW production and the $t\bar{t}$ process. The cross section for tW production $\sigma(tW + \bar{t}W) = (79.3 \pm 2.9)$ pb calculated at NLO in QCD is used to normalise the sample [126]. The $t\bar{b}$ and $\bar{t}b$ sample is normalised to the cross section calculated at NLO in QCD with the HATHOR 2.1 program [127, 128], $\sigma(t\bar{b} + \bar{t}b) = (10.32 \pm 0.38)$ pb.



5.3. Boson background samples

Additional background events originate from the associated production of W -bosons and Z -bosons with jets and diboson production. The W +jets and Z +jets samples are split into sub-samples according to the flavour of the associated jets. The SHERPA 2.2.11 generator [103] is used for event generation with the NNPDF3.0NLO PDF set. Matrix elements containing up to two partons are calculated at NLO in QCD, and at LO for up to five partons. The default SHERPA parton shower [129] is used with the cluster hadronisation model [130]. The samples are normalised to the cross sections obtained with the FEWZ package [131, 132] at NNLO in QCD including NLO electroweak corrections [133]. On-shell diboson production is simulated with SHERPA 2.2.1 using the same setup as for the W +jets and Z +jets samples. The matrix-element calculation includes all diagrams with four electroweak vertices and is carried out at NLO in QCD for up to one additional parton emission, and at LO for up to three additional emissions. The samples are normalised to the cross sections provided by SHERPA.

5.4. Multijet background samples

The multijet background comprises events with no lepton in the final state of the hard-scattering interaction. It is modelled from both recorded data and simulated dijet events, as described in Chapter 8. The simulated dijet events are generated with PYTHIA 8.186 at LO. Both μ_r and μ_f are set to the square root of the geometric mean of the squared transverse masses of the two outgoing particles in the matrix element, $\mu_r = \mu_f = \sqrt[4]{(p_{T,1}^2 + m_1^2) \cdot (p_{T,2}^2 + m_2^2)}$. The events are filtered during generation to ensure that at least one jet with $p_T > 17 \text{ GeV}$ exists. The parton shower is simulated in PYTHIA 8.186 using the NNPDF2.3LO PDF set and the A14 tune.

6. Object reconstruction and identification

The different kinds of particles produced in collision events leave unique signatures in the detector that can be used to identify particles when the information collected by the various detector subsystems are combined. In the busy environment of high-energy proton-proton collisions, the attribution of measured signals to single particles provides a challenging task. Dedicated algorithms are used to reconstruct low-level objects, such as tracks and energy clusters, which serve as input for the reconstruction and identification of high-level objects, such as electrons or jets. These objects additionally need to be calibrated, and the precision up to which their properties are known needs to be evaluated. The procedures used to reconstruct the particles of interest for this analysis are described in the following.

6.1. ID tracks and vertices

The reconstruction of tracks in the ID left by charged particles is a prerequisite for the subsequent reconstruction of most higher-level objects. Signals detected by individual pixel and strip sensors, referred to as *hits*, form the basic input for track reconstruction [134]. Clusters are formed from hits via a *connected component analysis* [135], as the charge deposited by a traversing particle is usually collected in multiple adjacent sensors. Three-dimensional *space-points* are reconstructed from the clusters as the most likely position of the detected particle. Three space-points are required to form a track seed, from which the track reconstruction proceeds by using a *Kalman filter* [136] to add additional space-points to the track candidates based on the trajectory expected due to the deflection in the magnetic field of the detector. The agreement between the expected trajectory and the added space-points is evaluated with a χ^2 fit. Multiple track candidates can be reconstructed from a single seed, and single clusters can be assigned to multiple track candidates. Ambiguities are solved with a sophisticated procedure that evaluates the quality of track candidates based on properties such as the number of associated hits and rejects those failing the criteria. An artificial neural network is employed to identify clusters created from charge deposits of multiple particles, which may be used in the reconstruction of multiple tracks. Hits recorded by the TRT are finally used to extend surviving track candidates, thereby improving the momentum resolution.

The trajectory of a track is characterised by five parameters, as schematically shown in Figure 6.1. The *longitudinal* and *transverse impact parameters* d_0 and z_0 describe

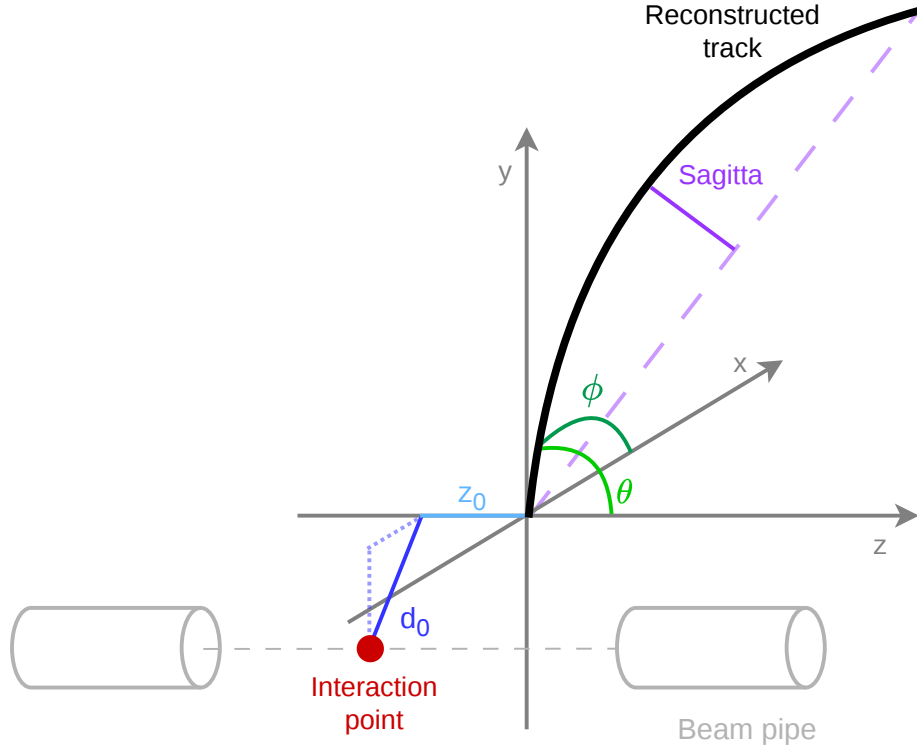


Figure 6.1: Schematic representation of a reconstructed track in the ID. The five properties needed to describe its trajectory, ϕ , θ , d_0 , z_0 and the sagitta, are shown.

the shortest distance between the track and the interaction point. The polar and azimuthal angles θ and ϕ parameterise the track's direction, and the *sagitta* describes its curvature, from which the ratio of charge over transverse momentum q/p_T is determined.

The reconstructed ID tracks are used to identify *vertices*, i.e. the positions at which proton-proton collisions occurred. A vertex seed is built from the positions of all tracks, and an adaptive vertex finder algorithm [137] based on a χ^2 minimisation optimises the compatibility of the tracks and the vertex, thereby refining the vertex position. The algorithm proceeds iteratively, reducing the weight of tracks with a low compatibility. After the vertex position has converged, incompatible tracks are removed from it. The procedure is then repeated using only the removed tracks as input until no unused tracks remain or no further vertices can be located. The vertex with the highest sum of squared momenta of all associated tracks is defined as the *primary vertex* of the event, at which the hard-scattering process took place. Additional vertices originate from pileup interactions or the decay of long-lived particles, if they are found outside of the beam-overlap region. The latter are termed *secondary vertices*.



6.2. Topological clusters

Electrons and hadronic particles produced in a collision deposit their energy in the calorimetry system in the form of electromagnetic and hadronic showers. To reconstruct the energy deposited by a single particle, clusters are formed from topologically connected calorimeter cells [138]. The basic observable controlling the cluster formation is a cell's signal significance defined as the ratio of the cell signal to the average expected noise caused by pileup interactions and the detector electronics. Cells with a high signal significance are used as seeds for the *topo-clusters*. Neighbouring cells are added to the topo-cluster if their significance is above a given threshold until no further cells above the threshold are adjacent to the cluster. If a cell would be added to two separate clusters by the algorithm, the two clusters are merged instead.

The algorithm can lead to clusters that are too large to provide meaningful input to the reconstruction of higher-level objects. If a topo-cluster contains two or more cells with local energy maxima, it is split between those cells by a dedicated algorithm.

6.3. Electrons

Electron candidates are reconstructed from localised energy clusters in the ECal and matched tracks of charged particles measured in the ID [139]. For the reconstruction of energy clusters, the ECal is divided into 200×256 cells in the $\eta \times \phi$ plane with a size of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. Preliminary clusters are identified by the topo-cluster reconstruction algorithm, and the ID tracks are matched to the clusters via their distance in the $\eta \times \phi$ plane [140]. Several tracks can be associated with a single cluster, as electrons travelling through matter may emit bremsstrahlung. The emitted photons then may convert into electron-positron pairs which are usually emitted in a collimated fashion. The cluster reconstruction in the ECal is then revisited, and superclusters are formed by identifying seed clusters with high transverse energy and an associated track with at least four hits. Neighbouring clusters are added to the seed cluster, as they are assumed to originate from bremsstrahlung.

For this analysis, the energy clusters of electron candidates are required to have $|\eta_{\text{cluster}}| < 2.47$, where the transition region $1.37 < |\eta_{\text{cluster}}| < 1.52$ is excluded. A requirement for the transverse momentum of tracks $p_T > 10 \text{ GeV}$ is imposed and the tracks must be matched to the primary vertex of the hard-scattering event with a transverse-impact-parameter significance $|d_0/\sigma_{d_0}| < 5$ and a longitudinal impact parameter $|\Delta z_0 \sin \theta| < 0.5 \text{ mm}$.

A likelihood-based identification is employed to distinguish *prompt* electrons, which originate from the hard-scattering interaction, from light-flavour jets and non-prompt



electrons originating from photon conversions or heavy-flavour decays. Various variables quantifying the properties of the primary track, the evolution of the electromagnetic shower and the spatial compatibility of the track and the energy cluster are used as inputs to build a discriminant. Several working points (WPs), referred to as *loose*, *medium* and *tight*, are defined which provide an increasing rejection rate of misidentified jets and non-prompt electrons at the cost of a decreasing selection efficiency for prompt electrons. The selection efficiency increases significantly with the transverse momentum of the electron and decreases slightly with the pseudorapidity. For the *tight* WP used in this analysis, the selection efficiency lies between 60 % and 90 %.

Prompt electrons are usually characterised by lower detector activity in the direct vicinity of the reconstructed object, compared to misidentified jets and non-prompt electrons. An isolation criterion is therefore imposed to further enhance the purity in prompt electrons. A boosted decision tree (BDT), known as the *prompt-lepton BDT*, is trained on the energy deposits and reconstructed tracks found in a cone around the electron candidate [141]. Again, different WPs are defined and the *PLVTight* WP used for this analysis achieves a selection efficiency of approximately 80 % for prompt electrons.

The selection efficiencies that are introduced in measured spectra due to particle reconstruction, identification and isolation as well as trigger-related efficiencies need to be evaluated quantitatively as measurements of absolute quantities require correction factors for each efficiency. For electrons, the selection efficiencies are measured in data using the well known $Z \rightarrow ee$ and $J/\Psi \rightarrow ee$ resonances. A *tag-and-probe* method is employed, where the tag-electron is required to pass strict selection criteria and the efficiencies are then measured with the other electron, referred to as probe. Selection efficiencies obtained for MC events through detector simulations are corrected to the efficiencies observed in data by applying multiplicative *scale factors* (SFs) to the event weight.

The electric charge of an electron candidate is inferred from the curvature of the associated ID track. The track straightens for candidates with high momenta or high pseudorapidities, thereby making the curvature difficult to determine. Additionally, electron candidates that have multiple associated tracks due to bremsstrahlung may have the wrong one assigned as primary track. To suppress the misidentification of the electron charge, driven by the outlined factors, a dedicated BDT trained on simulated single-electron samples is utilised. The charge misidentification rate is thereby reduced to sub-percent levels, even for candidates with a high momentum or pseudorapidity.

6.4. Muons

Muons traverse the whole detector and deposit only a small fraction of their energy in the calorimeters. They are therefore reconstructed from tracks measured in the ID



and MS subsystems [142, 143]. MS track reconstruction starts with the identification of short, straight-lined track segments using a *Hough transform*, which is a method to detect patterns in incomplete or noise-affected data [144]. Multiple segments are combined into preliminary candidates, based on the expected bending of muon tracks in the magnetic field of the detector. Information from the muon trigger detectors is added to create three-dimensional track candidates. The final trajectory through the magnetic field is obtained from a χ^2 fit, taking detector misalignments and interactions of the traversing particle with detector material into account.

Different strategies are available for combining the ID and MS tracks, some of which are optimised for more extreme phase spaces that require special treatment due to reduced detector acceptances. This analysis only uses *combined muons* (CB), which are reconstructed by matching the tracks from the different subdetectors in a global fit. To improve the fit quality, hits detected in the MS may be added to or removed from the tracks. For this analysis, the tracks of muon candidates are required to have $p_T > 10 \text{ GeV}$, $|\eta| < 2.5$ and need to be matched to the primary vertex within $|d_0/\sigma_{d_0}| < 5$ and $|\Delta z_0 \sin \theta| < 0.5 \text{ mm}$.

The quality of muon candidates is evaluated from the number of hits recorded in the ID and the MS, the compatibility between the measurements and track fit properties. The trajectories of non-prompt muons from light-flavour decays usually exhibit a change in direction caused by the in-flight decay of the light-flavour hadron and are therefore reliably rejected. Analogously to the electron identification, different WPs are defined. This analysis uses the *medium* WP for muon identification, which provides identification efficiencies above 95 % with almost no dependence on the muon p_T and $|\eta|$. Non-prompt muons from heavy-flavour decays provide high-quality tracks but are accompanied by large energy deposits in the calorimeters. An isolation criterion is therefore imposed to reject those muons by using the *PLVTight* WP of the prompt-lepton BDT.

The selection efficiencies of the muon reconstruction, identification and isolation are measured in $Z \rightarrow \mu\mu$ and $J/\Psi \rightarrow \mu\mu$ events using a tag-and-probe method. The simulated events are corrected to the efficiencies seen in data with dedicated SFs. Additional SFs are extracted from data to correct the momentum scale and resolution of simulated muons, as the precision of the detector simulation is limited to the per-mille and percent level respectively.

6.5. Jets

Collimated sprays of neutral or charged hadrons, referred to as jets, are the predominant constituents in the final states of collisions at the LHC. Due to their complex structure, jets are reconstructed in multiple steps, and sophisticated techniques are applied to correct the measured energy and evaluate the resolution. The full procedure performed to define and calibrate jets is outlined in the following.



The *particle flow* (PFlow) [145] algorithm combines the information from ID tracks and topo-clusters to reconstruct jets with a high resolution. For low-energetic charged particles, the momentum resolution of the tracks is significantly better than the energy resolution of the calorimeter, which in turn provides better accuracy at high energies. To avoid double-counting of the energy deposited by a particle with an associated track, a subtraction procedure is employed. High-quality tracks are matched to a single topo-cluster each, based on their distance in the $\eta \times \phi$ plane. If a track's trajectory suggests that the energy of the initial particle was deposited in multiple clusters, the clusters in question are combined. The expected energy deposit in the calorimeter is estimated from the momentum of the track and subtracted cell by cell from the matched cluster. The remnant of the cluster is afterwards removed if its energy is consistent with the expected shower fluctuations. Clusters that were not matched to any track are kept and used to reconstruct jets originating from neutral particles.

After the subtraction is complete, PFlow jets are constructed from the tracks and remaining clusters using the *anti- k_t algorithm* [146]. The distance between two objects i and j is defined as

$$d_{ij} = \min \left(\frac{1}{p_{T,i}}, \frac{1}{p_{T,j}} \right) \cdot \frac{\Delta_{ij}^2}{R^2},$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ is calculated from the rapidities and azimuth angles and R denotes the radius parameter, which is set to $R = 0.4$. The two objects with the smallest d_{ij} are grouped together, and the distances are then recalculated. If the distance between an object i and the beam, defined as $d_i = 1/p_{T,i}$ is smaller than all d_{ij} , the object is classified as a jet and removed from the input list. The usage of the transverse momentum of the objects for the definition of distances causes low- p_T objects from soft radiation to cluster around those with high- p_T without distorting the shape of the final jet, as shown in Figure 6.2.

The *jet energy scale* (JES) [147] is calibrated in a multi-stage process, addressing inaccuracies due to detector effects and modelling limitations. First, the transverse momenta of the jets are corrected for pileup effects by subtracting the p_T expected to originate from pileup interactions. The pileup contribution is estimated from the median p_T density of jets in the central detector region. The impact on each jet is then evaluated by taking its area into account. Residual differences seen in simulation between jets reconstructed after and before the detector simulation, which are referred to as *detector-level* jets and *particle-level* jets, are evaluated as a function of jet- η and the number of reconstructed primary vertices.

Next, the absolute jet energy and pseudorapidity are calibrated to account for energy losses in passive detector material and biases in the jet- η reconstruction. Detector-level jets in simulated dijet events are matched geometrically to particle-level jets within $\Delta R = 0.3$. The *jet response* is then defined as the mean of the jet-energy ratio $E_{\text{det}}/E_{\text{part}}$. The inverse of the jet response is used to correct the detector-level jets. A global sequential calibration is performed afterwards to improve the resolution. The

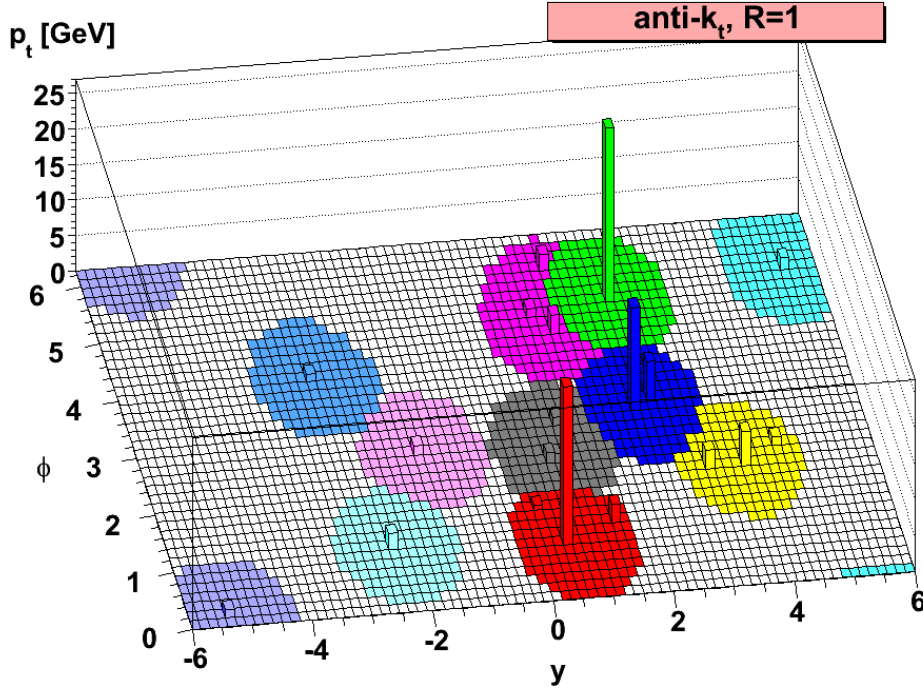


Figure 6.2: Jets reconstructed with the anti- k_t algorithm in a simulated event containing both high- p_T and low- p_T energy depositions [146].

jet response is affected by various factors such as the flavour and energy distribution within the jet, the nature of the initiating particle and fluctuations in the shower development. Correction factors are again obtained from simulated dijet events to account for the dependence of the jet response on six global observables related to the spatial distribution of energy and tracks. For this, tracks in the MS are considered in addition to ID tracks to correct for *punch through* effects [147], where a jet is not fully contained in the calorimeters.

The corrections obtained in all the steps above are applied to both measured and simulated events. The final step in the calibration procedure accounts for residual differences between data and simulation caused by imperfect simulations. The *in-situ calibration* measures the jet response in data and simulation and uses the ratio of the two to correct the data. Here, the jet response is defined as the ratio of the transverse momenta of the jet and a well-calibrated reference object, such as a Z -boson. Corrections for jets in the forward region of the detector, $|\eta| > 0.8$, are extracted in the η *intercalibration* analysis. Subsequently, corrections are derived for differences in the low- p_T regime to account for effects from pileup and thresholds in the jet reconstruction algorithms. The final step of the in-situ calibration targets jets with p_T above the range covered in the previous parts.



The *jet energy resolution* (JER) depends on several factors and can be parameterised as a function of the jet's transverse momentum [147],

$$\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C.$$

The noise term N includes the effects from electronic noise and pileup interactions. Statistical fluctuations in the energy depositions are captured by the stochastic term S , and the constant term C summarises fluctuations that are independent of the jet- p_T , such as the energy deposited in passive detector material. The S and C terms are measured in dijet events, and the noise is estimated from random cones reconstructed in data events that are selected at random with no trigger requirements. In jet- p_T regions where the JER is better in simulation than in data, the simulated jets are smeared to match the data.

For this analysis, jets are required to have $p_T > 30$ GeV and $|\eta| < 4.5$. The *jet vertex tagger* [148] (JVT), a multivariate combination of track-based variables, is employed to suppress jets originating from pileup collisions. Jets with $p_T > 60$ GeV and $|\eta| < 2.4$ are required to have a JVT discriminant larger than 0.5. Thereby, 98 % of all pileup jets are rejected, while a selection efficiency of 92 % is reached for non-pileup jets. The *forward JVT* (fJVT) [149] utilises topological correlations between particles from pileup interactions to extrapolate the JVT beyond the tracking coverage of the ID. It is used for forward jets with $p_T > 60$ GeV and $|\eta| > 2.5$, which are required to have an fJVT value below 0.5. The efficiencies of the JVT and fJVT are measured in simulated and measured $Z \rightarrow \mu\mu + \text{jets}$ events, and SFs are applied to the MC simulations to correct for observed differences.

6.6. Flavour tagging

Jets originating from the decay of b -hadrons, c -hadrons or light-flavour hadrons each have distinct features that can be exploited to differentiate between them. The substructure of jets is influenced by properties such as the high mass or the high decay multiplicity of an initiating b -hadron or c -hadron. Due to the large lifetime of b -hadrons, their decay vertex can exhibit a displacement from the primary vertex of several millimetres.

For this analysis, b -jets are identified with the DL1R tagger [150], a multi-layer feed-forward neural network which combines the output of several low-level tagging algorithms. The impact-parameter based algorithms IPD2 and IPD3 [151] use the significance of the impact parameters of tracks associated with the jet. The RNNIP [152] algorithm utilises a neural network and takes correlations between the significances and other track properties into account. A different approach is chosen by the SV1 tagger [153], which reconstructs one secondary vertex within each jet to evaluate the



displacement from the primary vertex. The **JetFitter** algorithm complements the other methods and attempts to reconstruct the full decay of b -hadrons or c -hadrons inside a jet.

The outputs of these low-level tagging algorithms are used as input for the DL1R tagger which has a multidimensional output assigning probabilities for a jet to originate from a b -hadron, a c -hadron or a light-flavoured hadron; p_b , p_c and p_{light} . The final b -tagging discriminant is defined as

$$D_{DLr} = \ln \left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\text{light}}} \right),$$

where f_c denotes the effective c -jet fraction in the simulated $t\bar{t}$ and $Z \rightarrow q\bar{q}$ events used for the training of the neural network.

Different working points are defined based on the obtained selection efficiency for b -jets. This analysis uses the 60 % WP which provides an excellent rejection of other jets, having an acceptance of around 2.5 % for c -jets and a sub-permille acceptance for light jets. The inputs to the DL1R tagger include information from the ID, therefore b -tagging is only provided for jets with $|\eta| < 2.5$.

Differences in the tagging rates between data and simulated events are corrected in the simulated events with dedicated SFs. The tagging rates are also affected by the choice of the parton-shower program, therefore MC-to-MC SFs are applied to samples which do not use the nominal PYTHIA 8 configuration.

6.7. Overlap removal

The different physics objects are reconstructed by independent algorithms that utilise the same detector information. Therefore, a single track or energy deposit may be associated with more than one object candidate. To avoid double counting, an *overlap removal* procedure is introduced, where reconstructed objects are removed in the following order:

1. Electrons sharing an ID track with a muon,
2. Jets within $\Delta R = 0.2$ of a remaining electron,
3. Electrons within $\Delta R = 0.4$ of a remaining jet,
4. Jets within $\Delta R = 0.2$ of a muon if the jet has two or fewer associated tracks,
5. Muons within $\Delta R = 0.4$ of a remaining jet.



6.8. Missing transverse momentum

Neutrinos cannot be detected directly, as they do not interact with the detector. Their presence is inferred from a momentum imbalance, exploiting the fact that the protons are collided head-on. Momentum conservation dictates that the sum of the transverse momenta $\vec{p}_T$ of all particles produced in the scattering process must be zero. The total visible transverse momentum is defined as the vectorial sum over the transverse momenta of all reconstructed objects and an additional *soft term* accounting for tracks which are not associated with any reconstructed object but satisfy the conditions $p_T > 500 \text{ MeV}$ and $|z_0 \sin \theta| < 2 \text{ mm}$ [154]. The negative of the resulting vector is the *missing transverse momentum* $\vec{p}_T^{\text{miss}}$ of the event, and its magnitude is commonly referred to as *missing transverse energy* E_T^{miss} .

7. Event selection and top-quark reconstruction

The event selection defines the phase space considered in an analysis. The general goal is to select a large fraction of the signal process and suppress contributions from background processes, although the required acceptance and purity in signal events differs from analysis to analysis. The differential measurement presented in this thesis requires a high signal purity, which is not trivial to achieve for tq and $\bar{t}q$ production since important background processes, specifically $t\bar{t}$ and W +jets production, have much larger cross sections.

The event selection employed in the measurement of the total tq and $\bar{t}q$ cross sections [2] is applied and extended by a criterion based on a neural network (NN) discriminant. All imposed selection criteria and the reasoning behind them are presented in the following. A compact overview is given in Table 7.1.

The measurement targets events with semileptonically decaying top quarks, where τ -leptons are not considered, i.e. $\ell = e, \mu$ for the rest of this thesis. The most probable LO processes for the production of signal events are shown in Figure 7.1, and basic cuts are applied based on the expected final state. Candidate events are required to contain missing transverse energy $E_T^{\text{miss}} > 30 \text{ GeV}$ and one charged lepton with $p_T(\ell) > 28 \text{ GeV}$, where the lepton must be matched to the object that activated the single-lepton trigger to record the event (cf. Table 2.1). Events that contain an additional lepton with $p_T(\ell) > 10 \text{ GeV}$ are rejected to reduce the contribution from dileptonic $t\bar{t}$ events. To measure the tq and $\bar{t}q$ production separately, two selection regions are defined, which are separated by the sign of the charged lepton. Exactly two jets with $p_T(j) > 30 \text{ GeV}$ and $|\eta(j)| < 4.5$ are required, but events that contain additional jets with a transverse momentum below the threshold are not vetoed. Ex-

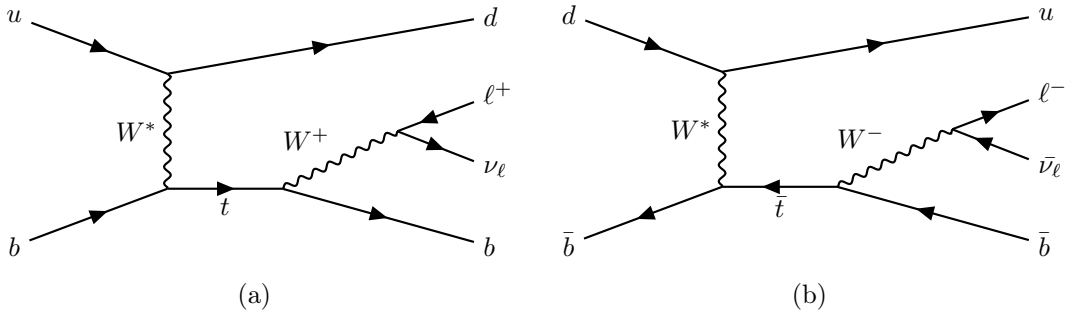


Figure 7.1: LO Feynman diagrams for (a) tq and (b) $\bar{t}q$ production, including the leptonic decay of the W -boson.



actly one of the jets is required to be b -tagged using the DL1R tagger with the 60 % working point. The spectator b -quark usually has a low p_T and does not add to the jet count in an event, therefore the tight b -tagging requirement can be used to further reject background events. The b -tagged jet is explicitly required to have $|\eta(j)| < 2.5$. Events with a *forward jet* with $2.3 < |\eta(j_f)| < 4.5$ are rejected if $p_T(j_f) < 35$ GeV, as this improves the modelling of the η -distribution of forward jets.

The requirement $p_T(\ell) > 40 \text{ GeV} \cdot |\Delta\phi(j_1, \ell)|/\pi$ is imposed to reject multijet events, which predominantly are dijet events where one jet is misidentified as a lepton. The leading jet, ordered in p_T , j_1 and the reconstructed lepton are therefore typically emitted back-to-back, and the imposed requirement vetoes the majority of multijet events as illustrated in Appendix C.1. Another common trait of multijet events is a low E_T^{miss} and transverse W -boson mass $m_T(W)$ in comparison to events with prompt W -bosons. Therefore, the criterion $m_T(W) > 50$ GeV is imposed, where the transverse W -boson mass is calculated as

$$m_T(W) = \sqrt{2p_T(\ell)E_T^{\text{miss}}(1 - \cos \Delta\phi(\vec{p}_T^{\text{miss}}, \ell))}.$$

An additional requirement is imposed on the invariant mass of the lepton and the b -tagged jet, $m(\ell b) < 160$ GeV, to exclude a phase-space that is poorly modelled in the simulated signal samples.

To finally achieve a high purity in signal events, the feed-forward NN that was trained in Ref. [2] to distinguish between signal and background events is utilised. The NN is applied in the phase spaces defined above, which are in the following referred to as ℓ^+ region and ℓ^- region. The NN is implemented with the NEUROBAYES package [155, 156] and comprises three layers; the input layer, one hidden layer and the output layer. The input consists of 17 variables describing the event kinematics, which are predominantly built from transverse momenta, invariant masses and angular distributions of the final-state particles.

Although all events in the $\ell^\pm$ regions necessarily contain the same reconstructed particles, their kinematic properties can differ significantly based on the production mode. A characteristic trait of tq or $\bar{t}q$ production is that the light jet in the final state is typically emitted in a forward direction and has a high momentum. This is reflected in the invariant mass of the two jets $m(jb)$ and the pseudorapidity of the light jet $|\eta(j)|$, which provide the highest discrimination power between signal and background events. A list of all input variables sorted by their discriminating power is given in Appendix C.2. A complex preprocessing is applied to the variables within NEUROBAYES to optimise the input for the NN training. The preprocessing involves the translation of event counts into signal purities, a transformation to map all distributions on the same interval centred around zero and linear decorrelation. The signal samples and all MC simulated background processes were used to train the NN.

The NN assigns an output score $D_{nn} \in [0, 1]$ to each event, where signal-like events are assigned high values and background-like events are sorted towards low scores.

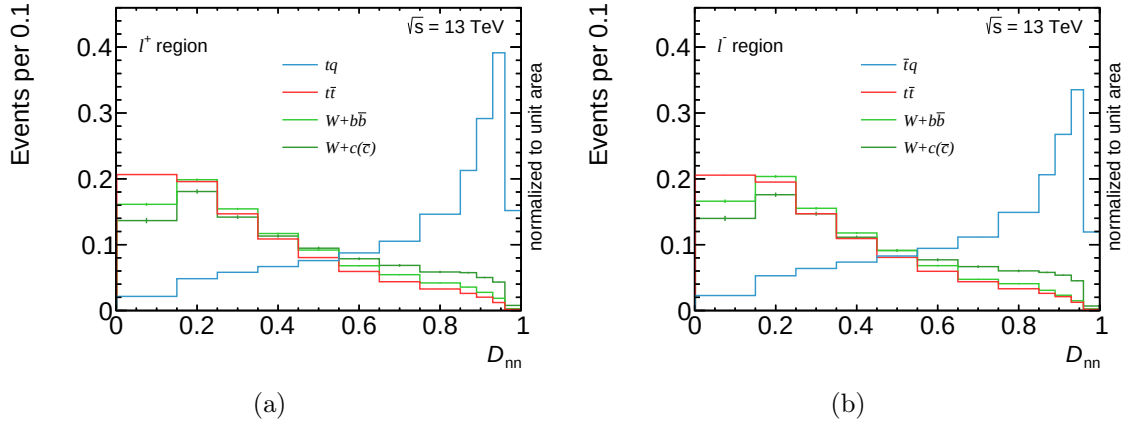


Figure 7.2: Shape of the D_{nn} distributions for the signal process and the most important background processes in the (a) ℓ^+ region and (b) ℓ^- region. All event selection criteria given in Table 7.1 except for the D_{nn} requirement are applied. The W +jets background is split according to the jet flavour as described in Chapter 8.

The D_{nn} distributions for the signal processes and the most important background processes are shown in Figure 7.2. The fraction of events that are assigned very high D_{nn} values is larger for the tq process than for $\bar{t}q$. The main reason lies with the $|\eta|$ -distribution of the light jet, which is shown in Appendix C.3. The light quark in the initial state of tq and $\bar{t}q$ production is most likely a valence quark, and the valence u -quarks have a higher probability to carry a large proton momentum fraction than the valence d -quark (cf. Figure 4.1). Therefore, the $|\eta(j)|$ distribution for tq production tends towards higher values and provides a better separation power.

The signal regions for the differential measurement, referred to as ℓ^+ SR and ℓ^- SR, are finally defined by adding the selection requirement $D_{nn} \geq 0.93$. The cut was optimised to obtain a high signal-over-background ratio $S/B \approx 4$ while retaining $\mathcal{O}(10\,000)$ signal events in both regions. Since the contribution from background events is reduced drastically by this requirement, further studies were conducted to ensure that the background modelling is reliable in the signal regions defined that way. The number of MC events in the ℓ^+ SR and ℓ^- SR is well above 1000 for all simulated processes, providing sufficient statistical power. The composition of background events as a function of different D_{nn} cut values between 0.84 and 0.95, shown in Appendix C.4, exhibits only gradual changes, which additionally shows that the D_{nn} distribution provides a powerful and well-behaved background reduction criterion.

The event selection defined above is applied to both the measured events and the simulated events that incorporate the detector response. The central idea behind a differential cross-section measurement is to correct the measured distributions for detector effects, and thereby transform the measured *detector-level* distributions into



Table 7.1.: Summary of the event selection requirements applied in the ℓ^+ SR and ℓ^- SR, which are separated by the lepton charge.

one charged lepton with $p_T(\ell) > 28 \text{ GeV}$
two jets with $p_T(j) > 30 \text{ GeV}$ and $ \eta(j) < 4.5$
one jet b -tagged at the 60 % WP
$E_T^{\text{miss}} > 30 \text{ GeV}$
$m_T(W) > 50 \text{ GeV}$
$p_T(\ell) > 40 \text{ GeV} \cdot \Delta\phi(j_1, \ell) /\pi$
$m(\ell b) < 160 \text{ GeV}$
$D_{nn} \geq 0.93$

their *truth-level* counterparts which can then be compared to the theoretical predictions introduced in Chapter 4. Since the MC simulation of events proceeds in several steps, multiple truth-levels can be defined. In this analysis, the final results are presented at *parton level*, which is defined as the last state in the event simulation before the top-quark decay. Therefore, the effects of FSR on the top-quark kinematics are incorporated in the distributions.

Differential analyses typically limit the phase space at truth level to exclude kinematic regions with soft or collinear divergencies. For tq and $\bar{t}q$ production however, no divergencies are present due to the large mass of the top quark and the t -channel nature of the process. Therefore, no event selection is applied at the parton level.

7.1. Top-quark reconstruction

The differential cross sections are measured as a function of the transverse momentum and rapidity of the top quark. To define these quantities at detector level, the top quark needs to be reconstructed from the four-vectors of its decay products, namely the b -jet, the lepton and the neutrino. The four-vectors of the lepton and the neutrino are added to form the W -boson, and the top quark is then reconstructed by adding the four-vectors of the W -boson and the b -jet. While the lepton and the b -jet are measured directly and reconstructed as described in Chapter 6, the neutrino does not interact with the detector and is instead detected in the form of missing transverse momentum $\vec{p}_T^{\text{miss}}$. The neutrino is the only source of $\vec{p}_T^{\text{miss}}$ in tq and $\bar{t}q$ events, notwithstanding minor contributions from inaccuracies in the reconstruction of the visible momenta and the production of additional neutrinos in heavy-flavour decays. The x - and y -components $P_{x,\nu}$ and $P_{y,\nu}$ of its four-momentum $\vec{P}_\nu$ are therefore directly meas-



urable. To reconstruct the z -component $P_{z,\nu}$, the mass of the reconstructed W -boson is required to match the measured world average $m(W) = 80.4 \text{ GeV}$ [157]. This yields a quadratic equation for $P_{z,\nu}$ depending on $m(W)$ and the known components of $\vec{P}_\nu$ and the four-momentum of the lepton $\vec{P}_\ell$. Out of the two solutions for $P_{z,\nu}$, the smaller one is selected.

A complication arises when the transverse mass of the W -boson, defined as

$$m_T(W) = \sqrt{(P_{T,\ell} + P_{T,\nu})^2 - (P_{x,\ell} + P_{x,\nu})^2 - (P_{y,\ell} + P_{y,\nu})^2},$$

is larger than $m(W)$, which can happen due to the limited resolution of the $\vec{p}_T^{\text{miss}}$ measurement. In this case, the quadratic equation will yield complex solutions for $P_{z,\nu}$, and a correction procedure is applied to $\vec{p}_T^{\text{miss}}$ to obtain a sensible solution [158]. In a first step, $m_T(W)$ is constrained to 80.4 GeV , which yields a single solution for $P_{z,\nu}$. Then, $P_{x,\nu}$ and $P_{y,\nu}$ are adjusted to maintain the constraint on $m(W)$. This again results in two possible solutions out of which the one that minimises the difference between the measured and the modified values is chosen.

At parton level, no reconstruction algorithm is needed, since the four-vector of the simulated top quark can be accessed directly. For the remainder of this thesis, the parton-level top quark is denoted as t or $\bar{t}$, and at detector level, the notation $\ell^+ \nu b$ or $\ell^- \nu b$ is used.

8. Background estimation

Several SM processes with event signatures similar to tq and $\bar{t}q$ production contribute to the signal regions. For example, a $t\bar{b}$ production event where one of the two b -jets in the final state is not b -tagged or a $t\bar{t}$ production event where the decay products of one top quark are not properly reconstructed can mimic the tq event signature. Although the stringent event selection utilising an NN (cf. Chapter 7) reduces the contributions from background processes considerably, they are not negligible and need to be taken into account. An overview of the considered processes and the method used to estimate their contribution are presented in the following.

8.1. MC simulated backgrounds

Most background processes are estimated from MC simulations. The most important backgrounds are the $t\bar{t}$ and W +jets production processes, due to their large cross sections. The W +jets production is split into two processes according to the jet flavour, denoted as $W + b\bar{b}$ and $W + c(\bar{c})$. Exemplary Feynman diagrams for the processes are shown in Figure 8.1. The $W + c(\bar{c})$ background comprises $gq \rightarrow Wc$ events and the associated production of a W -boson with a $c\bar{c}$ pair from gluon splitting, hence the notation with brackets is chosen. The $gq \rightarrow Wb$ process, which requires an up-type quark in the initial state, is suppressed by the CKM-matrix elements V_{ub} and V_{cb} respectively. Diagrams with a c -quark in the initial state are additionally suppressed by the c -quark PDF. Therefore, the $W + b$ production only yields a minor contribution to the $W + b\bar{b}$ background, which is reflected by the naming scheme. The associated

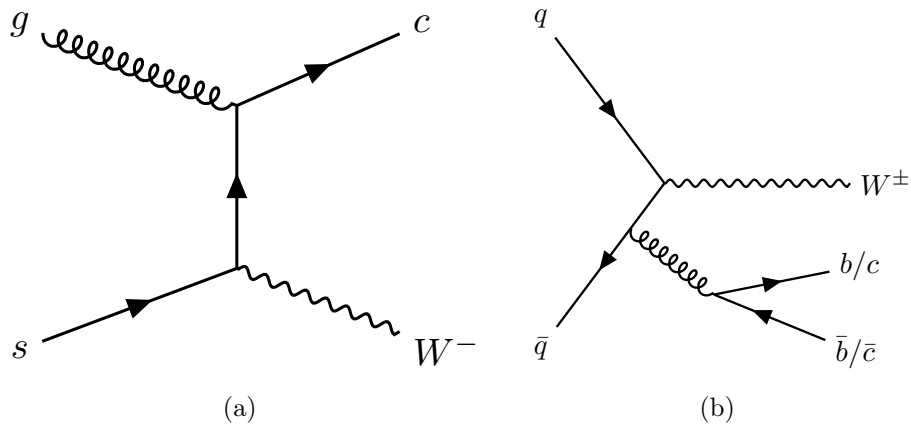


Figure 8.1: Exemplary Feynman diagrams for (a) $W + c$ and (b) $W + b\bar{b}$ or $W + c\bar{c}$ production.



production of a W -boson with a $b\bar{b}$ or $c\bar{c}$ pair are charge-asymmetric processes, as the production mode shown in Figure 8.1(b) is sensitive to the valence-quark PDFs. Their contribution is therefore larger in the ℓ^+ SR. The contribution of W +light-jets production in the signal regions is negligible, mainly because of the stringent b -tagging requirement, and therefore not considered.

The tW and s -channel production of single top quarks contribute much less to the signal regions, as expected from their lower cross sections, and they are summarised in the $tW + \bar{t}W, t\bar{b}/\bar{t}b$ background. Similarly, the Z +jets production is combined with the diboson production, where the latter is abbreviated as VV .

8.2. The multijet background

Processes with no primary lepton in the final state of the hard-scattering interaction are summarised in the multijet background. This background comprises events with *fake leptons* or *non-prompt leptons*, where the former refers to jets misidentified as leptons and the latter denotes real leptons that are produced in hadron decays inside jets or from photon conversions. The cross section of multijet events is extraordinarily large, but the rate at which these events are selected is tiny due to the stringent lepton requirements imposed in this analysis. It is therefore not feasible to simulate the multijet background with the MC methods used for the other processes. The kinematics of the multijet background can however be modelled from dedicated samples using the methods described in the following.

The *jet-electron method* [159] is used to model events in which a jet is misidentified as an electron from simulated dijet samples. Jets that deposit a large fraction of their energy in the ECal, $f_{\text{EM}} \geq 80\%$, are classified as an electron, with a randomly assigned electric charge. Events that then fulfil the signal-region event selection are used to build templates for the electron component of the multijet background. Separate templates are constructed for events with $|\eta(e)| < 1.37$ and $|\eta(e)| > 1.52$, labelled $\text{mj } e$ and $\text{mj } fe$ respectively.

The muon component of the multijet background, $\text{mj } \mu$, consists of events with non-prompt muons from hadron decays; the contribution from events where a jet is misidentified as a muon is negligible. The *anti-muon method* [159] utilises a data sample enriched in events with non-prompt muons by inverting or modifying the muon isolation criteria, such that the resulting data sample has no overlap with the nominal one. The template is constructed from events in this sample that then pass the signal-region event selection.



8.3. Estimation of the background rate

Neither the jet-electron method nor the anti-muon method provides an estimate for the absolute number of multijet events. The background normalisation in the signal regions is therefore extracted from a dedicated maximum-likelihood fit that operates on binned distributions. The general idea behind such a fit is to find the optimal parameter values of a statistical model, i.e. the values for which the model best describes the data, by maximising a likelihood function.

8.3.1. Maximum-likelihood fit

The chosen approach incorporates the impact of systematic uncertainties, which account for the limited measurement precision and uncertainties in the modelling of physics processes and are described in detail in Chapter 10. Continuous variables known as *nuisance parameters* (NPs) are associated with the systematic uncertainties, which usually consist of two systematic templates. The NPs interpolate between the variations, where the NP values of ± 1 represent the templates, and a value of 0 corresponds to the nominal estimate. The interpolation is performed separately for the shape and normalisation aspects of the uncertainties. A linear function is used for the former, and an exponential function is applied for the latter to avoid negative event yields. The number of expected events in bin i of the distribution can then be expressed as the sum over the signal process S and all background processes B_k , all of which are functions of the vector of all NPs $\vec{\theta}$:

$$\hat{n}_i(\mu, \vec{\theta}) = S_i(\vec{\theta}) + \mu \cdot \sum_{k=1}^{N_{\text{bkg}}} B_{k,i}(\vec{\theta}).$$

The normalisation μ scales the background contribution, as this is the parameter of interest in this particular fit.

As the measurement constitutes a counting experiment, the number of events in each bin follows a Poisson distribution, and the likelihood function can be defined as the product over all N bins. Gaussian constraint terms are added for all M NPs to penalise configurations that include large deviations from the pre-fit assumption that all NPs are equal to zero. The likelihood function can then be written as

$$\begin{aligned} L(\mu, \vec{\theta}) &= \prod_{i=1}^N \mathcal{P}(n_i, \hat{n}_i) \cdot \prod_{l=1}^M \mathcal{G}(\theta_l) \\ &= \prod_{i=1}^N \frac{\left(\hat{n}_i(\mu, \vec{\theta})\right)^{n_i}}{n_i!} \exp\left(-\hat{n}_i(\mu, \vec{\theta})\right) \cdot \prod_{l=1}^M \frac{1}{\sqrt{2\pi}} \exp\left(-(\theta_l^2/2)\right), \end{aligned}$$



where n_i denotes the number of data events measured in bin i . To account for the statistical uncertainty originating from the limited number of MC events x , a Poisson-constrained γ -factor is added for each bin, and the respective Poisson term in the likelihood function is altered:

$$\mathcal{P}(n_i, \hat{n}_i) \rightarrow \mathcal{P}(n_i, \gamma_i \cdot \hat{n}_i) \cdot \mathcal{P}(x_i, \gamma_i \cdot x_i).$$

The set of parameters $\hat{\mu}$ and $\hat{\theta}$ for which the probability of obtaining the observed data is maximised also maximises the likelihood function. In practice, the negative logarithm of the likelihood function $-\ln(L)$ is minimised to enhance the numerical stability of the method. The technical implementation of the fit is based on the HISTFACTORY framework [160].

8.3.2. The fit setup

The fit performed to extract the background normalisation employs multiple kinematic distributions in orthogonal phase spaces. The D_{nn} distributions are fitted in the ℓ^+ region and ℓ^- region, in which all selection criteria of the signal regions except for the D_{nn} requirement are applied. The signal regions of the differential analysis, i.e. the regions $D_{nn} \geq 0.93$, are excluded from the fit. Dedicated control regions are added for the components of the multijet background. They are enriched in the respective component by inverting certain selection criteria of the $\ell^\pm$ regions. Six control regions are defined in total, one per lepton charge and multijet component. The control regions for the muon multijet are defined with an inversion of the cut on the lepton transverse momentum, $p_T(\ell) < 40 \text{ GeV} \cdot |\Delta\phi(j_1, \ell)|/\pi$, and an inverted E_T^{miss} requirement, $E_T^{\text{miss}} < 30 \text{ GeV}$, is used for the electron components.

A preliminary multijet normalisation extracted in Ref. [2] is applied to the components with an uncertainty of 30 %. The MC simulated processes are normalised to their theoretical cross sections given in Chapter 5. The uncertainty in the theoretical cross sections is assigned as rate uncertainty to the $t\bar{t}$ and $tW + \bar{t}W, t\bar{b}/\bar{t}b$ processes. For the $W + b\bar{b}$ process, the rate uncertainty is estimated as 40 % to cover differences between the prediction and data seen in previous measurements [161], and a rate uncertainty of 20 % for the $W + c(\bar{c})$ and $VV, Z + \text{jets}$ backgrounds is estimated based on the theoretical uncertainties in the involved processes. The rate uncertainties are decorrelated between lepton charges for the $W + b\bar{b}$ and $W + c(\bar{c})$ processes to account for their charge-asymmetric nature. No rate uncertainty is applied for the signal tq and $\bar{t}q$ processes, and no systematic uncertainties related to their modelling are considered to ensure that the nominal background estimate is not influenced by systematic variations in the modelling of the signal. All other systematic uncertainties that are considered in the differential analysis are included in the fit.



8.3.3. Fit results

The pre-fit and post-fit D_{nn} distributions are shown in Figure 8.2. The pre-fit distributions present the simulated processes with the initial normalisations, where all considered uncertainties are incorporated in the uncertainty band. For the post-fit distributions, the NPs are set to their best estimators, and the yield of the simulated processes is adjusted accordingly. The uncertainty band shows the residual uncertainty, where correlations between NPs are taken into account. A striking feature of the post-fit distribution in the ℓ^+ region is that the simulation does not agree with the data within the uncertainties in the last two bins. This is a result of the missing signal modelling uncertainties, whose impact becomes large in bins with a high signal purity. The difference is fully covered when all uncertainties are considered, as shown in Section 8.4, and is therefore no cause for concern.

The best fit result for the overall background normalisation is $\mu = 0.95 \pm 0.07$. The overall normalisation is strongly anticorrelated with the normalisation of the individual background processes, which is expected as both μ and the individual background rate uncertainties only alter the normalisation of processes. Some NPs exhibit large pulls, meaning that their best fit value deviates from zero. This behaviour is also expected, since deviations between data and simulation that would be covered by signal modelling uncertainties are absorbed by other NPs. Additional figures showing the pre-fit and post-fit plots of the control regions, the NP pulls and the correlations can be found in Appendix B.1.

The background processes are normalised to the fit result by applying SFs to each process. The SFs are defined as the post-fit yield divided by the pre-fit yield, and the relative uncertainty in the post-fit yield is assigned as rate uncertainty. This approach is used for both the multijet and the MC simulated backgrounds to keep the estimate self-consistent. The obtained SFs and uncertainties are given in Table 8.1. For most background processes, the obtained estimate is compatible with the pre-fit estimate within the assigned uncertainty. The $t\bar{t}$ contribution is decreased compared to the initial MC prediction while the $W + b\bar{b}$ contribution is increased, which is consistent with the trends observed in Ref. [2].

8.4. Event yields and data/MC comparisons in the signal regions

The expected and observed event yields in the signal regions are presented in Table 8.2. The background SFs and rate uncertainties from Table 8.1 are applied for the background processes. The most important background processes are $t\bar{t}$, $W + b\bar{b}$ and $W + c(\bar{c})$ production. As shown in Figure 8.3, the backgrounds constitute 13.9% of the events in the ℓ^+ SR and 20.8% in the ℓ^- SR, which corresponds to a respective

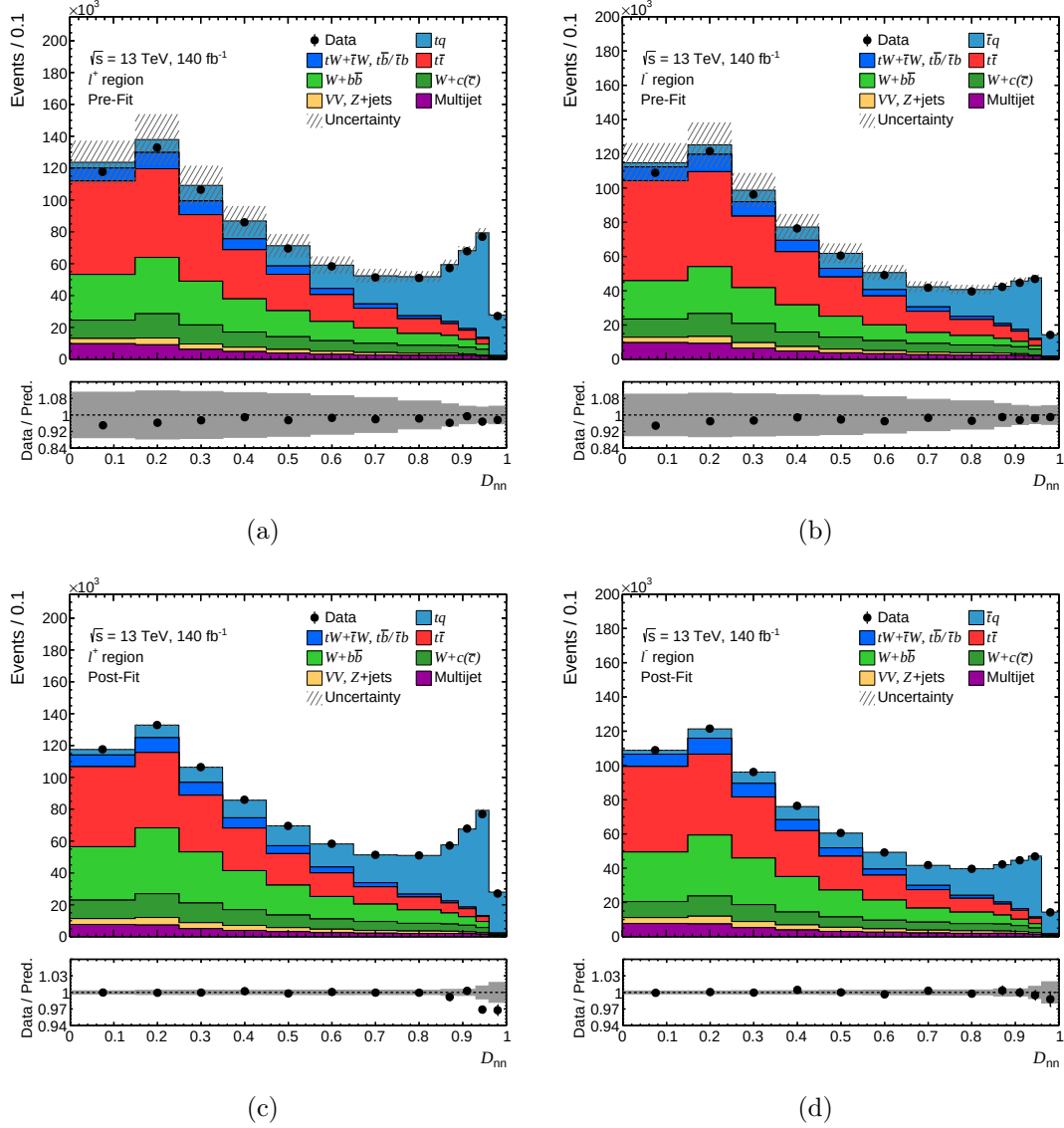


Figure 8.2: Comparison between the data and MC predictions shown for the D_{nn} distribution in the (a), (c) ℓ^+ region and (b), (d) ℓ^- region. The uncertainty band in the (a), (b) pre-fit distributions incorporates all statistical and systematic uncertainties except for those related to the modelling of the signal processes. For the uncertainty in the (c), (d) post-fit distributions, the correlations between NPs are taken into account.



Table 8.1.: Scale factors and relative rate uncertainties per background process for both signal regions. The normalisations of the $W + b\bar{b}$ and $W + c(\bar{c})$ backgrounds are decorrelated between the signal regions.

Process	ℓ^+ SR		ℓ^- SR	
	Scale factor	Rate uncertainty	Scale factor	Rate uncertainty
$t\bar{t}$	0.85	0.04	0.85	0.04
$tW + \bar{t}W, t\bar{b}/\bar{t}b$	0.93	0.10	0.93	0.10
$VV, Z + \text{jets}$	1.12	0.19	1.12	0.19
$W + b\bar{b}$	1.16	0.11	1.29	0.10
$W + c(\bar{c})$	1.00	0.20	0.88	0.16
mj e	0.72	0.28	0.72	0.28
mj fe	0.80	0.30	0.80	0.30
mj μ	0.92	0.29	0.92	0.29

signal-over-background ratio of 6.1 and 3.8. The asymmetry between the SRs is caused by the charge-asymmetric nature of the signal process, whereas most background processes are charge symmetric, and the better separation power of the NN in the ℓ^+ region discussed in Chapter 7. For both signal regions, the expected event yield agrees with the observed data within 1%.

Comparisons between data and simulation are shown in Figure 8.4 for the observables considered in the differential measurement. Additional kinematic variables are presented in Appendix B.2. The uncertainty band incorporates all uncertainties considered in the differential analysis, and the expectation agrees well with the data for all distributions.



Table 8.2.: Expected event yields per process and observed event yields in both signal regions. The given uncertainties are the rate uncertainties defined as the relative uncertainty in the post-fit event yields.

Process	ℓ^+ SR	ℓ^- SR
tq	$29\,740 \pm 590$	15 ± 15
$\bar{t}q$	7 ± 7	$15\,550 \pm 300$
$t\bar{t}$	1020 ± 40	1050 ± 40
$tW + \bar{t}W, t\bar{b}/\bar{t}b$	200 ± 20	210 ± 21
$VV, Z + \text{jets}$	290 ± 60	300 ± 60
$W + b\bar{b}$	1360 ± 150	940 ± 90
$W + c(\bar{c})$	1340 ± 270	1080 ± 170
Multijet	610 ± 120	500 ± 100
Total expected	$34\,580 \pm 680$	$19\,630 \pm 380$
Observed	33 883	19 730

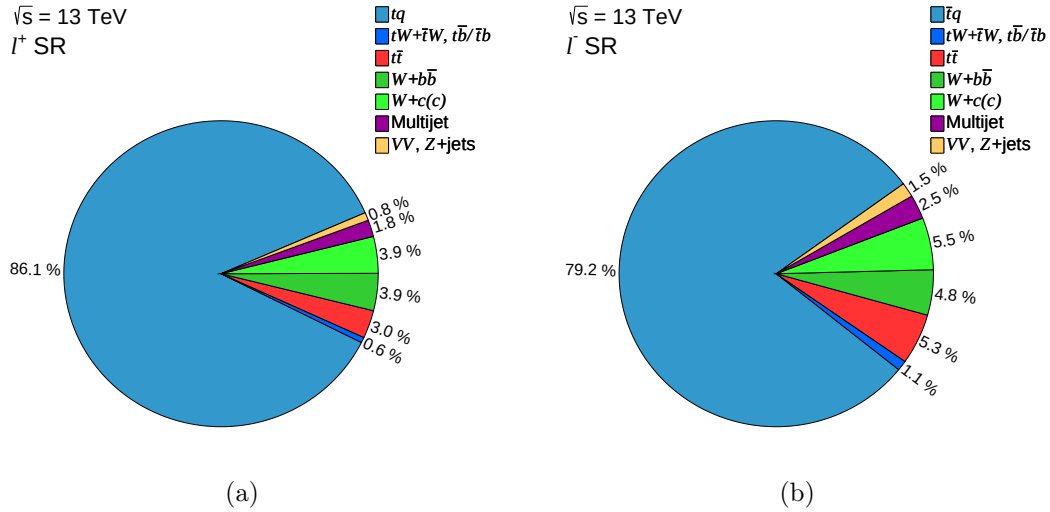


Figure 8.3: Expected event composition in the (a) ℓ^+ SR and (b) ℓ^- SR.

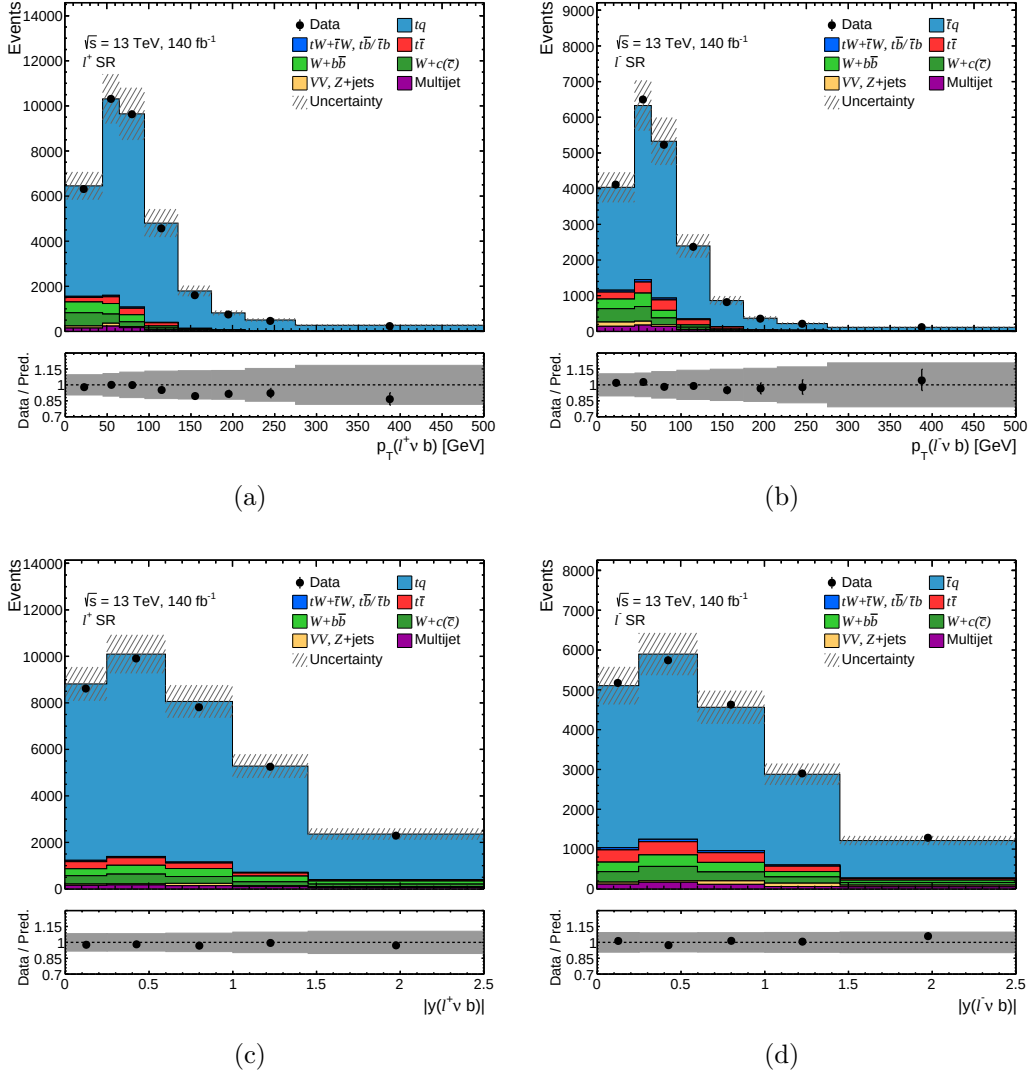


Figure 8.4: Comparison between the expected and observed event yields for the (a) $p_T(\ell^+ \nu b)$, (b) $p_T(\ell^- \nu b)$, (c) $|y(\ell^+ \nu b)|$ and (d) $|y(\ell^- \nu b)|$ distributions. All uncertainties are incorporated in the uncertainty band.

9. The unfolding method

Differential cross-section measurements aim to determine cross sections as a function of some event observables. The biggest challenge is to correct the measured distributions for distortions introduced by the detector response, as schematically shown in Figure 9.1. The number of recorded events is lower than the number of produced events due to acceptance effects, like the limited spatial coverage of the detector or the trigger requirements. The limited detector resolution additionally leads to migration effects, where events are produced and reconstructed in different phase spaces, which affects the shape of reconstructed distributions. The goal of a differential measurement is to infer the true quantity from the measured one.

Mathematically speaking, the measured quantity m can be parameterised as a convolution of the true quantity t with the detector response R :

$$g(m) = \int R(m | t) \cdot f(t) dt,$$

where $g(m)$ and $f(t)$ denote the quantities' probability density functions [162]. Since cross-section measurements are counting experiments in binned observables, the convolution can be simplified to a matrix multiplication. A simple inversion of the response

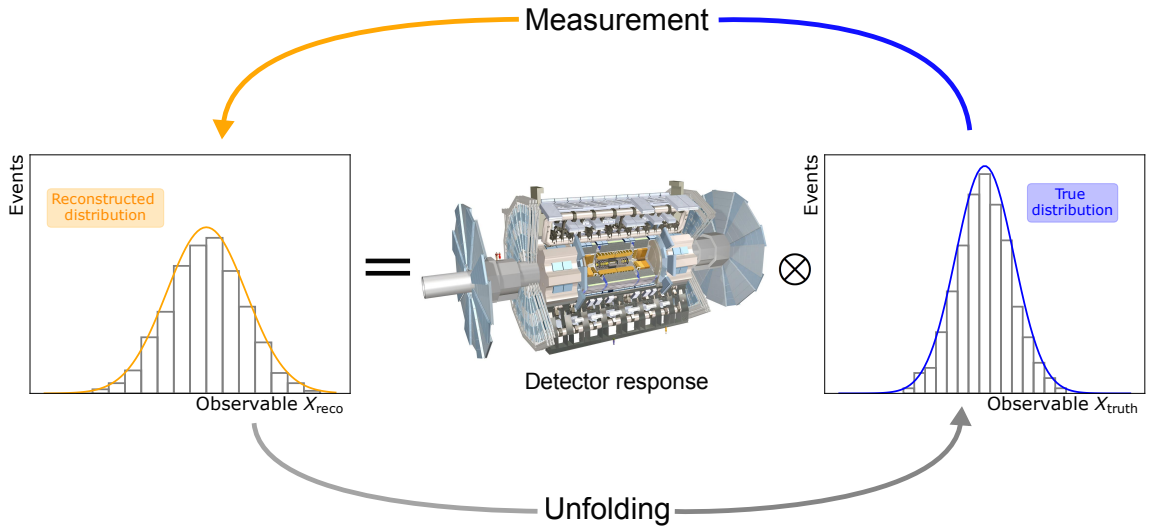


Figure 9.1: Schematic representation of the unfolding principle.



matrix however is not guaranteed to be numerically stable, therefore an *unfolding* procedure is applied instead. The unfolding method employed in this analysis is described in Section 9.1, followed by the chosen binning of the observables in Section 9.2, the required unfolding corrections in Section 9.3 and the validation of the method in Section 9.4. The measured and true quantities are referred to as detector-level and parton-level quantities, as introduced in Section 7.1.

9.1. Theoretical background

The analysis presented in this thesis uses D'Agostini's iterative approach [163], which is also referred to as *Iterative Bayesian Unfolding* (IBU) as it is based on Bayes' theorem. To be applicable to collision experiments, the theorem is expressed in terms of several independent causes C_j that can lead to multiple effects E_i . The effects can then be identified with the observation of an event with certain kinematic properties, as for example a particular value of $p_T(\ell^\pm \nu b)$, whereas the causes comprise all possible true values of the property. Bayes theorem can be expressed as

$$P(C_j | E_i) = \frac{P(E_i | C_j) \cdot P_0(C_j)}{\sum_{l=1}^{N_{\text{causes}}} P(E_i | C_l) \cdot P_0(C_l)}, \quad (9.1)$$

where $P_0(C_j)$ denotes the initially assumed probability for a cause C_j to occur. While each effect needs a cause, not every cause has to lead to an effect. This is captured by the *efficiency*

$$\epsilon_j \equiv \sum_{i=1}^{N_{\text{effects}}} P(E_i | C_j) \leq 1, \quad (9.2)$$

which needs to be larger than zero for all causes under study, as $\epsilon_j = 0$ implies that the experiment provides no sensitivity to C_j . Performing the experiment yields the number of events observed with a given effect $n(E_i)$, which can then be used to calculate an estimate for the number of events originating from a given cause C_j ,

$$\hat{n}(C_j) = \frac{1}{\epsilon_j} \sum_{i=1}^{N_{\text{effects}}} n(E_i) P(C_j | E_i), \quad (9.3)$$

and the updated probability for C_j ,

$$P_0(C_j) \rightarrow \hat{P}(C_j) = \frac{\hat{n}(C_j)}{\sum_{l=1}^{N_{\text{causes}}} \hat{n}(C_l)}. \quad (9.4)$$

If the initial distribution of probabilities for all causes $P_0(\vec{C})$ is not consistent with the experimental result, $\hat{P}(\vec{C})$ will differ from $P_0(\vec{C})$ and it will be closer to the true probability distribution. The method therefore proceeds iteratively and is regularised by the number of iterations:



1. Choose the initial probabilities $P_0(\vec{C})$.
2. Calculate $\hat{n}(\vec{C})$ and $\hat{P}(\vec{C})$.
3. Update Equation 9.1 by replacing $P_0(C_j)$ with $\hat{P}(C_j)$.
4. Repeat from Step 2. until $\hat{P}(\vec{C})$ is sufficiently close to the true distribution.

The general IBU formula described above can be tailored to the problem of extracting differential cross sections from a measurement by relating the generic variables used until now to physical quantities. The distribution of the data events recorded by the ATLAS detector as a function of some kinematic variable X is the experimental input. Then, $n(E_i)$ corresponds to the number of signal events reconstructed in bin i of the detector-level distribution. It can be estimated from the number of recorded events in that bin N_i^{data} and the expected number of events originating from background processes N_i^{bkg} , which is estimated from MC simulations as described in Section 8. The efficiency ϵ_j can also be estimated from simulation as the fraction of all signal MC events produced in a parton-level bin j that pass the signal-region event selection in an arbitrary detector-level bin. The $P(C_j | E_i)$ refers to the probability for an event measured in bin i to have originated in bin j . Equation 9.1 can then be rewritten as

$$P(C_j | E_i) \equiv \mathcal{M}_{ji} = \frac{M_{ij} \cdot N_j^{\text{parton}}}{\sum_{l=1} M_{il} \cdot N_l^{\text{parton}}}, \quad (9.5)$$

where the element M_{ij} of the *migration matrix* M denotes the probability for a signal event originating in bin j to be reconstructed in bin i . The prediction for the parton-level distribution of the signal process N_j^{parton} is initially obtained from MC simulations and updated in the iterative procedure. Finally, $\hat{n}(C_j)$ corresponds to the estimator for the number of signal events produced in bin j . It can be expressed in terms of the differential cross section $\frac{d\sigma}{dX_j}$, the bin width ΔX_j and the integrated luminosity,

$$\hat{n}(C_j) = \frac{d\sigma}{dX_j} \cdot \Delta X_j \cdot \mathcal{L}_{\text{int}}.$$

Performing all replacements in Equation 9.3 yields the central formula to determine differential cross sections with IBU:

$$\frac{d\sigma}{dX_j} = \frac{1}{\epsilon_j \cdot \Delta X_j \cdot \mathcal{L}_{\text{int}}} \sum_{i=1}^{N_{\text{bins}}} \mathcal{M}_{ji} (N_i^{\text{data}} - N_i^{\text{bkg}}). \quad (9.6)$$

The iterative approach circumvents the need to invert the migration matrix and thereby enhances the numerical stability of the method. The RooUnfold [164] package provides the implementation of the IBU method used in this analysis.



9.2. Binning of the observables

For a differential measurement, the binning of the distributions requires careful consideration. A fine binning provides a better resolution of the differential cross sections, but limitations on the bin width must be obeyed. The main aspects taken into account are discussed in the following.

Detector resolution

As discussed in Chapter 6, the accuracy in the reconstruction of properties of physical objects, such as the transverse momentum, is limited by the detector resolution. The bin width therefore needs to be larger than the detector resolution to avoid large migration effects. The top quark at detector level is reconstructed from the b -jet, lepton and E_T^{miss} , all of which are measured with phase-space dependent precision. The resolutions of the top-quark rapidity and transverse momentum are therefore estimated with the aid of the parton-level values. The difference between the parton-level and detector-level values is determined as a function of the parton-level value as exemplarily shown in Figures 9.2(a) and 9.2(b). The standard deviation of the distributions then defines the resolution of the variables as depicted in Figures 9.2(c) and 9.2(d) for the ℓ^+ SR. The resolutions obtained in the ℓ^- SR are very similar and shown in Appendix D.1. For the p_T and $p_T(\bar{t})$ distributions, the resolution lies between 10–20 GeV and increases with the p_T , reflecting the p_T -dependence of the detector resolution. It should be noted however that the relative resolution improves with increasing p_T . For the $|y(t)|$ and $|y(\bar{t})|$ distributions, a resolution between 0.2–0.4 is obtained. The steep increase around $|y(t \text{ or } \bar{t})| = 1.5$ reflects the lower detector resolution in the forward region.

Event migration

Due to the limited detector resolution, reconstructed values of observables are smeared around their true value. The reconstructed top quark can therefore have a different transverse momentum or rapidity than its parton-level counterpart. This migration between parton-level and detector-level bins of a distribution is encoded in the migration matrix (cf. Equation 9.5). For the binning of the observables, the unfolding procedure imposes the constraint to keep the migration of events to off-diagonal bins of the migration matrix below 50 %, i.e. at least half of the events that are produced in one bin at parton level are required to be reconstructed in the same bin at detector level. The event migration becomes the determining factor in the low- $p_T(\ell^\pm \nu b)$ and high- $|y(\ell^\pm \nu b)|$ regions.

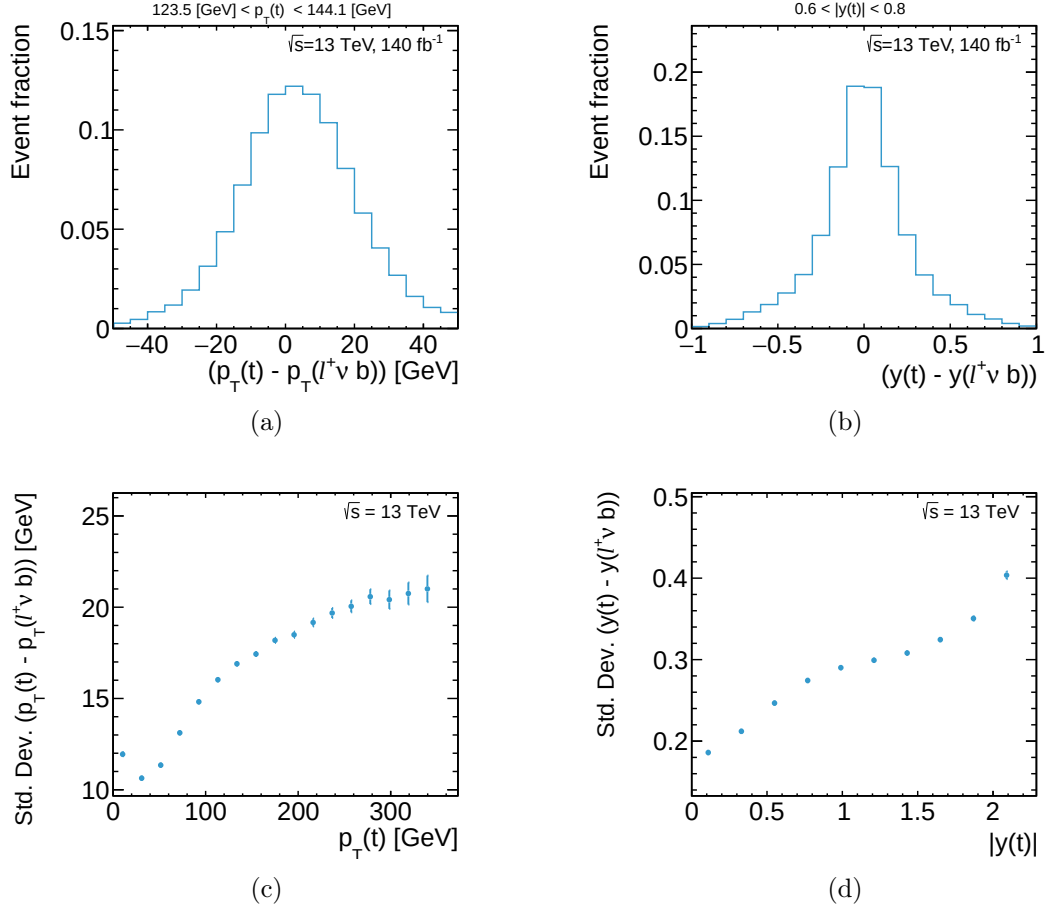


Figure 9.2: Exemplary distributions of the difference between the parton-level and detector-level values for (a) $123.5 \text{ GeV} < p_T(t) < 144.1 \text{ GeV}$ and (b) $0.6 < |y(t)| < 0.8$. The resolution of (c) $p_T(\ell^+ \nu b)$ and (d) $|y(\ell^+ \nu b)|$, defined as the standard deviation of the distributions, is shown as a function of the respective top-quark property at parton level.

Data statistical uncertainty

To ensure that the final results are not dominated by statistical fluctuations, the statistical uncertainty in data is kept around 10 %. For counting experiments, the number of events is Poisson distributed, therefore the uncertainty in the number of observed events N is given by $\sqrt{N}$. Generally, the amount of data events in both signal regions is high enough for the uncertainty to stay between 1–5 % for any binning not ruled out by the resolution and migration constraints. The only exception is the high- $p_T(\ell^\pm \nu b)$ region, where the data statistical uncertainty becomes the most important criterion.



In addition to the discussed requirements, the binning of each variable has to be synchronised between the two signal regions to allow for the measurement of the differential cross-section ratios. Taking all these constraints into account, the bin boundaries are chosen as

$$p_T(\ell^\pm \nu b) \text{ bin boundaries} = [0, 45, 65, 95, 135, 175, 215, 275, 500, 2000] \text{ GeV, and}$$

$$|y(\ell^\pm \nu b)| \text{ bin boundaries} = [0.0, 0.25, 0.6, 1.0, 1.45, 2.5].$$

The same bin boundaries are also used for the parton-level distributions.

There are seven data events in the ℓ^+ SR, and eight in the ℓ^- SR, that are reconstructed with $p_T(\ell^\pm \nu b) > 500$ GeV. Increasing the width of the $[275, 500]$ GeV bin to include all those events would dilute the measurement in that bin and is therefore not done. A shadow bin $[500, 2000]$ GeV is added instead as a technical measure to take the migration from and into this phase-space region into account. The differential cross section is not measured in the shadow bin, which is therefore not shown in any following figures.

9.3. Unfolding corrections

The IBU method requires several inputs that are estimated from the simulated signal samples, namely the efficiency, the migration matrix and the number of iterations. Details on these inputs and their determination are provided in the following.

9.3.1. Migration matrix

The migration matrix parametrises the migration of events between bins of a distribution at parton and detector level due to the limited detector resolution. It is calculated from all signal MC events that pass the event selection at detector level. The migration matrices obtained for both observables in both signal regions are shown in Figure 9.3. The rows are normalised to unity, such that each bin shows the fraction of events produced in the corresponding parton-level bin that are reconstructed in the respective detector-level bin. As described in Section 9.2, the binning of the observables was optimised to keep the off-diagonal migration below 50 % to ensure the stability of the unfolding procedure. For the $p_T(t)$ and $p_T(\bar{t})$ distributions, the migration is below 40 % for all parton-level bins.

For all observables, the migration is asymmetric as objects measured by the detector are more likely to be reconstructed with lower than with higher energy. The migration of events to the off-diagonal is mostly contained in the adjacent bins. For the $p_T(t)$ and $p_T(\bar{t})$ distributions, less than 5 % of all events are reconstructed further away from the diagonal, and for the $|y(t)|$ and $|y(\bar{t})|$ distributions, the fraction stays below 10 %.

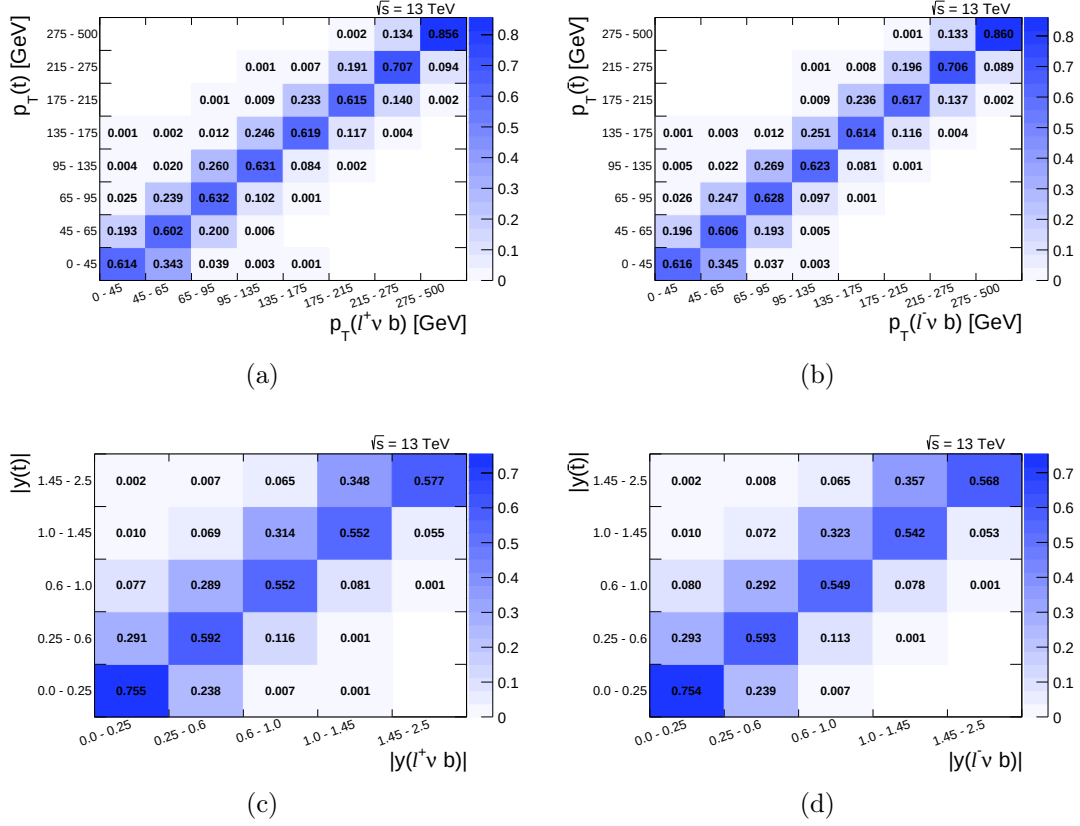


Figure 9.3: Migration matrices for the (a) $p_T(t)$, (b) $p_T(\bar{t})$, (c) $|y(t)|$ and (d) $|y(\bar{t})|$ distributions. The rows are normalised to unity.

No significant differences are observed between the migration matrices for $p_T(t)$ and $p_T(\bar{t})$, or for $|y(t)|$ and $|y(\bar{t})|$.

9.3.2. Selection efficiency

Due to the limitations of the detector and the imposed event selection criteria, only a subset of all tq and $\bar{t}q$ events produced in collisions is recorded, properly reconstructed and consecutively accepted in a signal region. This is accounted for by the selection efficiency ϵ_j , which is defined per parton-level bin j as the fraction of simulated signal events produced in that bin that pass the detector-level event selection

$$\epsilon_j = \frac{N_j^{\text{sel}}}{N_j^{\text{prod}}}. \quad (9.7)$$

The selection efficiencies obtained for both distributions in both signal regions are shown in Figure 9.4. As a result of the narrow selected phase space, which is required

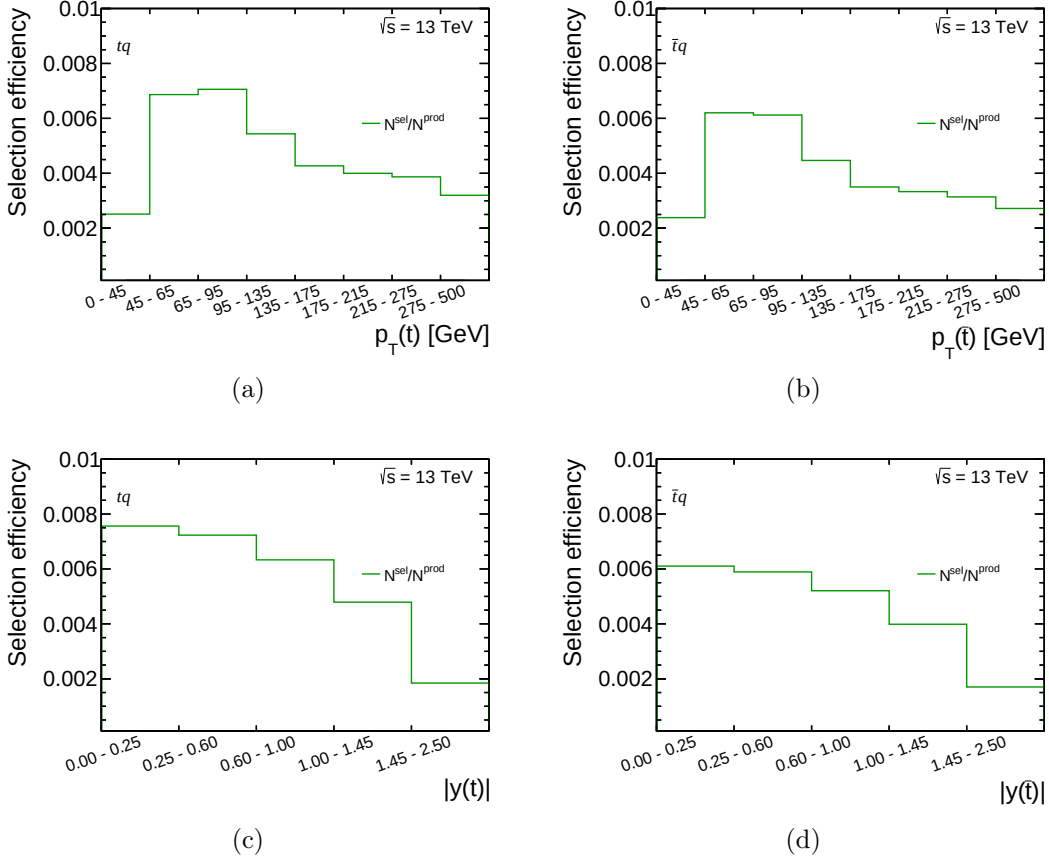


Figure 9.4: Selection efficiencies for the (a) $p_T(t)$, (b) $p_T(\bar{t})$, (c) $|y(t)|$ and (d) $|y(\bar{t})|$ distributions.

to keep the contribution from background processes sufficiently low, the majority of the signal events is rejected. The selection requirement of exactly two jets with exactly one b -tag already leads to selection efficiencies below 5 % as shown in Appendix D.2. The additional requirements reduce the efficiency further to the sub-percent level, where the D_{nn} requirement has the largest impact. It is also the reason behind the different selection efficiencies for tq and $\bar{t}q$ events, as the NN reaches a better separation power in the ℓ^+ SR and thereby assigns a larger fraction of signal events a score $D_{nn} > 0.93$ (cf. Chapter 7).

The selection efficiency of the $|y(t)|$ and $|y(\bar{t})|$ distributions decreases steeply in the high-rapidity region because the efficiency of the b -tagging algorithm decreases significantly for jets with $|\eta| > 1.5$ [165]. The decrease in the selection efficiency for high- $p_T(t)$ and high- $p_T(\bar{t})$ events is again caused by the event selection requirement of exactly two reconstructed jets, as most of those events contain additional jets radiated off the top quark. A detailed study of the selection efficiency for the $p_T(t)$ and $p_T(\bar{t})$ distributions is presented in Appendix D.2. The feasibility of extending the event selection to allow events with additional jets was studied, but it was found that

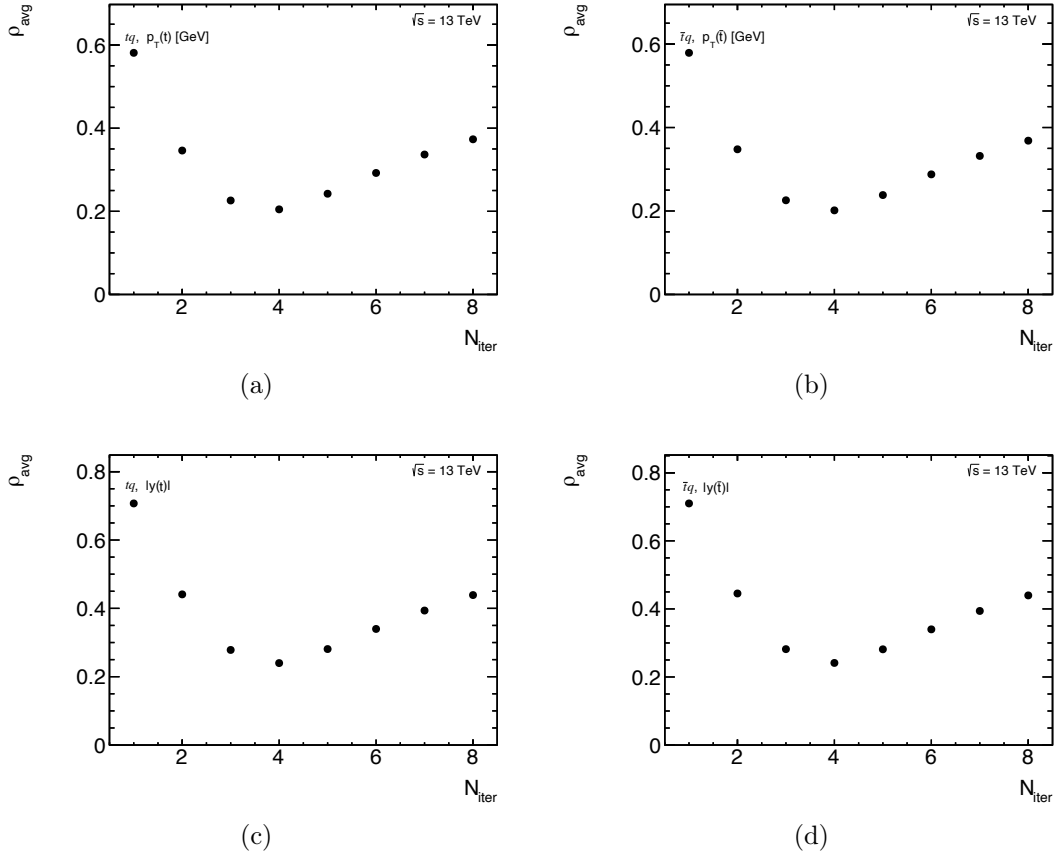


Figure 9.5: Average global correlation coefficient ρ_{avg} after N_{iter} iterations for the (a) $p_T(t)$, (b) $p_T(\bar{t})$, (c) $|y(t)|$ and (d) $|y(\bar{t})|$ distributions.

the inclusion of events containing three jets already increases the contribution from $t\bar{t}$ events beyond the acceptable level.

9.3.3. Number of iterations

The unfolding is regularised by the number of performed iterations, where the regularisation strength decreases with the number of iterations. The *average global correlation coefficient* ρ_{avg} provides a measure to define the optimal number of iterations. It is defined as

$$\rho_{\text{avg}} = \frac{1}{N_b} \sum_{j=1}^{N_b} \sqrt{1 - ((\text{Cov}_{N_b})_{jj} (\text{Cov}_{N_b}^{-1})_{jj})^{-1}}, \quad (9.8)$$

where N_b denotes the number of bins of the unfolded distribution and Cov_{N_b} indicates the statistical covariance matrix. The latter is calculated in RooUnfold by using an error-propagation matrix. The statistical covariance matrix obtained from this



method agrees with the one obtained from the classical approach of using pseudo experiments [164]. The statistical correlation between the bins of the distribution is positive at the beginning of the iterative process, as the method accounts for bin-by-bin migrations, but negative correlations appear for larger numbers of iterations, where the method approximates an inversion of the migration matrix and statistical fluctuations arise. Therefore, the number of iterations that minimises ρ_{avg} optimises the regularisation [166]. To determine ρ_{avg} , an alternative signal sample generated with POWHEG BOX v2 +HERWIG 7.3 is unfolded using the nominal migration matrix and efficiency, and Cov_{N_b} is calculated after each iteration. The values obtained for ρ_{avg} after each iteration for all distributions are shown in Figure 9.5. For all distributions, ρ_{avg} is minimised after four iterations.

9.4. Validation of the unfolding method

The unfolding of the measured distributions is the technical centrepiece of the analysis. Therefore, several tests are performed to ensure that the method is implemented correctly, does not introduce a significant bias to the result and its performance is robust against changes in the shape of the unfolded distributions.

9.4.1. Technical closure test

The technical closure test is performed to validate the technical implementation of the IBU method. The unfolding corrections, i.e. the selection efficiency and migration matrix, are estimated using the nominal signal MC samples. It follows that the detector-level distributions of the nominal signal samples have to agree perfectly with their parton-level counterparts when they are unfolded with the nominal unfolding corrections. This is verified by the technical closure test. The results of the test for both distributions in both signal regions are presented in Figure 9.6. Perfect closure between the unfolded and the parton-level distributions is observed. The detector-level distributions are additionally shown in the figures; the large difference in magnitude is an effect of the selection efficiency.

9.4.2. Pull test

The pull test is performed to check whether a bias is introduced by the unfolding, and whether the statistical uncertainty is estimated correctly. Pseudo experiments are constructed by fluctuating each bin of the nominal signal MC distribution at detector level according to a Poisson distribution with a mean of the expected number of signal events in that bin. The pseudo experiments are then unfolded using the nominal

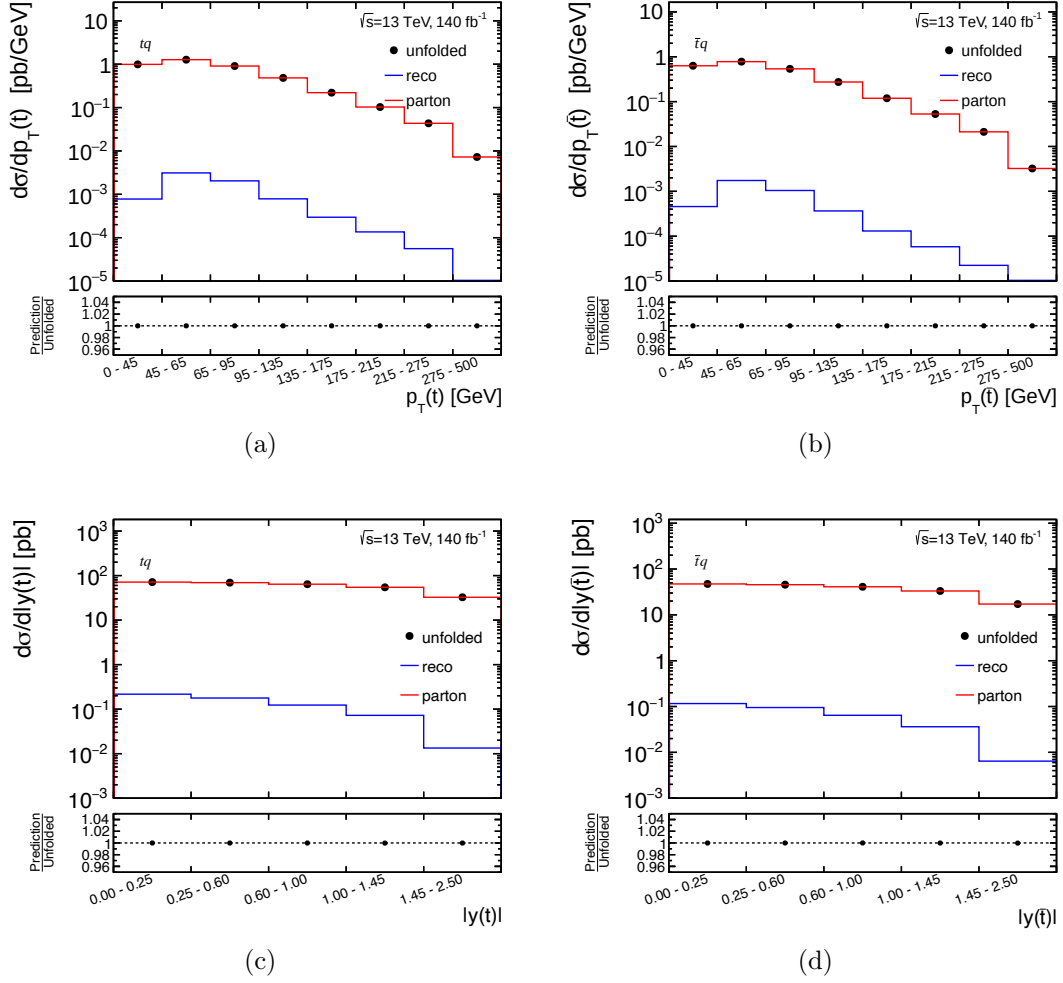


Figure 9.6: Results of the technical closure test for the (a) $p_T(t)$, (b) $p_T(\bar{t})$, (c) $|y(t)|$ and (d) $|y(\bar{t})|$ distributions. The distributions of the signal MC sample at detector and parton level are shown in addition to the unfolded detector-level distributions.

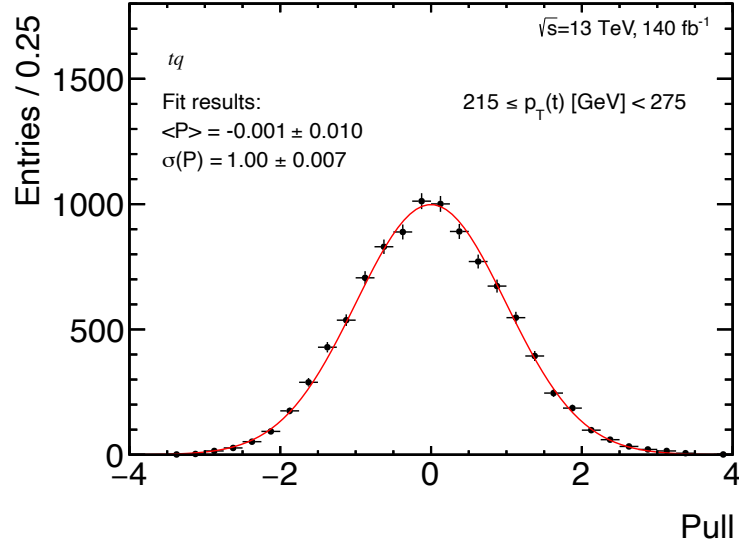


Figure 9.7: Distribution of the pulls of 10 000 pseudo experiments obtained in the region $215 \text{ GeV} < p_T(t) < 275 \text{ GeV}$. A Gaussian function is fitted to the distribution. The best fit has a mean $\langle P \rangle = (-0.001 \pm 0.010) \text{ GeV}$ and a standard deviation $\sigma(P) = (1.00 \pm 0.07) \text{ GeV}$.

unfolding corrections, and the distribution of the pulls is calculated. The pull of pseudo experiment n in bin j is defined as

$$P_j^n = \frac{N_j^n - N_j^{\text{part}}}{\sigma_j}, \quad (9.9)$$

where N_j^{part} denotes the event yield in bin j of the parton-level distribution of the nominal signal sample. The content of the unfolded pseudo-experiment in bin j is given by N_j^n , and σ_j denotes the standard deviation of the distribution of all N_j^n . The pull distributions are expected to follow a Gaussian distribution with a mean of zero and a standard deviation of one. A Gaussian function is fitted in each bin to extract the mean and the width. The result of such a fit is exemplarily shown in Figure 9.7 for the pulls observed for tq production in the region $215 \text{ GeV} < p_T(t) < 275 \text{ GeV}$. Deviations in the mean value would indicate a bias, and a width of the distribution smaller or larger than one would respectively indicate an over- or underestimation of the statistical uncertainty. The fit results for the $p_T(t)$ and $p_T(\bar{t})$ distributions are presented in Figure 9.8, and the results for $|y(t)|$ and $|y(\bar{t})|$ are shown in Figure E.1. The results are compatible with the expectations for all distributions, meaning that no bias is introduced, and the statistical uncertainty is estimated correctly.



9.4. Validation of the unfolding method

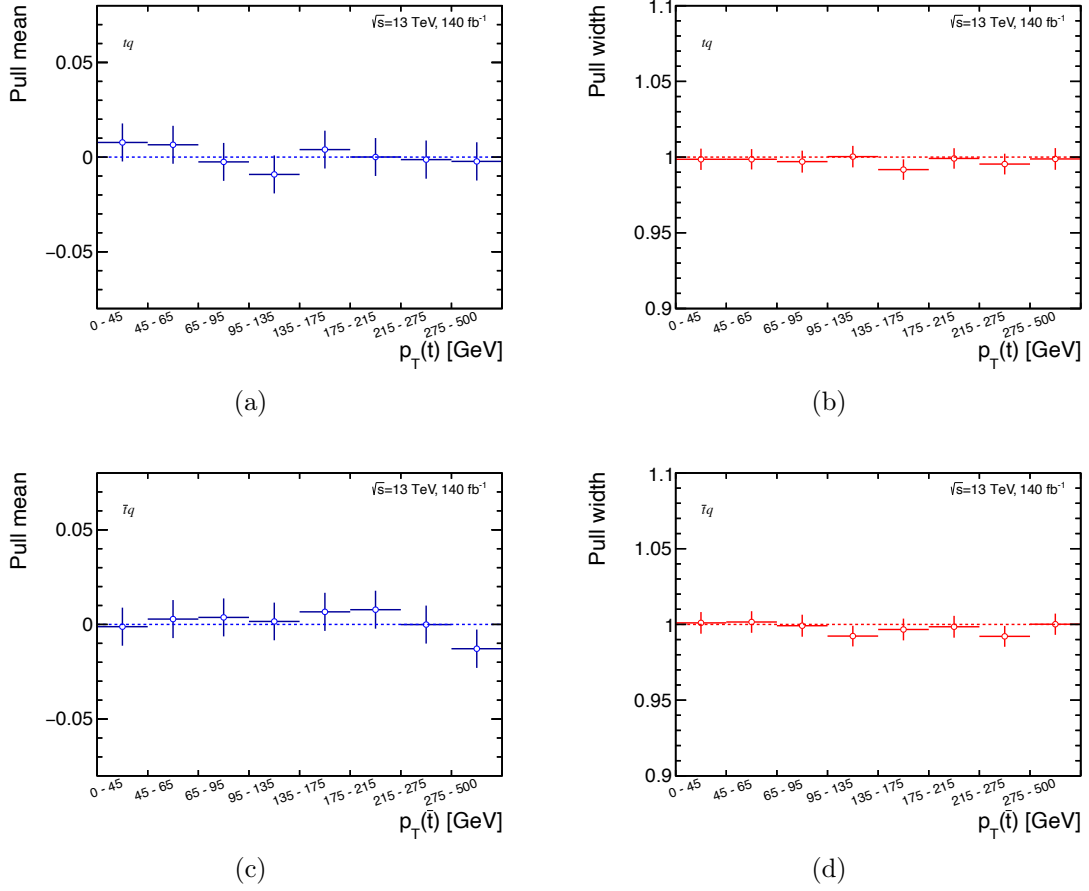


Figure 9.8: Results of the pull test for (a), (b) $p_T(t)$ and (c), (d) $p_T(\bar{t})$. The dashed lines show the expected values for the pull distribution of a mean equal to zero and a width equal to one.

9.4.3. Stress test

Stress tests are performed to check whether the unfolding can recover distributions whose shapes differ from the nominal signal MC. It is important that the unfolding performs well in this regard, as it may otherwise distort the shape of the measured distributions towards the MC expectation. Several stress tests are performed to ensure the robustness of the unfolding method. For each test, the nominal simulated signal distributions are reweighted synchronously at detector level and parton level to alter the shape. The reweighted detector-level distribution is then unfolded using the nominal unfolding corrections, and the unfolded distribution is compared to the reweighted parton-level distribution. Large differences indicate a potential shape distortion introduced by the unfolding.



Reweighting to data

The inputs to the differential measurement are the distributions measured in data subtracted by the nominal background estimate (cf. Equation 9.6). It is therefore vitally important that the unfolding method works well for these distributions. For the main stress test, the nominal signal distribution is reweighted to match the background subtracted data. The reweighting factors are derived separately for each observable from the detector level distributions. To check for hidden correlations between the variables, the events are additionally reweighted according to the $p_T(t)$ or $p_T(\bar{t})$ distribution, but unfolded in $|y(t)|$ or $|y(\bar{t})|$, and vice versa.

The results of the tests are presented in Figure 9.9. The upper ratio panel in the figures shows the reweighted parton-level distributions divided by the nominal ones. The difference between the unfolded reweighted distributions and the reweighted parton-level distributions is presented in the lower ratio. Generally, the differences between the signal events and the background subtracted data are larger in the p_T distributions than in the $|y|$ distributions. All reweighted shapes are recovered well, with residual differences at parton level below 2%. No hidden correlations are observed, as the cross-variable reweighting yields distributions that are almost identical to the original ones.

Linear reweighting

As an additional test to check how the unfolding procedure responds to greater shape differences in the input distributions, the distributions are reweighted according to linear functions with different slopes. The maximum deviations are chosen such that they cover twice the maximum difference between the background subtracted data and the simulated signal. For the $p_T(t)$ and $p_T(\bar{t})$ distributions, the reweighting is only performed in the first three bins in which the majority of events is located. As the distributions are normalised to their integral, this approach yields a change in the shape of the desired magnitude.

The results of these stress tests are presented in Figure 9.10. For all distributions, the shape is well recovered by the unfolding. For the $p_T(\bar{t})$, $|y(t)|$ and $|y(\bar{t})|$ distributions, single bins show residual differences of up to 2%, and the most extreme reweighting of the $p_T(t)$ distribution results in a residual difference of $\pm 3\%$ in the second and fourth bin. Taking the magnitude of the induced shape differences into account, the observed deviations are sufficiently small. For both the $p_T(t)$ and $p_T(\bar{t})$ distributions, an anticorrelation between the residual differences in the second and fourth bin is observed, while all other bins show an excellent agreement. The results of the tests are satisfactory and show that the unfolding method does not distort the shape of the input distributions in any concerning way.

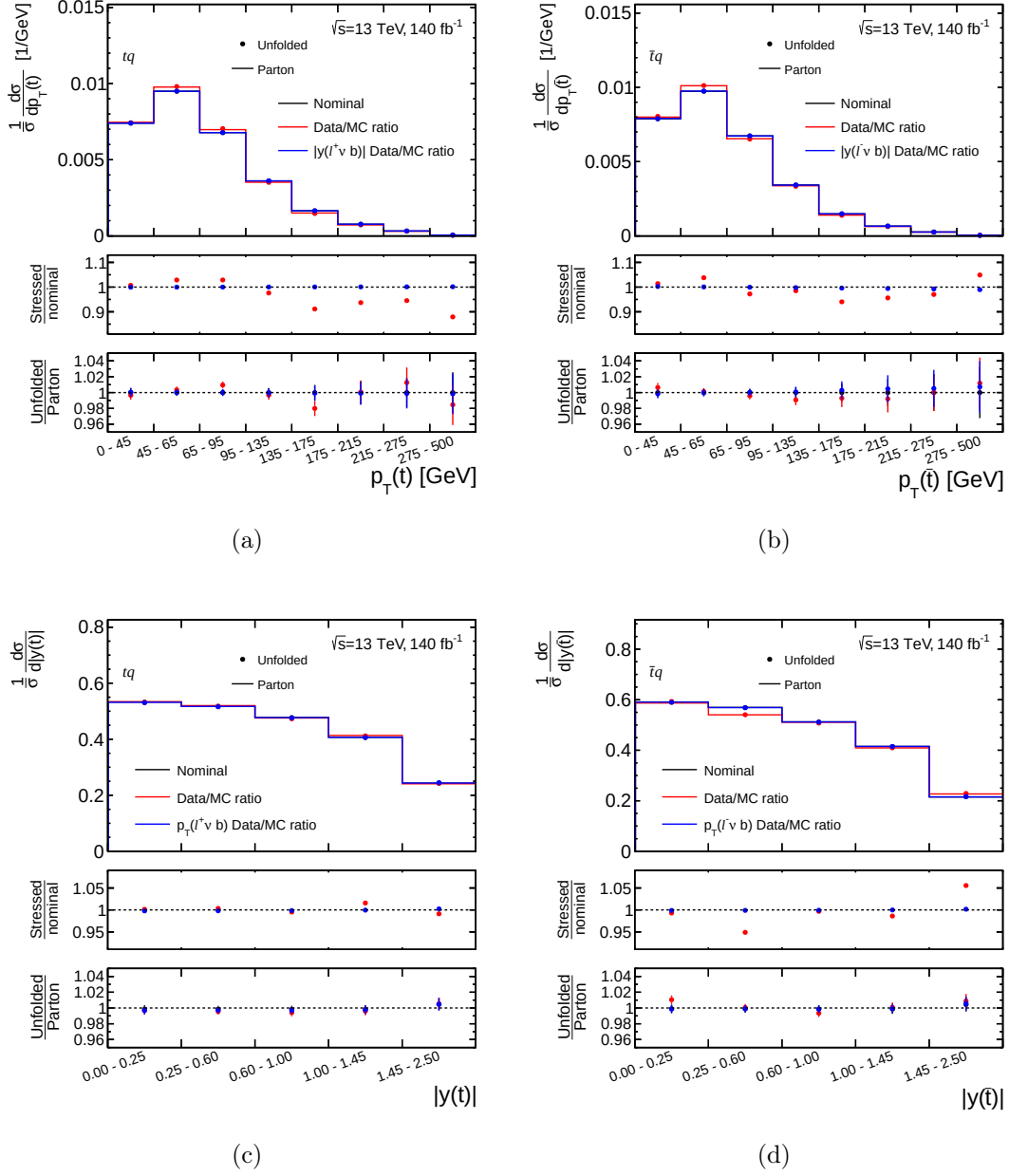


Figure 9.9: Results of the stress tests reweighting the simulated signal events at detector and parton level to the background subtracted data for the (a) $p_T(t)$, (b) $p_T(\bar{t})$, (c) $|y(t)|$ and (d) $|y(\bar{t})|$ distributions. The first ratio panel shows the difference between the reweighted and nominal distributions at parton level, and the second ratio panel shows the agreement between the unfolded reweighted distributions and the reweighted parton-level distributions. Only MC statistical uncertainties are shown.

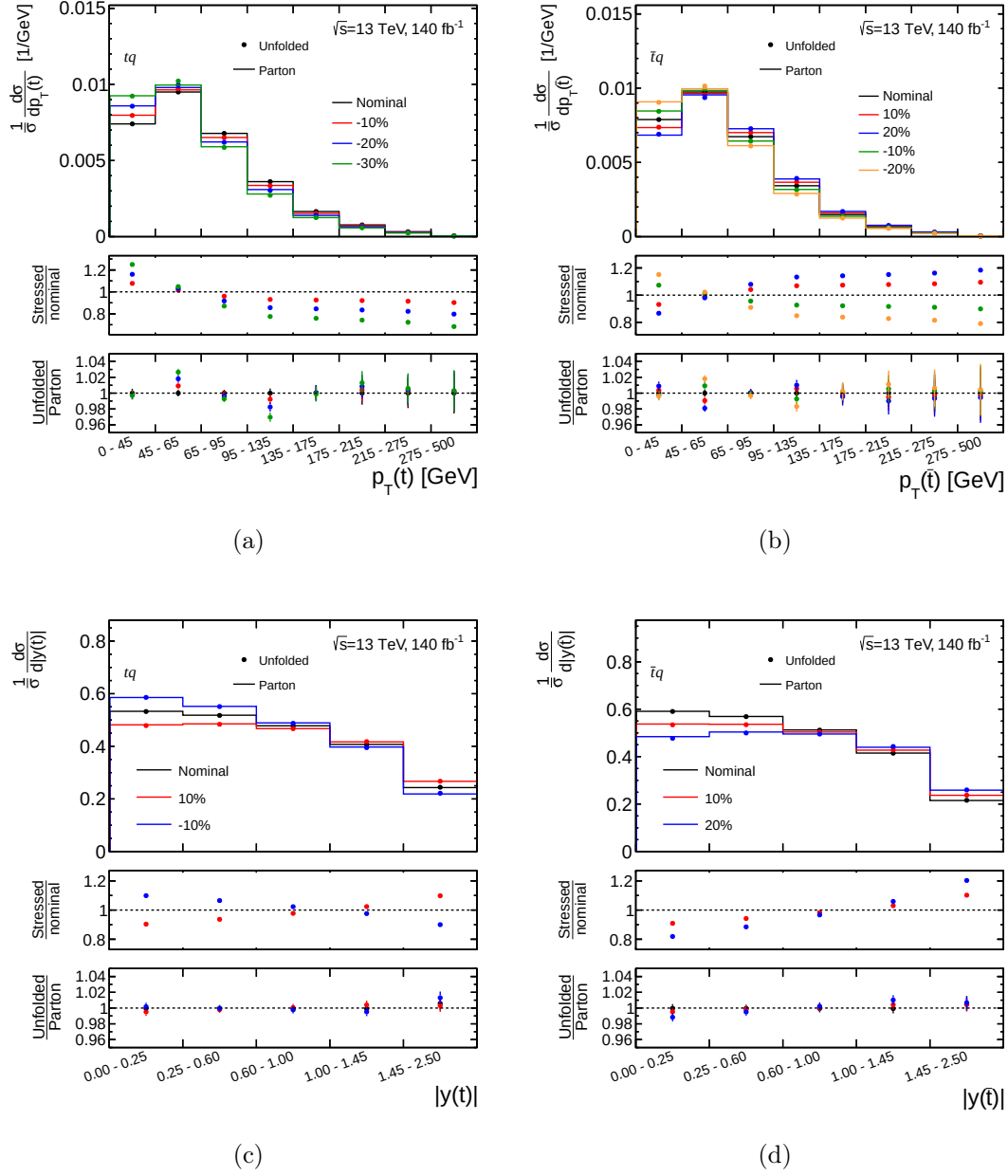


Figure 9.10: Results of the stress tests using linear reweighting functions at detector and parton level for the (a) $p_T(t)$, (b) $p_T(\bar{t})$, (c) $|y(t)|$ and (d) $|y(\bar{t})|$ distributions. The maximum slope is chosen per distribution to cover twice the maximum ratio between background subtracted data and simulated signal events. The first ratio panel shows the difference between the reweighted and nominal distributions at parton level, and the second ratio panel shows the agreement between the unfolded reweighted distributions and the reweighted parton-level distributions. Only MC statistical uncertainties are shown.

10. Uncertainties in the measurement

Any measurement of a physical quantity is affected by various uncertainties, whose evaluation is an integral part of physics analyses. The uncertainties are broadly divided into two categories, statistical and systematic uncertainties. Statistical uncertainties refer to potential fluctuations caused by the finite number of measured or simulated events and are typically large in phase spaces with rare topologies. Systematic uncertainties are further divided into experimental uncertainties, caused by the limited precision of the detector, and modelling uncertainties, which account for assumptions and ambiguities present in the simulation of events. For differential measurements, additional uncertainties related to limitations of the unfolding method can be defined. However, the tests performed to evaluate these limitations (cf. Section 9.4) proved the IBU method to introduce no bias and to be robust against changes in the shape of the unfolded distributions, and therefore no uncertainties related to the method are considered.

10.1. Sources and evaluation

The various sources of uncertainties considered in this measurement and their evaluation are described in the following. Experimental uncertainties are evaluated with systematically varied event weights or MC samples that deviate from the nominal estimate by $\pm 1\sigma$ in a single uncertainty. The variations are referred to as *up* and *down* variation. The same terminology is used for the modelling uncertainties, many of which are evaluated by changing the value of a parameter that affects the event simulation. The impact of each uncertainty is evaluated separately. A concise overview of all considered uncertainties is provided in Appendix F.1. The methodology used to evaluate the impact of systematic uncertainties leads to a change of the sign [78] which is corrected afterwards; the magnitude of the impact is expected to be approximated correctly.

Experimental uncertainties

To evaluate the impact of experimental uncertainties, pseudo data is constructed from the systematically varied signal and background MC distributions. The nominal background estimate is then subtracted, and the resulting distribution is unfolded using the nominal unfolding corrections. The difference of the resulting distribution to the



nominal parton-level distribution of the signal sample is taken as uncertainty. The considered experimental uncertainties are described in the following.

Lepton calibration

Scale factors are applied to the simulated samples to match the efficiencies for lepton triggers, reconstruction, identification and isolation to those observed in data. The efficiencies in data events are determined in well-known resonance decays with a tag-and-probe method as described in Chapter 6. By varying the selection criteria for the tag and the probe lepton, systematic uncertainties in the efficiencies are derived and propagated to the simulated samples by varying the SFs [139, 143, 167]. The uncertainties in the trigger, identification and isolation SFs for muons are divided into a statistical and a systematic component.

Uncertainties related to the calibration of lepton energy and momentum arise from various factors such as fluctuations in the shower shape or misalignments between the tracking detectors. Differences between simulation and data in the momentum scale of muons and in the energy scale and resolution of electrons are corrected in the simulated samples, and associated uncertainties are applied. Muons are affected by the *sagitta bias*, a charge-dependent bias in the muon momentum caused by a specific type of misalignments in the detector. If layers of the detector are rotated with respect to each other, the muon track will be reconstructed with a higher or lower curvature, depending on the electric charge. The bias is measured in well-known resonances and a statistical and a systematic uncertainty component are applied.

Electrons have a probability of about 0.2% to be reconstructed with the wrong electric charge [2]. The net effect is a migration of events from the ℓ^+ SR to the ℓ^- SR at a rate of 6×10^{-4} which is assigned in both SRs, where the sign of the up variation reflects the direction of the migration.

Jet calibration

As described in Section 6.5, the JES is calibrated in a sophisticated procedure involving multiple steps to extract correction factors from simulation and data. The full uncertainty on the JES comprises 125 individual terms, most of which are related to the in-situ analyses [147]. A reduction scheme is applied to find a more compact representation, using a smaller number of orthogonal terms, without losing information about correlations. The 30 resulting terms can be grouped into ten categories:

- Limited statistical power of the samples used for calibration (6 uncertainties),
- Modelling of jets (4 uncertainties),
- Modelling of the detector (2 uncertainties),



- Various minor uncertainties (3 uncertainties),
- Biases in the η intercalibration (6 uncertainties),
- Parameters in the pileup correction (4 uncertainties),
- Jet flavour response and composition (2 uncertainties),
- Response of b -jets (1 uncertainty),
- Response of high- p_T jets (1 uncertainty),
- Punch-through correction (1 uncertainty).

The uncertainty in the jet flavour composition is decorrelated between all processes involving top quarks.

Systematic uncertainties in the JER are propagated by smearing the jets according to a Gaussian function whose width is chosen such that applying the Gaussian smearing in addition to the nominal one (cf. Section 6.5) reproduces the $\pm 1\sigma$ deviation of the variation under study [147]. A systematic variation can either worsen or enhance the JER. This is accounted for by applying the Gaussian smearing to simulated events in the former case and to pseudo data in the latter. A reduction scheme is applied to break the uncertainty down into twelve orthogonal terms. When the JER is smaller in data than in simulation, the full difference is applied as an additional uncertainty. Finally, two uncertainties related to the scale factors that correct for the JVT and fJVT efficiencies are assigned.

Flavour tagging

The b -tagging efficiency is measured in data, and discrepancies in the simulated samples are corrected via p_T -dependent SFs. Uncertainties in these SFs cover the b -tagging efficiency for real b -jets and the mistagging for c -jets and light-jets.

The b -tagging efficiency is measured in dileptonic $t\bar{t}$ events, and the associated uncertainties are represented by 45 orthogonal components [165]. The misidentification of c -jets is measured in semileptonic $t\bar{t}$ events [168], and for light-jets, the associated production of a Z -boson with jets is used [169]. The uncertainties for both types of mis-tagged jets are parameterised by 20 orthogonal components each.

E_T^{miss} soft term

The missing transverse momentum is calculated from the p_T of all reconstructed objects and an additional soft term (cf. Section 6.8). The uncertainties related to the reconstructed objects are therefore propagated directly to the E_T^{miss} calculation, and dedicated uncertainties are only needed for the soft term [154]. Two components cover



the resolution of the soft term parallel and perpendicular to the p_T of all reconstructed objects, and a third term is associated with the scale.

Pileup reweighting

Simulated minimum-bias events are used to model the effect of pileup interactions in MC events (cf. Section 4.3). The distribution of the pileup μ is reweighted with a nominal scale factor $\langle\mu\rangle=1/1.03$ to match the average pileup observed in data [170]. The uncertainty in the reweighting is evaluated by varying the scale factor to $\langle\mu\rangle=1/0.99$ and $\langle\mu\rangle=1/1.07$.

Luminosity

The uncertainty in the integrated luminosity is 0.83 % [171]. The luminosity enters the calculation of the differential cross sections as a normalisation factor (cf. Equation 9.6) and therefore causes a flat uncertainty of 0.83 % in the absolute differential cross sections.

Modelling uncertainties

To evaluate the impact of uncertainties in the modelling of background processes, pseudo data is constructed from the nominal signal and the systematically varied background MC distributions. When an uncertainty is not evaluated for a background process, the nominal estimate is used for the construction of the pseudo data. The nominal background estimate is then subtracted from the pseudo data, and the resulting distribution is unfolded using the nominal unfolding corrections. The difference of the resulting distribution to the nominal parton-level distribution of the signal process is taken as uncertainty. For uncertainties in the modelling of the signal process, the systematically varied detector-level distribution is unfolded with the nominal corrections. The uncertainty is then defined as the difference between the resulting distribution and the systematically varied parton-level distribution. The considered modelling uncertainties are described in the following.

Renormalisation and factorisation scale

Matrix-element calculations depend on the scales μ_r and μ_f as discussed in Chapter 4. The systematic uncertainties related to the choice of scales are evaluated by varying both scales by factors of 2 and 0.5. These uncertainties are considered for all processes involving top quarks and W +jets production and are evaluated separately for each process.



ISR and FSR

Uncertainties related to the ISR are evaluated by varying the Var3c parameter of the A14 tune, which corresponds to variations of α_S for the ISR modelling [118]. Similarly, the uncertainties related to the FSR are evaluated by varying the scale μ_r at which α_S is evaluated for the FSR modelling by factors of 2 and 0.5. Both uncertainties are only evaluated for the processes involving top quarks.

PDFs

The PDF uncertainty is evaluated for all processes involving top quarks according to the PDF4LHC prescription [172]. Alternative samples are used that were simulated with the PDF4LHC15 set and its Hessian representation of uncertainties, consisting of 30 symmetric eigenvectors. The differences between each variation and the nominal value are added in quadrature, and the result is applied as PDF uncertainty to the nominal samples.

Parton-shower modelling

The choice of a parton-shower algorithm and hadronisation model introduces phenomenological uncertainties, which are evaluated for all processes involving top quarks. The nominal POWHEG + PYTHIA 8 sample is compared to an alternative sample where HERWIG 7 is interfaced to the POWHEG matrix event generator. For the signal tq and $\bar{t}q$ process, the HERWIG 7.3 version is used to produce the alternative sample. Since the version became available at a late stage of the analysis, and the parton-shower uncertainty in the $t\bar{t}$ and $tW + \bar{t}W$, $t\bar{b}/\bar{t}b$ processes were already found to have a minor impact, the alternative samples for these processes use HERWIG 7.1.

NLO matching

The NLO-matching scheme used by POWHEG (cf. Chapter 4) introduces an additional ambiguity when the generator is interfaced with PYTHIA [105]. Both POWHEG and PYTHIA implement p_T -ordered parton showers, but the definition of p_T , and thereby the definition of hardness of an emission, differs slightly. The PYTHIA parton shower should start at the scale of the POWHEG emission, which is by construction the hardest emission in an event. The diverging definitions can however lead to over- or under-counting of emissions. PYTHIA therefore offers different methods to calculate the initial scale of the parton shower that can be selected via the p_T^{hard} parameter. The default setting $p_T^{\text{hard}} = 0$ corresponds to an external definition of the scale taken from a dedicated Les Houches Event file [173]. To evaluate the uncertainty introduced by this choice as suggested in [105], alternative samples are generated where p_T^{hard} is set to



one. The shower is then initiated at the p_T of the parton emitted by POWHEG. This uncertainty is evaluated for the tq and $\bar{t}q$, $t\bar{t}$ and tW processes.

For $t\bar{t}$ and tW production, the uncertainty in the choice of the h_{damp} parameter that controls the dampening of parton-shower radiation with high transverse momenta is evaluated by varying the nominal $h_{damp} = 1.5 m_t$ to $h_{damp} = 3 m_t$.

DR/DS

The nominal tW sample employs the diagram removal (DR) [125] scheme to account for the interference between $t\bar{t}$ and tW production at NLO. As the name suggests, the relevant diagrams are removed from the matrix-element calculations. The uncertainty related to the interference removal is evaluated by comparing the nominal sample to an alternative one utilising the diagram subtraction (DS) approach, which implements a subtraction term modifying the tW cross section to cancel the $t\bar{t}$ contribution locally.

Multijet templates

The kinematics of multijet events are estimated separately for the electron and muon components with the jet-electron and anti-muon methods as explained in Section 8.2. The uncertainty associated with the jet-electron method is evaluated by varying the energy fraction a jet needs to deposit in the ECal to be classified as a lepton from the nominal $f_{EM} > 80\%$ to $f_{EM} > 90\%$ and $80\% < f_{EM} < 90\%$. For the anti-muon method, one variation is defined by changing the muon isolation criterion.

Background rate uncertainties

The estimation of the rate uncertainties in the background processes at detector level is described in Chapter 8. Their impact on the unfolded cross sections is evaluated separately for each process by creating pseudo data from the nominal signal sample, the varied background sample and the nominal samples of the remaining background processes. The nominal background estimate is then subtracted, and the resulting distribution is unfolded using the nominal unfolding corrections. The difference between the unfolded result and the nominal parton-level signal distribution is taken as an uncertainty.



Data statistical uncertainty

The statistical uncertainty in the data is evaluated from pseudo experiments. The measured data distribution is fluctuated per bin according to a Poisson distribution with the bin content as mean value. The nominal background estimate is subtracted from the fluctuated data, and the resulting distribution is unfolded using the nominal unfolding corrections. This way, 1000 pseudo experiments are created and in each bin of the unfolded results, the standard deviation normalised to the mean of the distribution is taken as the data statistical uncertainty.

MC statistical uncertainty

The statistical uncertainty in the simulated signal samples impacts the unfolding corrections. It is therefore evaluated by fluctuating each bin of the migration matrix and efficiency according to a Gaussian distribution with the nominal bin content as mean value and the bin uncertainty, i.e. the square-root of the number of MC events in that bin, as standard deviation. The nominal signal MC is unfolded using the fluctuated unfolding corrections. The process is repeated 1000 times, and in each bin of the unfolded results, the standard deviation normalised to the mean of the distribution is taken as the MC statistical uncertainty.

Evaluation of the total uncertainty

The total uncertainty in the absolute differential cross sections is calculated per bin by adding the individual uncertainties in quadrature. All contributions with a positive (negative) sign are added to the total Up (Down) variation, which are capitalised to distinguish them from the up and down variations of individual uncertainties. If both variations of an individual uncertainty have the same sign, the larger one is added to the corresponding total variation, and the contribution to the variation of the opposite sign is set to zero. Some modelling uncertainties, like the parton-shower uncertainty, are one sided; they are symmetrised by defining the full uncertainty with opposite sign as down variation.

The total uncertainty in the normalised differential cross sections is evaluated in the same manner. Before the impact of individual systematic uncertainties is evaluated at parton level by taking the difference to another distribution, both distributions are normalised.



Uncertainties in the cross section ratio

The uncertainties in the ratio of the tq and $\bar{t}q$ cross sections are evaluated at parton level, taking into account correlations between the tq and $\bar{t}q$ measurements for single sources of uncertainties. Using $\tilde{\sigma}_t$ and $\tilde{\sigma}_{\bar{t}}$ as short notations for the absolute differential tq and $\bar{t}q$ cross sections, the variation of the ratio due to a correlated systematic uncertainty sys is evaluated as

$$\left(\frac{\tilde{\sigma}_t}{\tilde{\sigma}_{\bar{t}}}\right)_{sys} = \frac{\tilde{\sigma}_t \cdot (1 + \delta_{\tilde{\sigma}_t}^{sys, rel.})}{\tilde{\sigma}_{\bar{t}} \cdot (1 + \delta_{\tilde{\sigma}_{\bar{t}}}^{sys, rel.})}. \quad (10.1)$$

Here, $\delta_{\tilde{\sigma}_t}^{sys, rel.}$ and $\delta_{\tilde{\sigma}_{\bar{t}}}^{sys, rel.}$ denote the relative difference in the differential tq and $\bar{t}q$ cross sections caused by sys . The up and down variations are evaluated separately, and the impact of sys on the ratio is defined as the relative difference between $(\frac{\tilde{\sigma}_t}{\tilde{\sigma}_{\bar{t}}})_{sys}$ and the nominal ratio. The statistical uncertainties and the rate uncertainties in the $W + b\bar{b}$ and $W + c(\bar{c})$ backgrounds, which are charge asymmetric, are decorrelated between tq and $\bar{t}q$ and therefore added in quadrature.

10.2. Results and discussion

The total uncertainties in the measured cross sections are presented in Figures 10.1 and 10.2 with a breakdown of the contributions of the different types of uncertainties. Tables that show the impact of each individual uncertainty are given in Appendix F.2. From Figure 10.1, it can be seen that the signal modelling and experimental uncertainties have the highest impact on the absolute differential cross sections. For the $p_T(t)$ and $p_T(\bar{t})$ distributions, the data statistical uncertainty becomes large in the high- p_T regions, with contributions of 9 % and 13 % in the last bin. The uncertainties related to the modelling and rate of the background processes are minor for all absolute differential cross sections.

The overall picture is similar for the normalised cross sections, but the total uncertainty is reduced, as the impact of systematic uncertainties on the normalisation is removed and only shape effects remain. The reduction is especially visible for the signal modelling uncertainties in the $|y(t)|$ and $|y(\bar{t})|$ distributions. The cross-section ratios benefit from cancellations of systematic uncertainties that are correlated between tq and $\bar{t}q$ events, although the impact of a few uncertainties is enhanced compared to the individual absolute cross sections. For instance, the impact of the background modelling uncertainties in the second highest bin of the $p_T(t \text{ or } \bar{t})$ distribution is enlarged because the up variation of the uncertainty in the $t\bar{t}$ parton-shower modelling has opposite signs for the tq and $\bar{t}q$ measurements.

The individual uncertainties with the highest impact on the absolute cross sections are related to the modelling of the signal process. A graphic breakdown of the individual

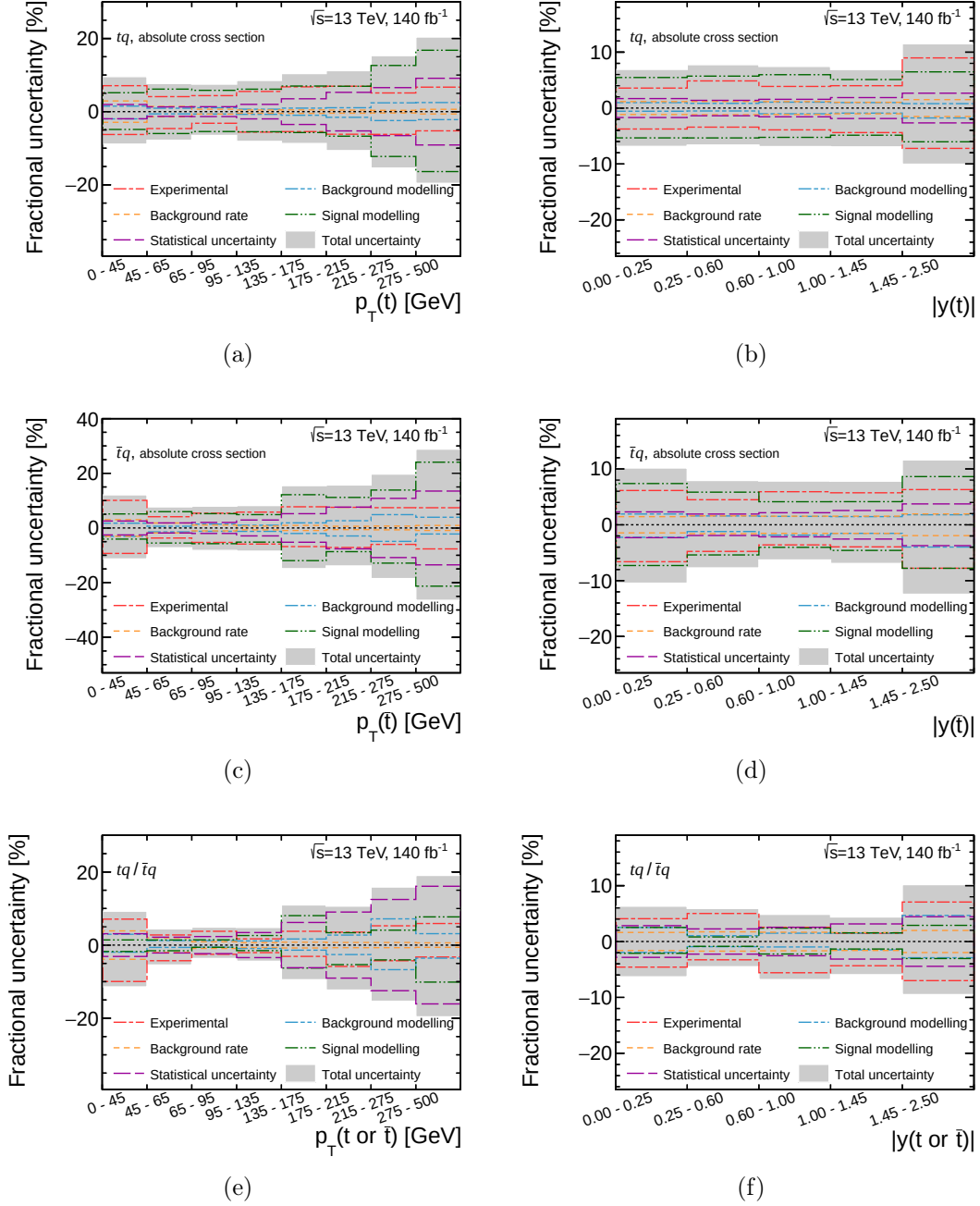


Figure 10.1: Uncertainties in the absolute differential tq and $\bar{t}q$ production cross sections measured as a function of (a) $p_T(t)$, (b) $|y(t)|$, (c) $p_T(\bar{t})$ and (d) $|y(\bar{t})|$ and in the ratio of the cross sections measured as a function of (e) $p_T(t \text{ or } \bar{t})$ and (f) $|y(t \text{ or } \bar{t})|$. The shaded band indicates the total uncertainty, defined as the quadratic sum of all sources of uncertainties, and the coloured bands show the contributions of the different categories of uncertainties.

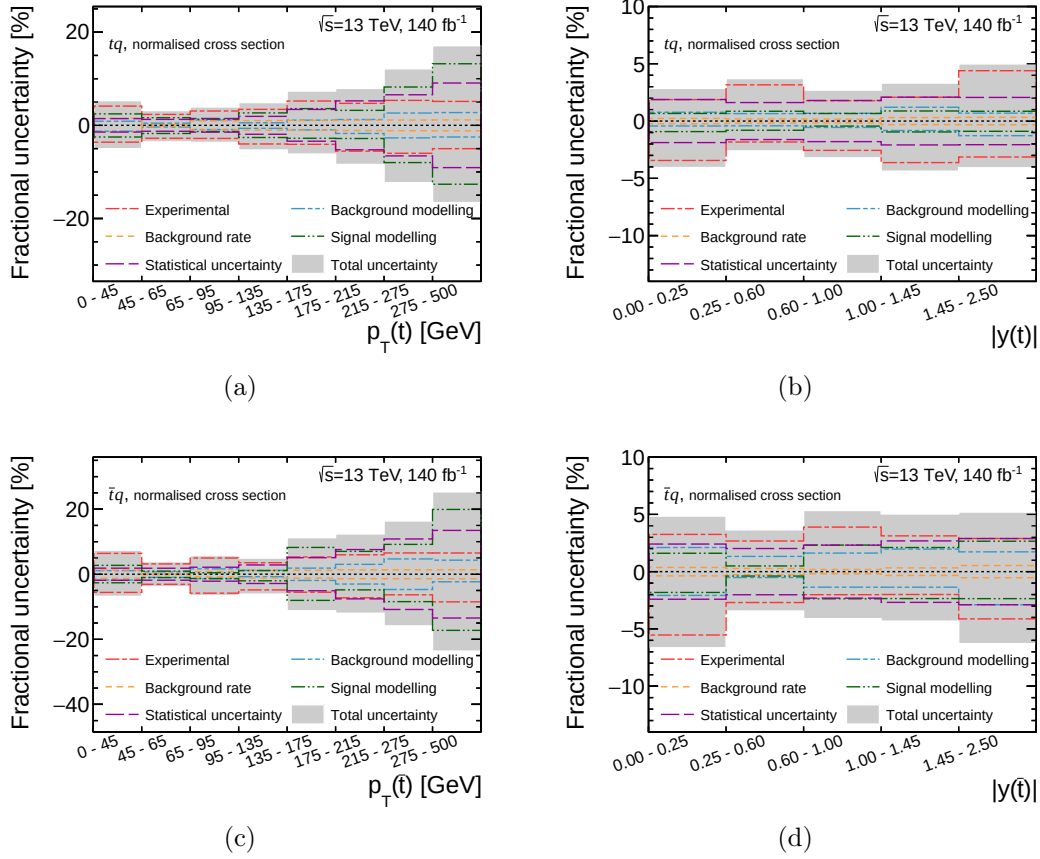


Figure 10.2: Uncertainties in the normalised differential tq and $t\bar{q}$ production cross sections measured as a function of (a) $p_T(t)$, (b) $|y(t)|$, (c) $p_T(\bar{t})$ and (d) $|y(\bar{t})|$. The shaded band indicates the total uncertainty, defined as the quadratic sum of all sources of uncertainties, and the coloured bands show the contributions of the different categories of uncertainties.

signal modelling uncertainties is shown in Appendix F.3. The NLO-matching uncertainty has the highest individual impact on all absolute cross sections, with more than 10% in the high- $p_T(t)$ and high- $p_T(\bar{t})$ regions, followed by the parton shower and FSR modelling uncertainties. For the normalised distributions, the impact is reduced significantly, especially in the $|y(t)|$ and $|y(\bar{t})|$ distributions where the combined impact of the signal modelling uncertainties is below 2%. The reasons behind these observations become apparent when the systematic variations are compared to the nominal distribution at parton level and detector level, as exemplarily shown in Figure 10.3 for the NLO-matching and parton-shower uncertainties in the tq distributions. At parton level, the differences by construction only affect the shape of the distribution since all samples are normalised to the same cross section. The parton-shower simulation contributes corrections to the top-quark kinematics, therefore some differences to the nominal distribution are visible in the $p_T(t)$ distribution. At detector level, the sys-

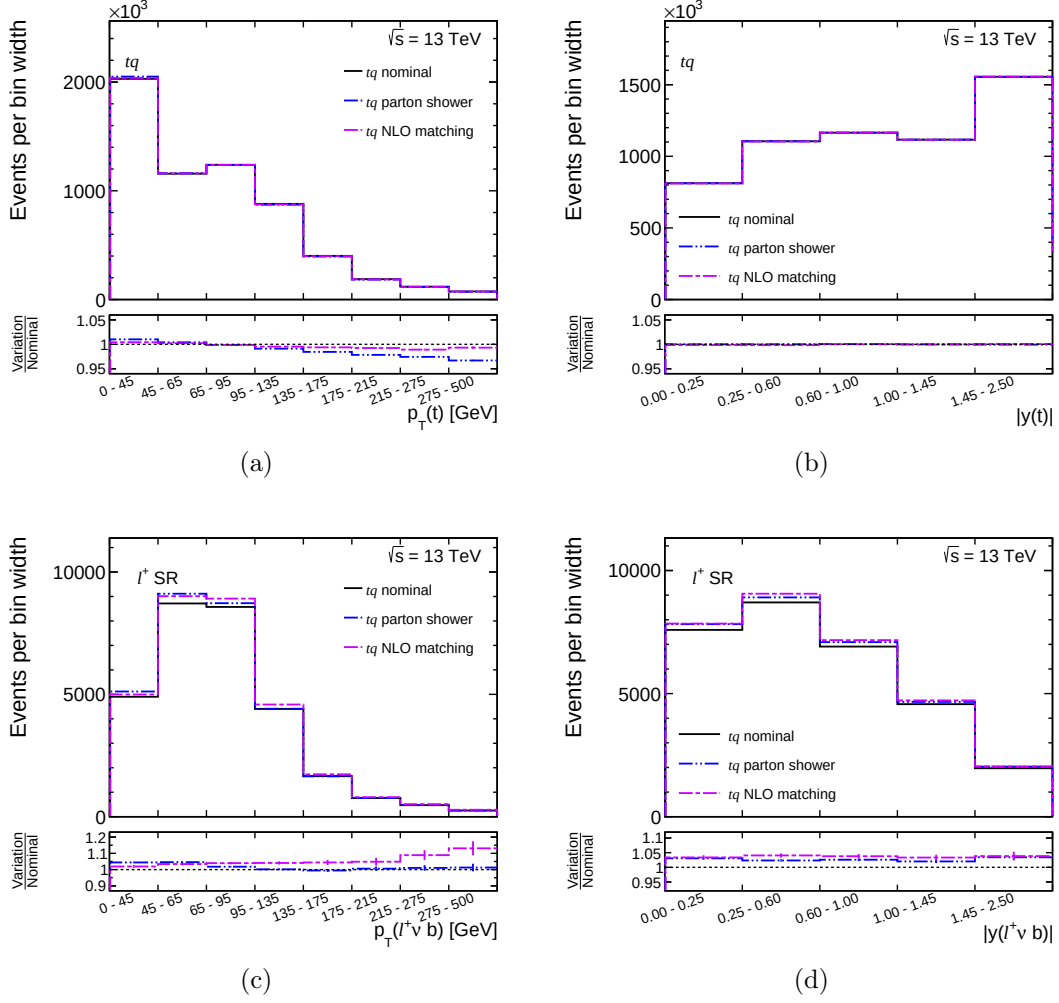


Figure 10.3: Impact of the parton-shower and NLO-matching variations on the parton-level (a) $p_T(t)$ and (b) $|y(t)|$ distributions and on the detector-level (c) $p_T(\ell^+\nu b)$ and (d) $|y(\ell^+\nu b)|$ distributions.

tematic variations predict a different number of observed events, as it can be seen very clearly in Figure 10.3(d). Since the unfolding technique cannot compensate for rate differences, this offset causes the large impact of the uncertainty in the absolute cross sections. For the normalised cross sections, the effect is again mitigated by construction.

For the $p_T(\ell^+\nu b)$ distribution, a strong shape effect is seen for the NLO-matching uncertainty, where the difference to the nominal prediction increases in the high- $p_T(\ell^+\nu b)$ region. The discussed uncertainties, as well as all other signal modelling uncertainties with a high impact, affect the modelling of additional QCD radiation. Therefore, the number of events that fulfil the selection requirement of exactly two jets with



$p_T(j) > 30 \text{ GeV}$ differs from the nominal prediction. For the discussed uncertainties, the number of those events increases as shown in Figure F.5.

Out of all experimental uncertainties, the JES and JER related ones have the highest impact. Their contributions exhibit fluctuations within single distributions, which are most prominent in the JER uncertainties but to a lesser degree also visible in the JES uncertainties as can be seen in the Figures in Appendix F.4. The same behaviour is observed for the background modelling uncertainties and can be traced back to fluctuations in the impact of individual uncertainties, as can be concluded from the Tables in Appendix F.2. The fluctuations are caused by the limited statistical power of the MC templates for background processes in the signal regions, and the impact is quantified by evaluating the statistical uncertainty in the systematic variations with the bootstrap method. This approach additionally serves as a cross check as it provides an alternative way to evaluate the systematic uncertainties.

For each MC event, 1000 Poisson-distributed random numbers with a mean of one are drawn and used as multipliers for the weight of the MC event. The random numbers are generated using the MC event number as random seed, to synchronise the modification between all systematic variations of the event. This way, 1000 pseudo experiments are constructed for each systematic variation and subsequently unfolded with the nominal unfolding corrections. The mean of the resulting distribution is taken as the central value of the systematic uncertainty, and the standard deviation is used to define its statistical uncertainty.

The obtained values for all distributions are listed in Appendix F.6. The central values are compatible with the impact of individual uncertainties obtained with the default method described in Section 10.1. The statistical uncertainties in the variations are highest for JES related uncertainties, where they reach a magnitude of about 1 % of the differential cross section in several bins. As expected, larger statistical uncertainties are found for the uncertainties in the $\bar{t}q$ cross sections and generally in bins with lower event statistics. The statistical uncertainties are not incorporated in the final results, but they are of interest for potential future combinations, for example in the context of PDF fits, as their inclusion can make the result of such combinations more robust to outliers and discrepancies among the input data [174].

10.3. The covariance matrix

To evaluate the agreement between measured differential cross sections and theoretical predictions, the covariance between the single bins of an unfolded distribution needs to be known. This information is encoded in the *covariance matrix*, whose elements $\text{Cov}_{k,l}$ represent the covariance between bin k and l . The covariance matrix incorporates the impact of all statistical and systematic uncertainties and is calculated from pseudo experiments. Each pseudo experiment *toy* is constructed using the following prescription:



1. Incorporate the data statistical uncertainty

The data distribution at detector level is used as a starting point to create the pseudo experiment. The data statistical uncertainty is incorporated by fluctuating each bin i according to a Poisson distribution with the number of data events in that bin N_i^{data} as mean value. The bin content after the fluctuation is denoted by $\mathcal{P}(N_i^{\text{data}})$.

2. Incorporate MC statistical, experimental and background related uncertainties

For each bin i and each experimental, background modelling and background rate uncertainty sys , the difference to the number of events in the nominal distribution $\delta_i^{sys} = N_i^{sys} - N_i^{\text{nom}}$ is calculated. A random number $g^{sys, toy}$ is generated from a Gaussian distribution with a mean of zero and a width of one. If $g^{sys, toy} > 0$, the up variation of the systematic is used to calculate δ_i^{sys} , otherwise the down variation is used. The fluctuation due to the uncertainty is then evaluated as $\Delta_i^{sys, toy} = |g^{sys, toy}| \cdot \delta_i^{sys}$.

The fluctuation due to the MC statistical uncertainty is defined analogously as $\Delta_i^{\text{MC}, toy} = |g_i^{\text{MC}, toy}| \cdot \delta_i^{\text{MC stat}}$, with the difference that separate random numbers are drawn for each bin.

The number of events in bin i for the pseudo-experiment toy is then calculated as

$$N_i^{toy} = \mathcal{P}(N_i^{\text{data}}) \cdot \left(1 + \frac{\Delta_i^{\text{MC}, toy} + \sum_{sys1}^{N_{sys}} \Delta_i^{sys, toy}}{N_i^{\text{nom}}} \right).$$

3. Unfold the pseudo experiment

The pseudo experiment is unfolded using the nominal unfolding corrections. The number of events in parton-level bin j is then denoted as $N_{j, \text{unf}}^{toy}$.

4. Incorporate signal modelling uncertainties

The impact of the signal modelling uncertainties is evaluated at parton level, following a similar prescription as for the other systematic uncertainties. For each signal modelling uncertainty mod , the normalised difference between the systematically varied unfolded distribution and its parton-level counterpart is calculated, $\delta_j^{mod} = (N_{j, \text{unf}}^{mod} - N_{j, \text{parton}}^{mod}) / (N_{j, \text{parton}}^{mod})$. Analogously to the other systematic uncertainties, a Gaussian random number $g^{mod, toy}$ is drawn and the fluctuation is evaluated as $\Delta_j^{mod, toy} = |g^{mod, toy}| \cdot \delta_j^{mod}$. Depending on the sign of $g^{mod, toy}$, δ_j^{mod} is calculated using either the up or the down variation.

The bin content of an unfolded pseudo experiment is then finally calculated as

$$N_j^{toy} = N_{j, \text{unf}}^{toy} \cdot \left(1 + \sum_{mod=1}^{N_{\text{mods}}} \Delta_j^{mod, toy} \right).$$



The elements of the covariance matrix $\text{Cov}_{k,l}$ are calculated from a set of $nToys$ pseudo experiments and the nominal signal MC distribution at parton level $N^{\text{nom, parton}}$ as

$$\text{Cov}_{k,l} = \frac{1}{nToys} \sum_{toy=1}^{nToys} (N_k^{\text{nom, parton}} - N_k^{toy}) \cdot (N_l^{\text{nom, parton}} - N_l^{toy}). \quad (10.2)$$

To calculate the covariance matrices for the cross-section ratios, the pseudo experiments constructed for the tq and $\bar{t}q$ distributions are synchronised, i.e. for pseudo experiment n , both distributions use the same Gaussian random number g for a given bin and uncertainty. The bin contents N in Equation 10.2 are replaced by the ratio $N_{tq}/N_{\bar{t}q}$.

Figure 10.4 shows the covariance matrices calculated from 1000 pseudo experiments for all tq production measurements. The matrices for the $\bar{t}q$ production measurements and the ratios are shown in Appendix F.7. A striking feature visible in the covariance matrices for all absolute cross-section measurements is that all bins are positively correlated. The reason behind this is that the overall uncertainty is dominated by only a few uncertainties related to the modelling of the signal process. As discussed in Section 10.2, the systematic uncertainties in the NLO matching, parton-shower modelling and FSR modelling of the signal process are the largest individual uncertainties for all distributions. The up and down variations of these uncertainties have the same sign in all bins of a given distribution, as exemplarily shown in Figure 10.5(a). As a cross check, the calculation of the covariance matrix is repeated with an inverted sign of the NLO-matching and parton-shower modelling uncertainties in the second and seventh bin of the distribution. The resulting covariance matrix is shown in Figure 10.5(b), and both bins exhibit anti-correlations with other bins of the distribution.

A useful tool to assess the correlations between bins is the *correlation matrix*, whose entries are calculated from the covariance matrix as

$$\text{Corr}_{i,j} = \frac{\text{Cov}_{i,j}}{\sqrt{\text{Cov}_{i,i} \cdot \text{Cov}_{j,j}}}.$$

The correlation matrices for all distributions are shown in Appendix F.8. The strong correlations discussed above are well visible for all measured distributions as the correlations between most bins are of the order $\mathcal{O}(10^{-1})$.

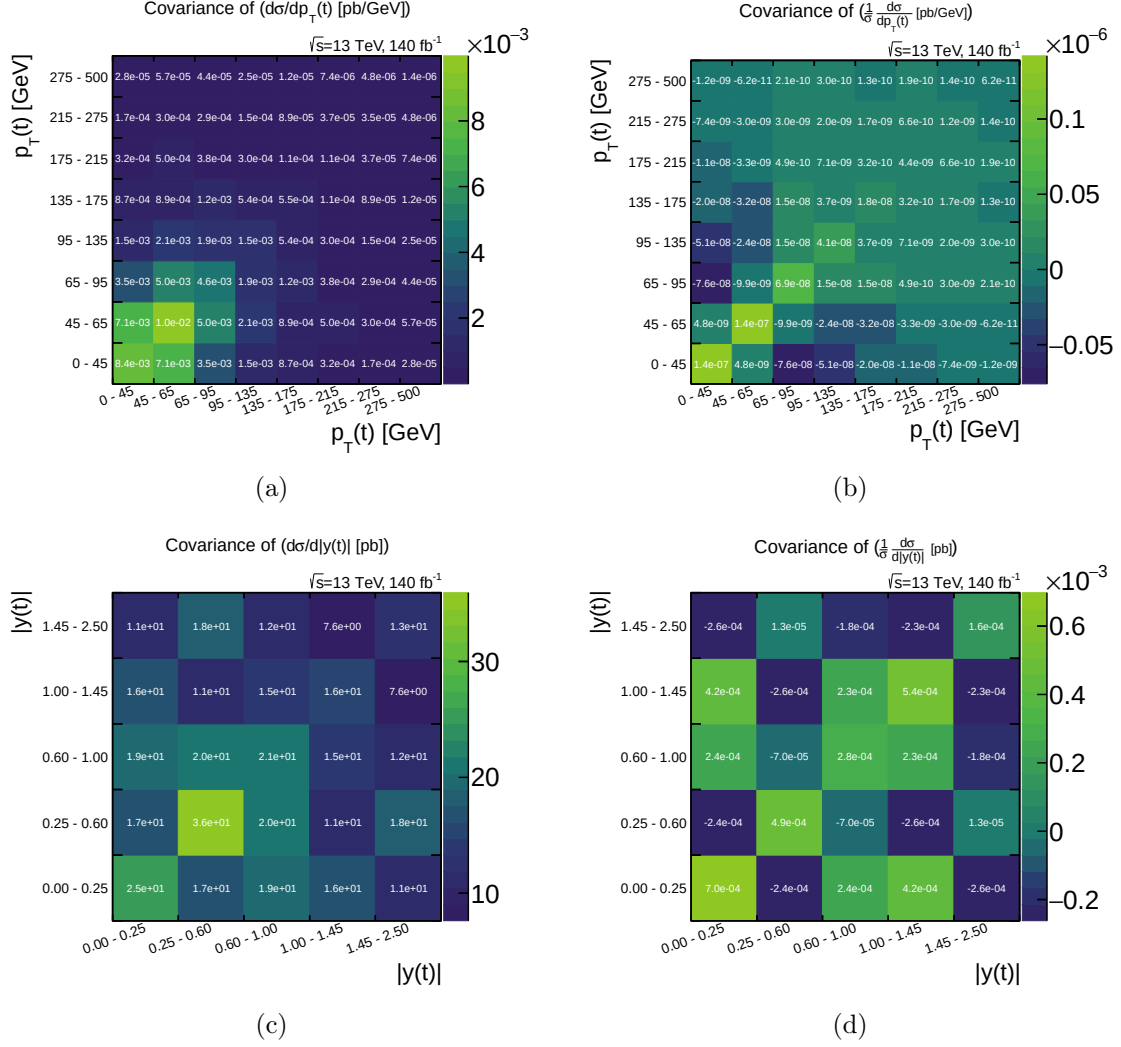


Figure 10.4: Covariance matrices of the absolute and normalised differential tq cross sections measured as a function of (a),(b) $p_T(t)$ and (c),(d) $|y(t)|$.

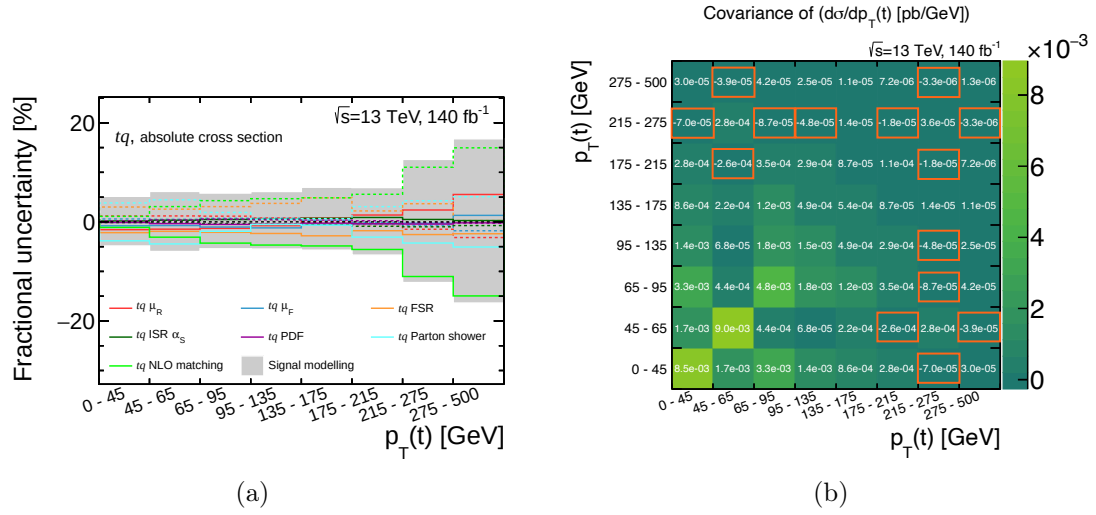


Figure 10.5: Both figures are related to the absolute tq production cross section as a function of $p_T(t)$. (a) shows the signal modelling uncertainties where the solid lines indicate the up variations and the dashed lines show the down variations. (b) shows the covariance matrix obtained with the sign of the NLO-matching and parton-shower uncertainties artificially inverted in the second and seventh bin. The orange boxes highlight negative correlations.

11. Results

The results of the differential cross-section measurement are presented in this chapter. The unfolded distributions are presented in Section 11.1, and the level of agreement with different theoretical predictions is evaluated. An interpretation of the measurement results in the context of SMEFT is provided in Section 11.2.

11.1. The differential cross sections

The results of this measurement comprise the absolute and normalised differential tq and $\bar{t}q$ cross sections and the ratio of the absolute cross sections. As described in Chapter 4, theoretical predictions for comparisons are obtained from fixed-order calculations with MCFM, different combinations of matrix-element generators and parton-shower programs and simulations with POWHEG +PYTHIA 8 employing different PDF sets. The number of obtained distributions is too large to provide a detailed discussion on all of them. Instead, overall trends and a few striking features of individual distributions are reviewed in the following. Distributions that are not mentioned explicitly are shown in Appendix G.1, and the numerical values of the differential cross sections are given in Appendix G.2.

The agreement between the measurement results and theoretical predictions for a given distribution is evaluated by calculating the χ^2 value

$$\chi^2 = \vec{V}^T \cdot \text{Cov}^{-1} \cdot \vec{V},$$

where Cov represents the covariance matrix of the measurement and $\vec{V}$ denotes the vector of differences between measurement and prediction per bin of the distribution. The χ^2 *probabilities* listed in Tables 11.1 and 11.2 are then calculated from the *cumulative distribution function* (cdf) of the χ^2 function and indicate the probability to obtain a χ^2 value at least as high as the observed one, if the prediction describes the measurement accurately. The cdf depends on the *number of degrees of freedom* (NDF) in the measurement, which is equal to the number of bins for the absolute cross sections and their ratio. For the normalised cross sections, the NDF is reduced by one as the content of the last bin is fixed by the normalisation. Therefore, the last entry of $\vec{V}$ and the corresponding entries of Cov are discarded for the calculation of the corresponding χ^2 values.

The uncertainties in the theoretical predictions are added in quadrature to the diagonal elements of the covariance matrix. The uncertainty in the MCFM predictions comprises the uncertainty in the renormalisation and factorisation scale choice and the uncertainty in the value of α_S . The uncertainty in the predictions obtained with



Results

Table 11.1.: χ^2 probabilities of the predictions for the absolute and normalised differential tq or $\bar{t}q$ production cross sections and the ratio of the absolute cross sections as a function of $p_T(t)$, $p_T(\bar{t})$ and $p_T(t \text{ or } \bar{t})$ respectively.

Prediction	$\frac{d\sigma(tq)}{dp_T(t)}$	$\frac{1}{\sigma(tq)} \frac{d\sigma(tq)}{dp_T(t)}$	$\frac{d\sigma(\bar{t}q)}{dp_T(\bar{t})}$	$\frac{1}{\sigma(\bar{t}q)} \frac{d\sigma(\bar{t}q)}{dp_T(\bar{t})}$	$\left(\frac{d\sigma(tq)}{dp_T(t)}\right) / \left(\frac{d\sigma(\bar{t}q)}{dp_T(\bar{t})}\right)$
	NDF=8	NDF=7	NDF=8	NDF=7	NDF=8
MCFM, with PDF4LHC21					
LO	0.03	0.0	0.02	0.0	0.99
NLO	0.55	0.50	0.83	0.69	1.0
NNLO	0.70	0.65	0.97	0.89	1.0
Event generators, with NNPDF3.0					
POWHEG PYTHIA 8 (4FS)	0.78	0.59	0.98	0.91	1.0
MG_AMC@NLO (4FS)	0.60	0.19	0.96	0.86	1.0
MG_AMC@NLO (5FS)	0.60	0.60	0.96	0.93	1.0
MG_AMC@NLO dyn. scale (5FS)	0.68	0.65	0.90	0.84	1.0
POWHEG +HERWIG 7 (4FS)	0.85	0.66	0.99	0.93	1.0
PDF sets, with POWHEG PYTHIA 8 (4FS)					
CT18	0.58	0.57	0.97	0.93	1.0
MSHT20	0.62	0.60	0.97	0.93	1.0
PDF4LHC21	0.63	0.63	0.96	0.92	1.0
ABMP16	0.64	0.70	0.96	0.90	0.34
NNPDF4.0	0.59	0.59	0.99	0.96	1.0
ATLASpdf21	0.55	0.62	0.91	0.92	1.0

different PDF sets evaluates the MC statistical uncertainty and the PDF uncertainty. For the predictions from different event generators, the MC statistical uncertainty, the uncertainty in the renormalisation and factorisation scale choice and the PDF uncertainty are considered.

Overall, a good agreement is observed between the predictions and the measurements. For the fixed-order calculations, the inclusion of higher orders improves the agreement as expected, and the LO calculations fail to describe the measured p_T spectra. The different generator combinations and PDF sets generally provide a good description of the measured distributions, where the χ^2 probabilities for the $p_T(\bar{t})$ distributions are larger than for the $p_T(t)$ spectra, while the situation is reversed for the rapidity distributions. In the case of the transverse momenta, this can be trivially explained by the larger uncertainties in the $\bar{t}q$ cross sections. For the absolute rapidities, slight discrepancies are visible in the second and fifth bins of the $|y(\bar{t})|$ distributions. Almost all predictions for the differential cross-section ratios show an excellent agreement with the measurement results.

The differential cross sections are measured as a function of $p_T(t)$, $p_T(\bar{t})$ and $|y(t)|$, $|y(\bar{t})|$ because these variables provide a high sensitivity to differences between the predictions from different event generators and PDF sets respectively. The transverse momentum of the top quark is affected by higher-order QCD radiation, where gluons emitted from the top quark lead to an increase in the transverse momentum due to



11.1. The differential cross sections

Table 11.2.: χ^2 probabilities of the predictions for the absolute and normalised differential tq or $\bar{t}q$ production cross sections and the ratio of the absolute cross sections as a function of $|y(t)|$, $|y(\bar{t})|$ and $|y(t \text{ or } \bar{t})|$ respectively.

Prediction	$\frac{d\sigma(tq)}{d y(t) }$	$\frac{1}{\sigma(tq)} \frac{d\sigma(tq)}{d y(t) }$	$\frac{d\sigma(\bar{t}q)}{d y(\bar{t}) }$	$\frac{1}{\sigma(\bar{t}q)} \frac{d\sigma(\bar{t}q)}{d y(\bar{t}) }$	$\left(\frac{d\sigma(tq)}{d y(t) }\right) / \left(\frac{d\sigma(\bar{t}q)}{d y(\bar{t}) }\right)$
	NDF=5	NDF=4	NDF=5	NDF=4	NDF=5
MCFM, with PDF4LHC21					
LO	0.65	0.54	0.82	0.86	0.99
NLO	0.97	0.93	0.68	0.81	1.0
NNLO	1.0	0.98	0.81	0.74	1.0
Event generators, with NNPDF3.0					
POWHEG PYTHIA 8 (4FS)	1.0	0.98	0.81	0.61	1.0
MG_AMC@NLO (4FS)	0.99	0.93	0.81	0.53	0.99
MG_AMC@NLO (5FS)	0.99	0.97	0.69	0.61	1.0
MG_AMC@NLO dyn. scale (5FS)	0.99	0.97	0.65	0.57	1.0
POWHEG +HERWIG 7 (4FS)	1.0	0.98	0.84	0.62	1.0
PDF sets, with POWHEG PYTHIA 8 (4FS)					
CT18	0.98	0.96	0.68	0.55	0.96
MSHT20	1.0	1.0	0.61	0.52	1.0
PDF4LHC21	0.99	0.98	0.70	0.65	1.0
ABMP16	0.91	0.98	0.38	0.18	0.21
NNPDF4.0	0.99	0.99	0.70	0.61	1.0
ATLASpdf21	0.92	0.99	0.64	0.84	1.0

recoil effects. The rapidity on the other hand increases with the momentum transfer in the hard-scattering event, which is in turn affected by the momentum of the light quark in the initial state. For the predictions from different matrix-element generators and parton-shower programs, it can indeed be seen that the differences between the predictions are larger in the $p_T(t)$ and $p_T(\bar{t})$ distributions. However, most of these differences are fully covered by the measurement uncertainties and are therefore not reflected in the χ^2 probabilities in a significant way. The different PDF sets on the other hand yield similar predictions for all distributions, except for ABMP16 and ATLASpdf21, whose predictions tend to differ from the others.

Results for the absolute differential cross sections are compared to the predictions from fixed-order calculations in Figure 11.1. Higher-order corrections introduce negative interference for the signal process, therefore the total tq and $\bar{t}q$ production cross sections decrease as it can be seen clearly in the $|y(t)|$ and $|y(\bar{t})|$ distributions. For the p_T spectra, a strong shape effect is visible for the LO prediction, which drastically overestimates the cross sections in the low- p_T regions but underestimates their magnitude in the tail of the distributions. This is expected for a LO calculation, as it does not consider additional QCD radiation in the final state. The visual impression is reflected in the χ^2 probabilities in Table 11.1, which are below 0.03 for both the absolute and normalised cross sections binned in $p_T(t)$ and $p_T(\bar{t})$. For the cross-section ratio however, the LO prediction reaches a decent agreement with the measurement,

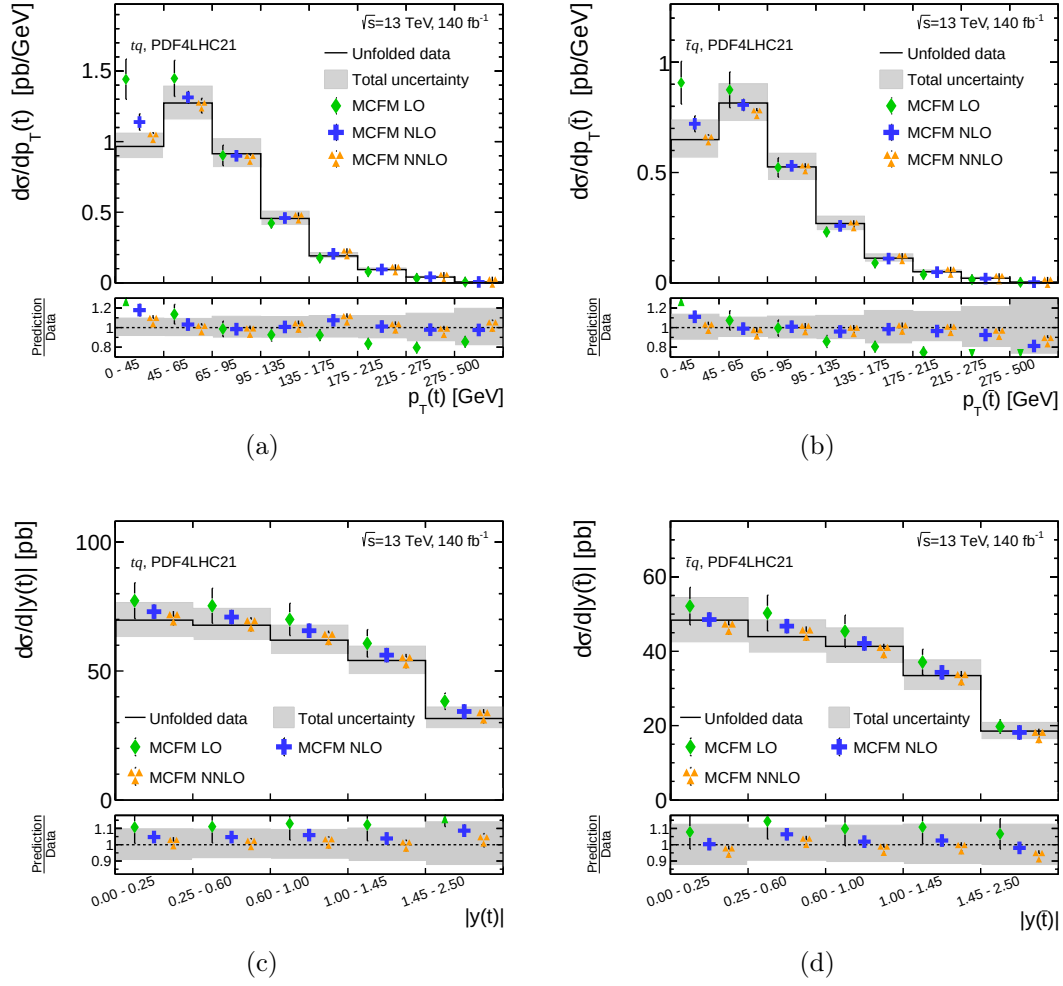


Figure 11.1: Absolute differential (a) (c) tq and (b) (d) $\bar{t}q$ cross sections compared to the theoretical predictions from fixed-order calculations done with MCFM at LO, NLO and NNLO. The shaded band indicates the total measurement uncertainty. The uncertainty in the theoretical predictions comprises the uncertainty in the renormalisation and factorisation scale choice and the uncertainty in the value of α_S .



as the relation between the valence-quark PDFs is the main aspect that determines the ratio.

The normalised differential cross sections are shown in Figure 11.2 together with the predictions from different matrix-element generators and parton-shower programs. The predictions are similar to each other, and no significant differences are visible between the 4FS and 5FS calculations. A striking feature is the low χ^2 probability of 0.19 for the MG_AMC@NLO (4FS) prediction in the $p_T(t)$ spectrum, as a visual inspection of Figure 11.2(a) would suggest a higher compatibility. The explanation lies in the correlation between bins, which enters the calculation of the χ^2 values. The correlation matrix for the distribution presented in Figure F.9 shows a strong positive correlation of 0.42 between the third and fifth bin, while all predictions lie slightly below the measured value in the third bin and up to 5% above in the fifth bin. The difference is largest for the MG_AMC@NLO (4FS) prediction which causes the low compatibility with the measurement result, as a quick test validates. Recalculating the χ^2 values with $\text{Cov}_{3,5} = \text{Cov}_{5,3} = 0$ results in a χ^2 probability above 0.6, which fits the visual impression. The χ^2 probabilities of the other predictions also increase in the test to above 0.8, showing that the correlation between those two bins is the main reason behind the comparatively lower agreement between the predictions and the measurement for the normalised $p_T(t)$ distribution.

Figure 11.3 shows the measured ratio of tq and $\bar{t}q$ production and the predictions from different proton PDF sets. The ratio increases with both $p_T(t \text{ or } \bar{t})$ and $|y(t \text{ or } \bar{t})|$ to approximately 2:1 as a consequence of the different proton PDFs for valence u -quarks and valence d -quarks. Events with a valence quark in the initial state dominate for high $p_T(t \text{ or } \bar{t})$ and $|y(t \text{ or } \bar{t})|$ values, as the valence quarks have the highest probability to carry a large fraction of the proton momentum and to therefore feature an exceptionally large momentum transfer Q^2 in the hard-scattering process. A large Q^2 results in top quarks with high energy and longitudinal momentum, i.e. with a high rapidity, and high top-quark energies also facilitate the radiation of hard gluons, leading to a higher transverse momentum of the top quark. It should be mentioned however that the tails of the p_T and $|y|$ distributions have only limited overlap in phase space, as shown in Appendix G.3.

The predictions generally show an excellent agreement with the measured ratios within the measurement uncertainties. The χ^2 probabilities are close to one, and a close visual inspection of Figure 11.3 reveals that the predictions also agree with the measurement within the uncertainties in the predictions. This suggests that the total uncertainty in the measurement may be overestimated, for which the statistical fluctuations in the systematic uncertainties (cf. Section 10.2) provide a possible explanation. Only the ABMP16 prediction exhibits a poor agreement with the measurement result and constantly overestimates the ratio in both distributions. This observation is consistent with the findings of previous ATLAS measurements of the ratio of the total tq and $\bar{t}q$ cross sections at $\sqrt{s} = 8 \text{ TeV}$ [74] and $\sqrt{s} = 13 \text{ TeV}$ [2].

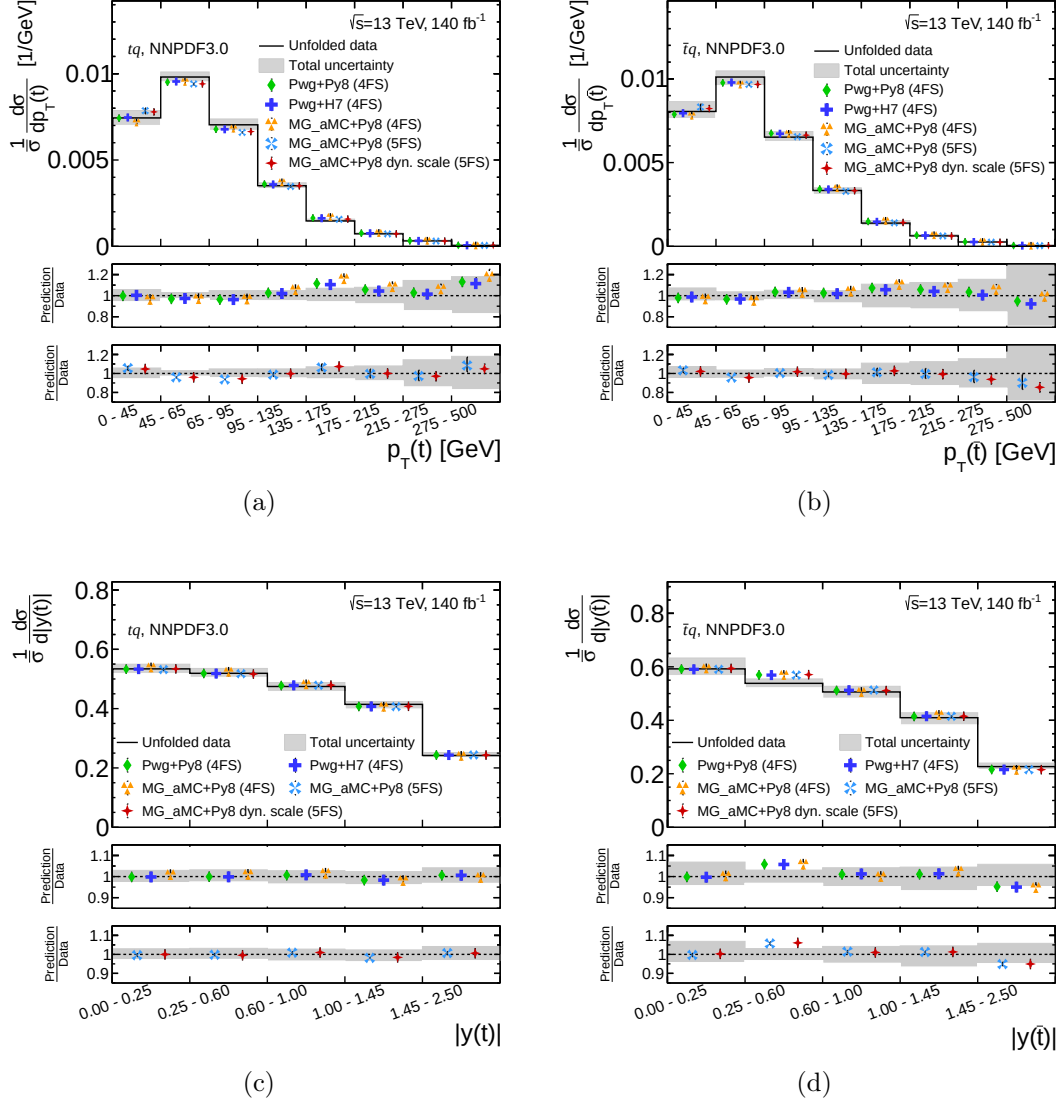


Figure 11.2: Normalised differential (a) (c) tq and (b) (d) $\bar{t}q$ cross sections compared to the predictions from different MC event generators and parton-shower programs. The shaded band indicates the total measurement uncertainty. All predictions are generated with the NNPDF3.0 PDF set. The uncertainty in the theoretical predictions comprises the MC statistical uncertainty, the uncertainty in the renormalisation and factorisation scale choice and the PDF uncertainty.

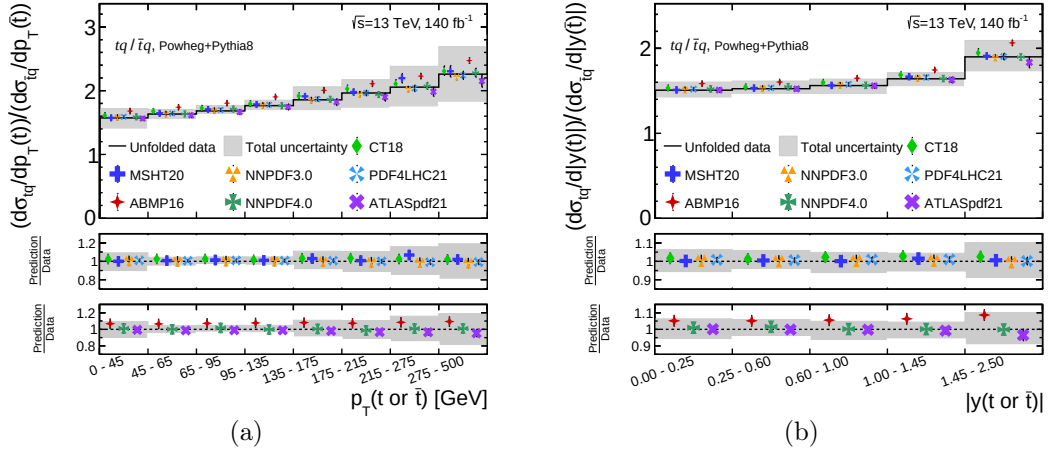


Figure 11.3: Ratio of the differential cross sections as a function of (a) $p_T(t \text{ or } \bar{t})$ and (b) $|y(t \text{ or } \bar{t})|$ compared to the predictions obtained from POWHEG + PYTHIA 8 with different PDF sets. The shaded band indicates the total measurement uncertainty. The uncertainty in the theoretical predictions comprises the MC statistical uncertainty and the PDF uncertainty.

Both ATLAS and CMS measured differential tq and $\bar{t}q$ production cross sections as a function of the same kinematic variables in previous analyses. A straightforward comparison of the results is not feasible since the previous ATLAS measurement [74] analysed data taken at a different centre-of-mass energy and the CMS analysis [75] measured combined tq and $\bar{t}q$ production cross sections. However, some qualitative statements can be made.

The previous ATLAS measurement at $\sqrt{s} = 8 \text{ TeV}$ measured absolute and normalised differential tq and $\bar{t}q$ cross sections as a function of $p_T(t)$ or $p_T(\bar{t})$ up to 300 GeV, with relative uncertainties in the highest bin of $+21.7\%/-22.1\%$ and $+39.1\%/-35.2\%$ for the $p_T(t)$ and $p_T(\bar{t})$ distributions. This measurement reaches a better precision of $+20.4\%/-19.6\%$ and $+28.8\%/-26.5\%$ in the highest bin of the $p_T(t)$ and $p_T(\bar{t})$ distributions, which covers the kinematic range [275, 500] GeV. For the normalised cross sections binned in the absolute top-quark rapidity, the measurement at $\sqrt{s} = 8 \text{ TeV}$ reached a precision of about 7 % in $|y(t)|$ and 9 %–16 % in $|y(\bar{t})|$, whereas this measurement provides uncertainties of about 3 % and 3 %–6 % in the respective distributions. The improvements can be attributed to the larger number of data events in the signal regions and a reduction in the background contribution. The number of data events in the signal regions is increased by a factor of five, and the signal-over-background ratios in the signal regions, which were also separated by lepton charge in the previous measurement, are improved from 2.2 and 1.3 to 6.1 and 3.8. Thereby, the relative statistical data uncertainty is reduced by a factor of two, and the uncertainties related to the modelling and rate of the background processes are diminished to minor uncertainties, whereas they comprised the largest single uncertainties in the previous measurement.



The measurement from CMS at $\sqrt{s} = 13 \text{ TeV}$ uses only a partial Run 2 data sample, corresponding to an integrated luminosity of 35.9 fb^{-1} , to measure combined tq and $\bar{t}q$ cross sections and the ratio of tq over combined tq and $\bar{t}q$ production. The combined cross sections as a function of $p_T(t \text{ or } \bar{t})$ are measured up to 300 GeV . The relative uncertainties in the combined absolute cross sections as a function of $p_T(t \text{ or } \bar{t})$ and $|y(t \text{ or } \bar{t})|$ are comparable to the uncertainties obtained in this analysis for the $p_T(t)$ and $|y(\bar{t})|$ distributions respectively. Major uncertainties in the CMS analysis are related to the data statistics and the luminosity. Similar to this measurement, the uncertainty related to the parton-shower modelling of the signal process also has a large impact. The fact that this measurement provides separate results for tq and $\bar{t}q$ production can be seen as an improvement in the scope, but a proper comparison is complicated due to differences in the treatment of the uncertainties, as the CMS measurement includes the experimental uncertainties as nuisance parameters in the unfolding procedure.

11.2. EFT interpretation

As outlined in Section 1.8, the SMEFT provides a powerful framework to search for effects of BSM physics in a model-independent way. The measurement results of this analysis are particularly sensitive to the dimension-six operator $O_{Qq}^{3,1}$, which introduces a four-quark contact interaction as shown in Figure 11.4. Following the notation in Ref. [175] to express the SMEFT operators in the Warsaw basis, the two four-fermion operators relevant for single-top-quark production are

$$O_{qq}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l) \quad \text{and}$$

$$O_{qq}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l).$$

Here, τ^I are the Pauli matrices, γ^μ the Dirac matrices and q denotes the weak-isospin doublets with quark generation indices $ijkl \in [1, 2, 3]$. All four-quark subprocesses contributing to the signal process only depend on the linear combination of the associated Wilson coefficients

$$C_{Qq}^{3,1} = \sum_{i=1,2} C_{qq}^{3(ii33)} + \frac{1}{6} C_{qq}^{1(i33i)} - \frac{1}{6} C_{qq}^{3(i33i)},$$

where Q represents the doublet of the third quark generation. The t -channel production is also sensitive to the operators $O_{\Phi Q}^3$ and O_{tW} , which interfere with the tWb vertex, $O_{\Phi tb}^3$ and O_{bW} , whose interference with the SM is suppressed by the b -quark mass, and $O_{Qq}^{8,1}$, which does not interfere with the SM as it is a colour octet [176]. Dedicated analyses like Ref. [177] set constraints on all these operators and evaluate

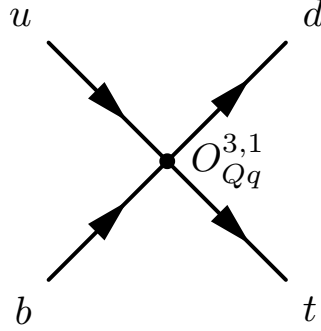


Figure 11.4: Exemplary LO Feynman diagram of single-top production via a four-quark contact interaction.

the correlations between them, but the aim of this interpretation is to set individual constraints on $C_{Qq}^{3,1}/\Lambda^2$, i.e. the other Wilson coefficients are set to their SM expectation of zero. The limits set in this interpretation assume a characteristic energy scale Λ of 1 TeV.

The $ub \rightarrow dt$ and $u\bar{d} \rightarrow \bar{b}t$ processes are related by a crossing symmetry, therefore the s -channel production is also altered by $O_{Qq}^{3,1}$ and considered as signal process for the interpretation by being included in the EFT MC samples as mentioned in Chapter 5. On a similar note, diagrams including quarks of the second generation, for example $cb \rightarrow st$, and/or antiquarks are also taken into account.

Top quarks produced via the $O_{Qq}^{3,1}$ vertex feature different angular and kinematic distributions than top quarks produced according to the SM and are specifically expected to have higher transverse momentum than their SM counterparts. The interpretation therefore uses the differential cross sections measured as a function of $p_T(t)$ and $p_T(\bar{t})$. The dependence of the differential cross sections on $C_{Qq}^{3,1}/\Lambda^2$ can be parameterised in each bin as

$$\frac{d\sigma_{t \text{ or } \bar{t}}}{dp_T} = \left(\frac{d\sigma_{t \text{ or } \bar{t}}}{dp_T} \right)_{\text{SM}} + \frac{C_{Qq}^{3,1}}{\Lambda^2} \cdot \left(\frac{d\sigma_{t \text{ or } \bar{t}}}{dp_T} \right)_{\text{int.}} + \left(\frac{C_{Qq}^{3,1}}{\Lambda^2} \right)^2 \cdot \left(\frac{d\sigma_{t \text{ or } \bar{t}}}{dp_T} \right)_{\text{BSM}}, \quad (11.1)$$

where the term linear in $C_{Qq}^{3,1}/\Lambda^2$ stems from the interference between the SM and BSM amplitudes and the term proportional to $(C_{Qq}^{3,1}/\Lambda^2)^2$ describes pure BSM contributions. This quadratic dependency is utilised for the interpretation to parameterise the expected change in the cross sections in each bin of the $p_T(t)$ and $p_T(\bar{t})$ distributions. The SM term in Equation 11.1 is set to the SM NNLO prediction to apply the NNLO corrections to the BSM case. The dependency of the cross section on $C_{Qq}^{3,1}/\Lambda^2$ is therefore evaluated in terms of relative changes with respect to the SM scenario, where $C_{Qq}^{3,1}/\Lambda^2$ equals zero. A *confidence interval* (CI) for $C_{Qq}^{3,1}/\Lambda^2$ is finally extracted from a comparison to the measurement results.



An important aspect to consider in the interpretation is the selection efficiency, which enters the main analysis as an unfolding correction as described in Section 9.3.2. Contributions from $O_{Qq}^{3,1}$ affect the selection efficiency significantly as shown in Figure 11.5, where the selection efficiencies calculated for the EFT MC samples are presented. The selection efficiency decreases in the high- p_T region compared to the SM prediction, especially for positive values of $C_{Qq}^{3,1}/\Lambda^2$. This is a direct consequence of the altered event kinematics. The larger transverse momentum of top quarks produced via $O_{Qq}^{3,1}$ vertices is connected to an increased probability for QCD radiation off the top quark that results in an additional jet with $p_T > 30$ GeV, in which case the event is rejected by the signal-region event selection.

The effect on the differential cross sections is substantial, as illustrated in Figure 11.6. The grey squares show the expected relative change in the cross sections at parton level obtained directly from parton-level distributions of the simulated EFT events. The dashed grey line shows the best extrapolation obtained from a least-squares fit. It follows a quadratic function in accordance with Equation 11.1. The interference between BSM and SM amplitudes is destructive for positive values of $C_{Qq}^{3,1}/\Lambda^2$ and dominates in the low- p_T region. The contribution from pure BSM events becomes larger with increasing p_T , as expected, and leads to drastic increases in the predicted cross sections for large absolute values of $C_{Qq}^{3,1}/\Lambda^2$.

The blue points in comparison are obtained by unfolding the detector-level distributions of the EFT events back to parton level using the nominal unfolding corrections. This approach takes the altered selection efficiencies into account, as the signal-region event selection is applied to the detector-level distributions. The blue line again shows the result of the least-squares fit. This time, the fit result resembles a linear function in all bins except for the last one. The interference term, which reduces the number of events for positive values of $C_{Qq}^{3,1}/\Lambda^2$, remains the dominating factor over

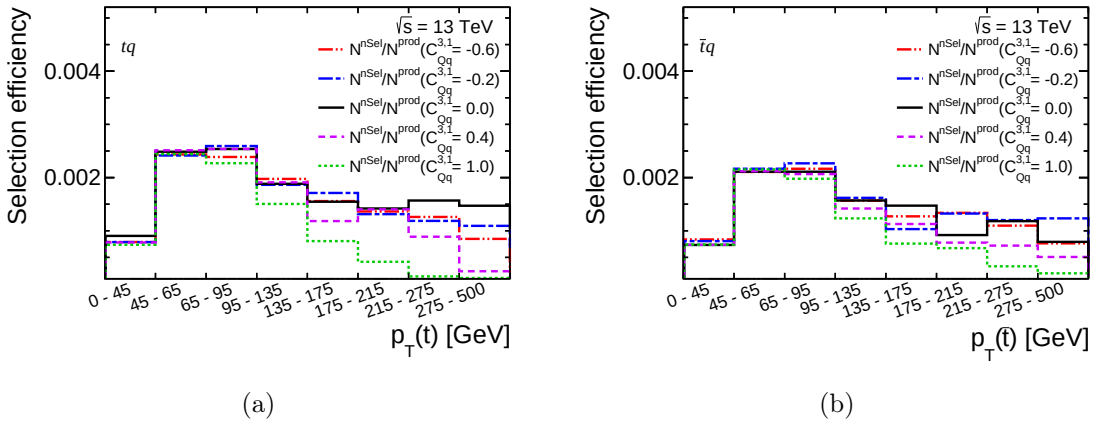


Figure 11.5: Selection efficiencies in the (a) ℓ^+ SR and (b) ℓ^- SR of the EFT MC samples generated with $C_{Qq}^{3,1}/\Lambda^2$ set to different values.

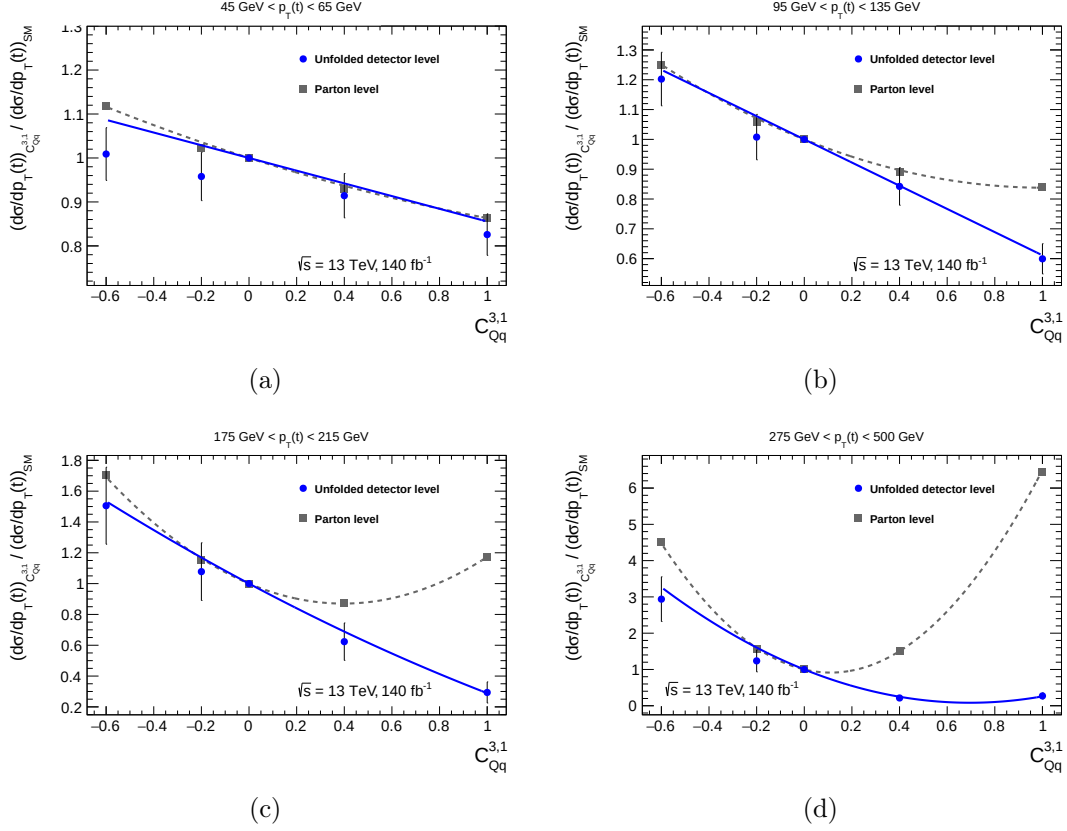


Figure 11.6: Expected relative change in the differential tq cross section measured as a function of $p_T(t)$. Every second bin of the distribution is shown exemplarily. Only MC statistical uncertainties are shown.

the whole distribution, as most BSM contributions are rejected by the signal-region event selection. The interpretation therefore utilises the parameterisations obtained with the unfolded detector-level distributions to properly account for the significant impact of the selection efficiency. The obtained best-fit values are given in Table G.7.

To extract constraints on $C_{Qq}^{3,1}/\Lambda^2$, an approach based on Bayesian inference is used. The posterior probability for a free parameter λ of some model M given a set of measurements $\vec{x}$ can be calculated according to Bayes theorem,

$$p(\lambda | \vec{x}) = \frac{\int p(\vec{x} | \vec{y}) p(\vec{y} | \lambda) d\vec{y} \cdot p(\lambda)}{\int p(\vec{x} | \lambda) p(\lambda) d\lambda}.$$

Here, $\vec{y}$ refers to the predictions for the observables for certain values of λ , hence $p(\vec{y} | \lambda) = \delta(y - y(\lambda))$. The probability $p(\vec{x} | \vec{y})$ can be calculated by using the



covariance matrix Cov of the measurement,

$$-2 \ln(p(\vec{x} | \vec{y})) = \sum_{i=1}^n \sum_{j=1}^n [\vec{x} - \vec{y}]_i \text{Cov}_{ij}^{-1} [\vec{x} - \vec{y}]_j.$$

The *EFTfitter* tool [178] offers an implementation of the method tailored to the needs of EFT interpretations by taking correlations and uncertainties in the measurements into account. Constraints on model parameters are obtained by sampling the posterior probability density function using a *Markov Chain Monte Carlo* algorithm. The required inputs to the calculation are described in the following.

The Wilson coefficient $C_{Qq}^{3,1}/\Lambda^2$ is the free parameter of the model. An estimate for the prior distribution is required, and a uniform distribution within the interval $[-0.5, 0.5]$ is chosen based on the constraints from previous measurements. The observables are the differential tq and $\bar{t}q$ cross sections binned in $p_T(t)$ and $p_T(\bar{t})$ respectively, where each bin of the distributions is treated as an individual observable. The predictions for the observables as a function of $C_{Qq}^{3,1}/\Lambda^2$ are parameterised according to Equation 11.1 with the best-fit values given in Table G.7. The parameterisations include the theoretical prediction for the SM cross sections, where the values obtained with MCFM at NNLO are used. The uncertainties in the prediction related to the renormalisation and factorisation scale choice and the value of α_S are considered as uncertainties in the model. The measured differential cross sections are used with the respective total uncertainties, which are symmetrised by taking the larger of the Up and Down variations. The covariance matrices discussed in Section 10.3 are used to account for the

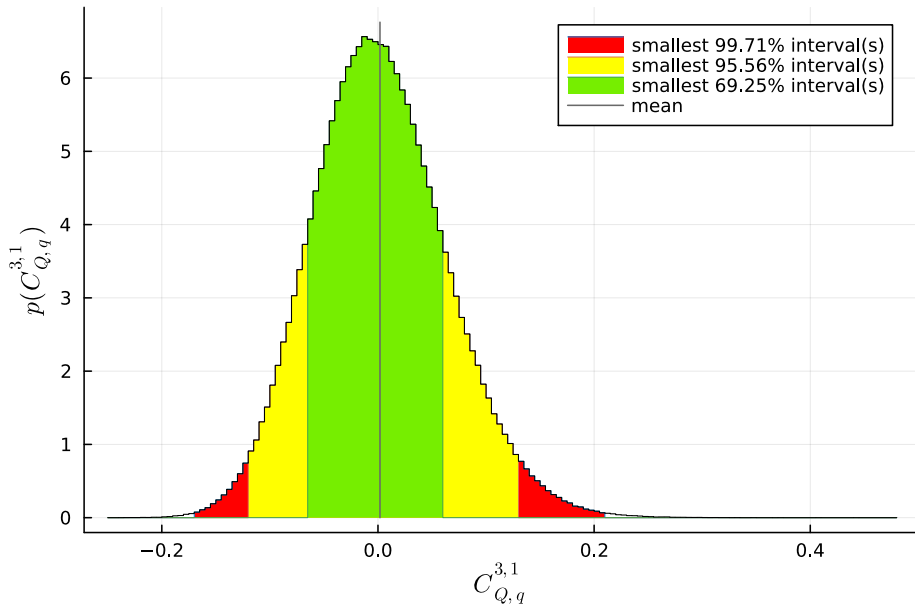


Figure 11.7: Posterior probability density for $C_{Qq}^{3,1}/\Lambda^2$.



correlations between the bins within one distribution, while the measurements in $p_T(t)$ and $p_T(\bar{t})$ are treated as uncorrelated.

From the posterior probability density shown in Figure 11.7, the central interval containing 95 % of the distribution is used to define the CI for $C_{Qq}^{3,1}/\Lambda^2$. The interpretation yields the result $C_{Qq}^{3,1}/\Lambda^2 \in [-0.12, 0.12] \text{ TeV}^{-2}$, which is compatible with the SM expectation of zero. A similar interpretation of the ATLAS measurement of the total tq and $\bar{t}q$ cross sections at $\sqrt{s} = 13 \text{ TeV}$ utilised the detector-level D_{nn} distributions of the signal events and yielded a 95 % CI of $C_{Qq}^{3,1}/\Lambda^2 \in [-0.37, 0.06] \text{ TeV}^{-2}$ [2]. The improvement reached in this interpretation can be attributed to the higher sensitivity of the considered distributions. A dedicated EFT analysis that set constraints on all operators affecting the t -channel production by using angular information of the top-quark decay obtained an individual 95 % CI of $C_{Qq}^{3,1}/\Lambda^2 \in [0.05, 0.29] \text{ TeV}^{-2}$ [177]. The comparison shows that the approach chosen in this interpretation is competitive for limits set on an individual operator, where the performance for constraining multiple operators simultaneously could be explored in future dedicated studies. The large impact of $C_{Qq}^{3,1}/\Lambda^2$ on the selection efficiencies however suggests to perform future interpretations at detector level, where the effect is automatically taken into account.

Conclusion and outlook

This thesis presents a measurement of differential cross sections for single top quarks produced via the t -channel exchange of a virtual W -boson in proton-proton collisions at the LHC. The analysed data was collected by the ATLAS detector in the years 2015–2018 at a centre-of-mass energy $\sqrt{s} = 13$ TeV and corresponds to an integrated luminosity of 140 fb^{-1} . The differential tq and $\bar{t}q$ production cross sections are measured at the parton level as a function of the transverse momentum and absolute rapidity of the top quark and top antiquark. Both absolute and normalised differential cross sections are determined, and the differential ratio of tq over $\bar{t}q$ production is measured for the first time. This measurement also constitutes the first separate measurement of differential tq and $\bar{t}q$ production cross sections at 13 TeV. The results are compared to predictions obtained from fixed-order calculations, different event-generator programs and various PDF sets.

The measurement builds upon the ATLAS measurement of the total tq and $\bar{t}q$ cross sections at 13 TeV [2] and considers the semileptonic top-quark decay channel. Candidate events are required to contain one electron or muon, two jets out of which one is b -tagged and missing transverse momentum. Two separate signal regions are defined based on the lepton charge. Additional selection criteria are imposed on the event kinematics to reduce the contribution from background processes. The most important criterion utilises the neural network trained in Ref. [2] to achieve high purities in t -channel events. To model the contribution of background events with no prompt lepton, templates are used which predict the shape but offer no estimate of the normalisation. The rate of all background processes is therefore determined in a dedicated maximum-likelihood fit that is performed in multiple phase-space regions simultaneously, all of which are orthogonal to the signal regions of the differential measurement.

The distributions measured at detector level are corrected for distortions related to the limited resolution and acceptance of the detector via an unfolding procedure. The method of Iterative Bayesian Unfolding is employed and thoroughly tested to ensure that it works correctly and introduces no bias to the unfolded distributions. The tests prove the method to be reliable and robust against variations in the shape of the measured distributions.

The measurement is affected by various uncertainties which are broadly categorised as statistical uncertainties and systematic uncertainties. The latter in turn comprise experimental uncertainties and modelling uncertainties. The impact of each uncertainty is evaluated separately, and the total measurement uncertainty is obtained by adding all contributions in quadrature. The uncertainties in the modelling of the signal process and the experimental uncertainties have the highest impact on the differential cross sections, while the uncertainties related to the modelling and rates of the



background processes have a minor impact. The statistical uncertainty in the data becomes significant in the high- $p_T(t)$ and high- $p_T(\bar{t})$ regions. The normalised cross sections and the cross-section ratios benefit from cancellation effects, which overall reduce the uncertainties. The statistical uncertainties in the experimental and signal modelling uncertainties are evaluated, as they may be of interest for future combinations.

The compatibility between the measured differential cross sections and the theoretical predictions is evaluated via the χ^2 probability, whose calculation takes the uncertainties in both measurements and predictions into account. In general, a good agreement is found between the measured distributions and the predictions. For the fixed-order calculations, the inclusion of higher order corrections increases the compatibility as expected. The differences between the predictions from different PDF sets and event-generator programs are mostly small and covered within the measurement uncertainties. For the ratios of the differential cross sections, most predictions provide an excellent description of the measurement results.

The measurement results are interpreted in an EFT approach to extract limits on the contribution of the four-fermion operator $O_{Qq}^{3,1}$. A significant impact of $O_{Qq}^{3,1}$ on the selection efficiencies is found and accounted for in the interpretation. A confidence interval for the associated Wilson-coefficient $C_{Qq}^{3,1}/\Lambda^2 \in [-0.12, 0.12] \text{ TeV}^{-2}$ is obtained.

Overall, the measurement presented in this thesis achieves a higher precision than previous measurements by ATLAS and CMS. Important factors for the improvements are the increased statistical power and a significant reduction of the contribution from background processes. The range of the $p_T(t)$ and $p_T(\bar{t})$ spectra is increased to 500 GeV, and the first measurement of the ratio of tq over $\bar{t}q$ production is provided. The previous results for the differential cross sections as a function of $|y(t)|$ and $|y(\bar{t})|$ proved to be of interest for global PDF fits and have been used by the NNPDF collaboration. At the time of writing this thesis, the presented results are not yet evaluated by any PDF group, but can be expected to be a useful addition to PDF fits.

For future measurements, the reduction of signal modelling uncertainties will be crucial to improve the precision. This is interconnected with the task of suppressing background contributions, which provides a considerable challenge for any measurement of the t -channel process. The event selection that provides the high signal purity reached in this analysis also increases the impact of certain signal modelling uncertainties. Therefore, these two challenges need to be approached together to enable further increases in the measurement precision. The differential cross sections measured as a function of $p_T(t)$ and $p_T(\bar{t})$ will benefit from increased event statistics in the high- p_T regions that are of special interest for searches for BSM effects.

An important insight gained from the BSM interpretation presented in this analysis is that the impact of an EFT operator on the selection efficiencies can alter the ex-



pected dependence of the unfolded cross sections on the operator significantly. This only poses an issue for operators that alter the Lorentz structure of events, but for those cases, the impact needs to be quantified. Alternatively, one can conclude that interpretations at detector level are preferable, as they take the effects into account by construction.

Appendices



A. Cross sections of the EFT signal samples

The cross sections of the simulated EFT signal samples described in Chapter 5 and utilised for the interpretation in Section 11.2 are given in Table A.1.

Table A.1.: Cross sections for the MC samples simulating t -channel and s -channel single top production for different values of the EFT Wilson-coefficient $C_{Qq}^{3,1}/\Lambda^2$. The cross sections are calculated with MADGRAPH5_AMC@NLO 2.7.3.

$C_{Qq}^{3,1}/\Lambda^2$ [TeV $^{-2}$]	Cross section [pb]	
	$tq + \bar{t}\bar{b}$ samples	$\bar{t}q + \bar{t}\bar{b}$ samples
−0.6	59.1	33.9
−0.2	49.2	29.6
0.0	46.7	27.8
0.4	43.8	26.7
1.0	48.9	28.2



B. Background estimate

In Appendix B.1, additional material regarding the maximum likelihood fit that is performed to estimate the normalisation of the background processes (cf. Chapter 8) is presented. Comparisons between data and simulation in the signal regions for various kinematic distributions are shown in Appendix B.2.

B.1. Results of the maximum-likelihood fit

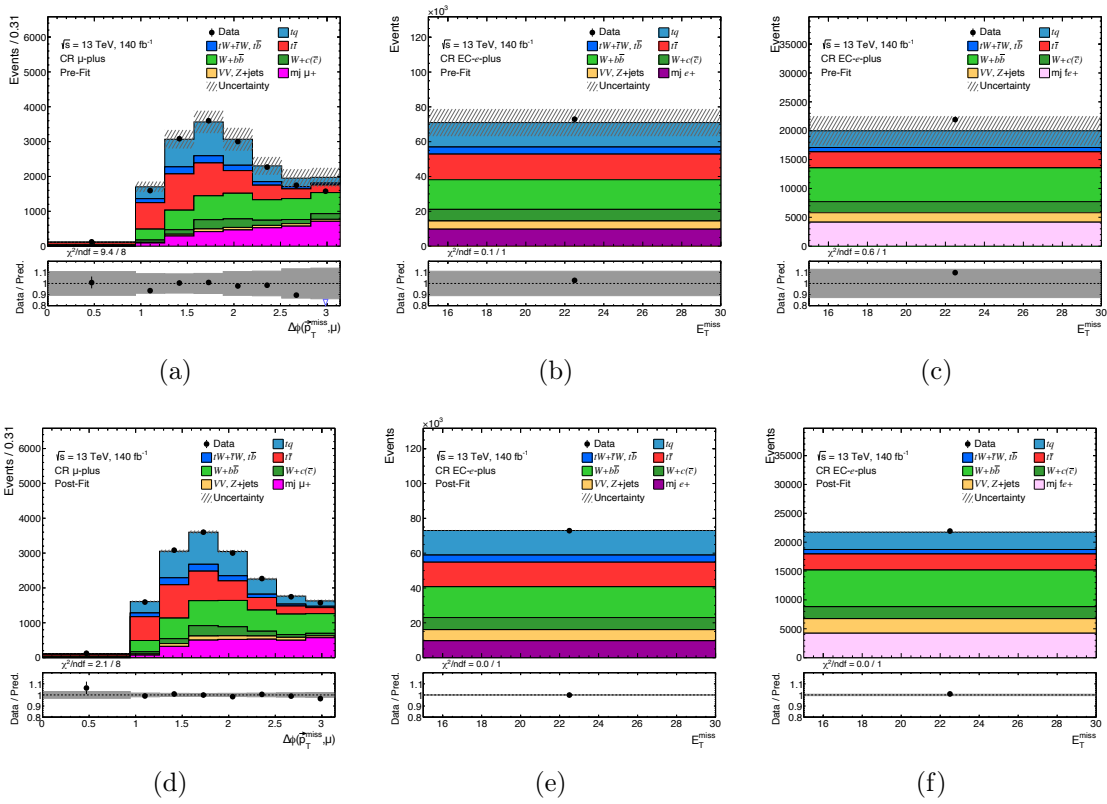


Figure B.1: Pre-fit and post-fit agreement in the ℓ^+ control regions for the (a), (d) muon, (b), (e) central electron and (c), (f) forward electron components of the multijet background.

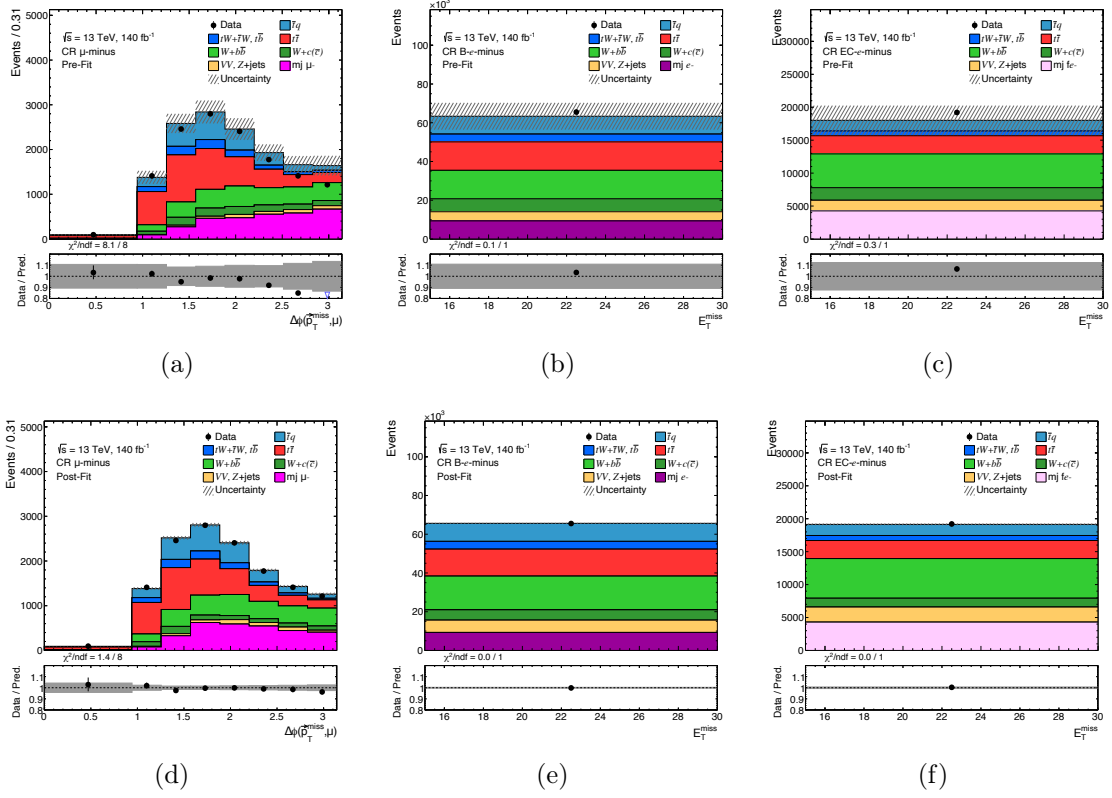


Figure B.2: Pre-fit and post-fit agreement in the ℓ^- control regions for the (a), (d) muon, (b), (e) central electron and (c), (f) forward electron components of the multijet background.

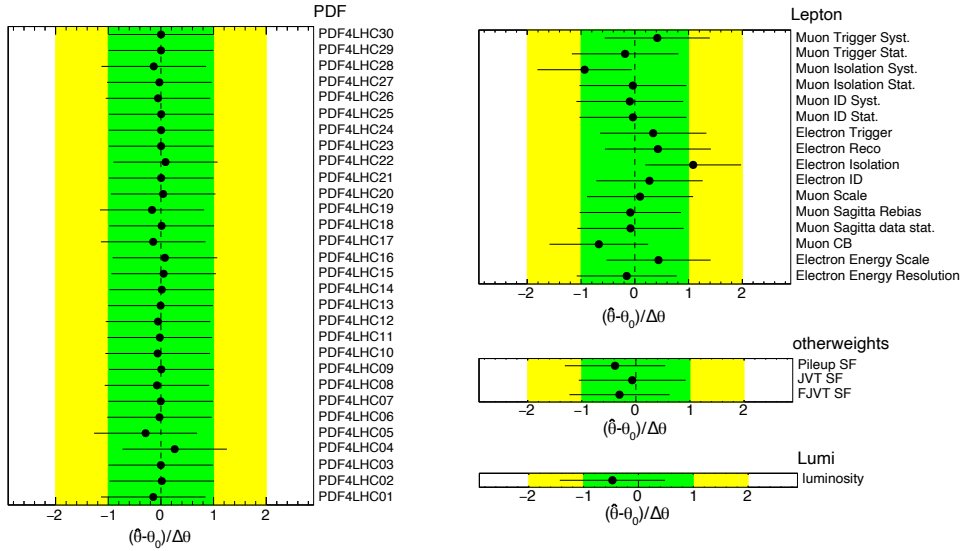


Figure B.3: Best fit results for the NPs included in the fit.

B. Background estimate

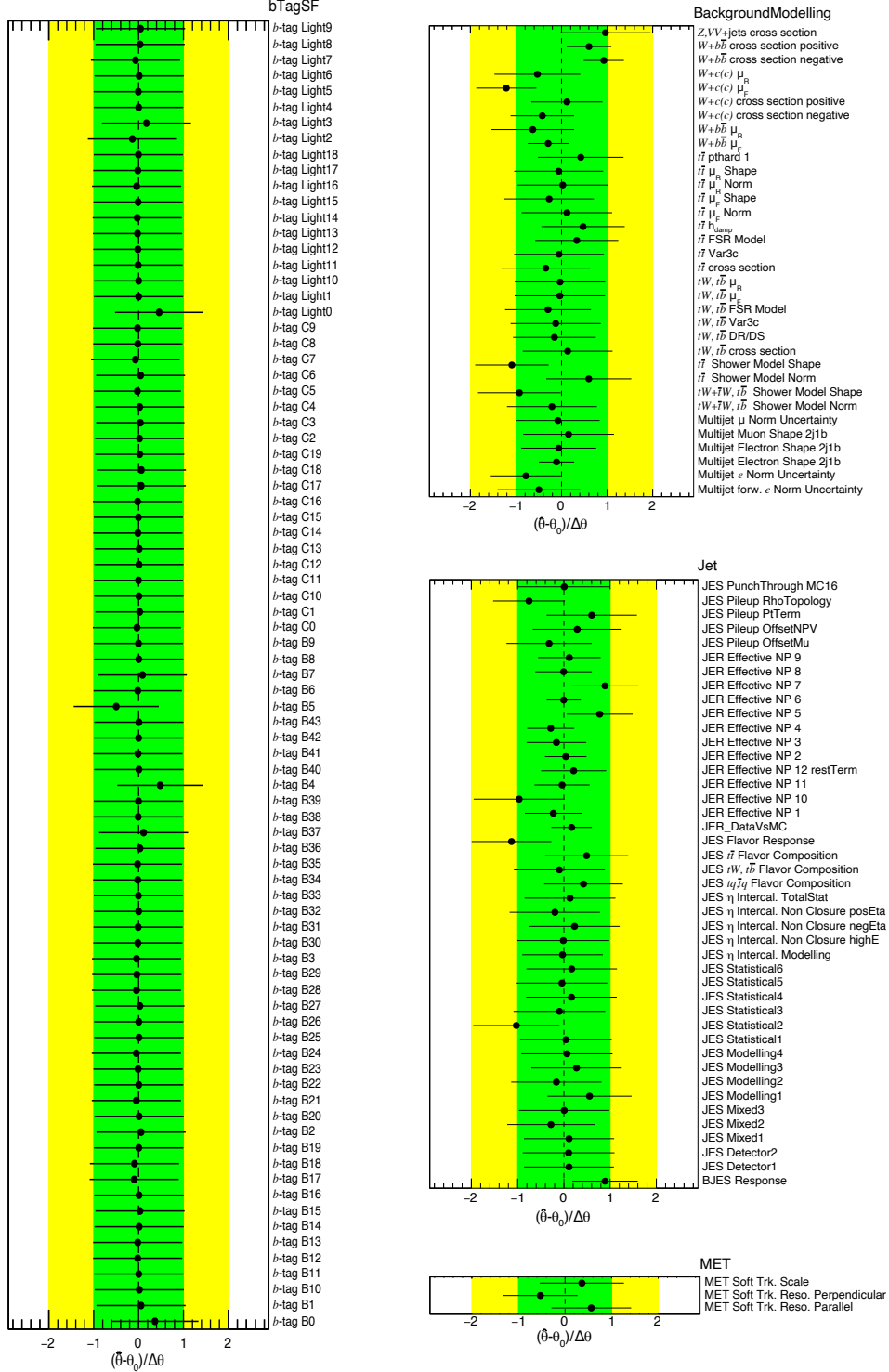


Figure B.4: Best fit results for the NPs included in the fit.



global Norm	100.0	36.7	7.5	22.3	-33.2	-28.2	-3.9	-22.9	-78.4	-82.3	-27.2
JES $t\bar{t}$ Flavor Composition	36.7	100.0	6.0	-5.0	10.6	-5.7	-5.5	-1.5	-21.0	-19.7	-13.9
JER Effective NP 5	7.5	6.0	100.0	9.4	-2.9	-21.6	12.0	10.8	2.4	-13.0	-2.0
JES Pileup RhoTopology	22.3	-5.0	9.4	100.0	-0.7	-5.0	15.7	-9.3	-28.0	-36.9	3.1
$t\bar{t}$ cross section	-33.2	10.6	-2.9	-0.7	100.0	7.6	4.7	-0.0	25.1	24.2	11.1
$W+c(c)$ cross section negative	-28.2	-5.7	-21.6	-5.0	7.6	100.0	44.9	5.9	-5.2	16.3	-7.7
$W+c(c)$ cross section positive	-3.9	-5.5	12.0	15.7	4.7	44.9	100.0	7.8	-2.1	-25.2	-5.7
Muon Isolation Syst.	-22.9	-1.5	10.8	-9.3	-0.0	5.9	7.8	100.0	14.6	11.6	12.2
$W+b\bar{b}$ cross section negative	-78.4	-21.0	2.4	-28.0	25.1	-5.2	-2.1	14.6	100.0	89.9	4.2
$W+b\bar{b}$ cross section positive	-82.3	-19.7	-13.0	-36.9	24.2	16.3	-25.2	11.6	89.9	100.0	6.2
Z,VV+jets cross section	-27.2	-13.9	-2.0	3.1	11.1	-7.7	-5.7	12.2	4.2	6.2	100.0
	global Norm	JES $t\bar{t}$ Flavor Composition	JER Effective NP 5	JES Pileup RhoTopology	$t\bar{t}$ cross section	$W+c(c)$ cross section negative	$W+c(c)$ cross section positive	Muon Isolation Syst.	$W+b\bar{b}$ cross section negative	$W+b\bar{b}$ cross section positive	Z,VV+jets cross section

Figure B.5: Correlations between all NPs that have a correlation of 20 % or larger with at least one other NP. The “global Norm” parameter represents the overall background normalisation μ .



B.2. Kinematic variables in the signal regions

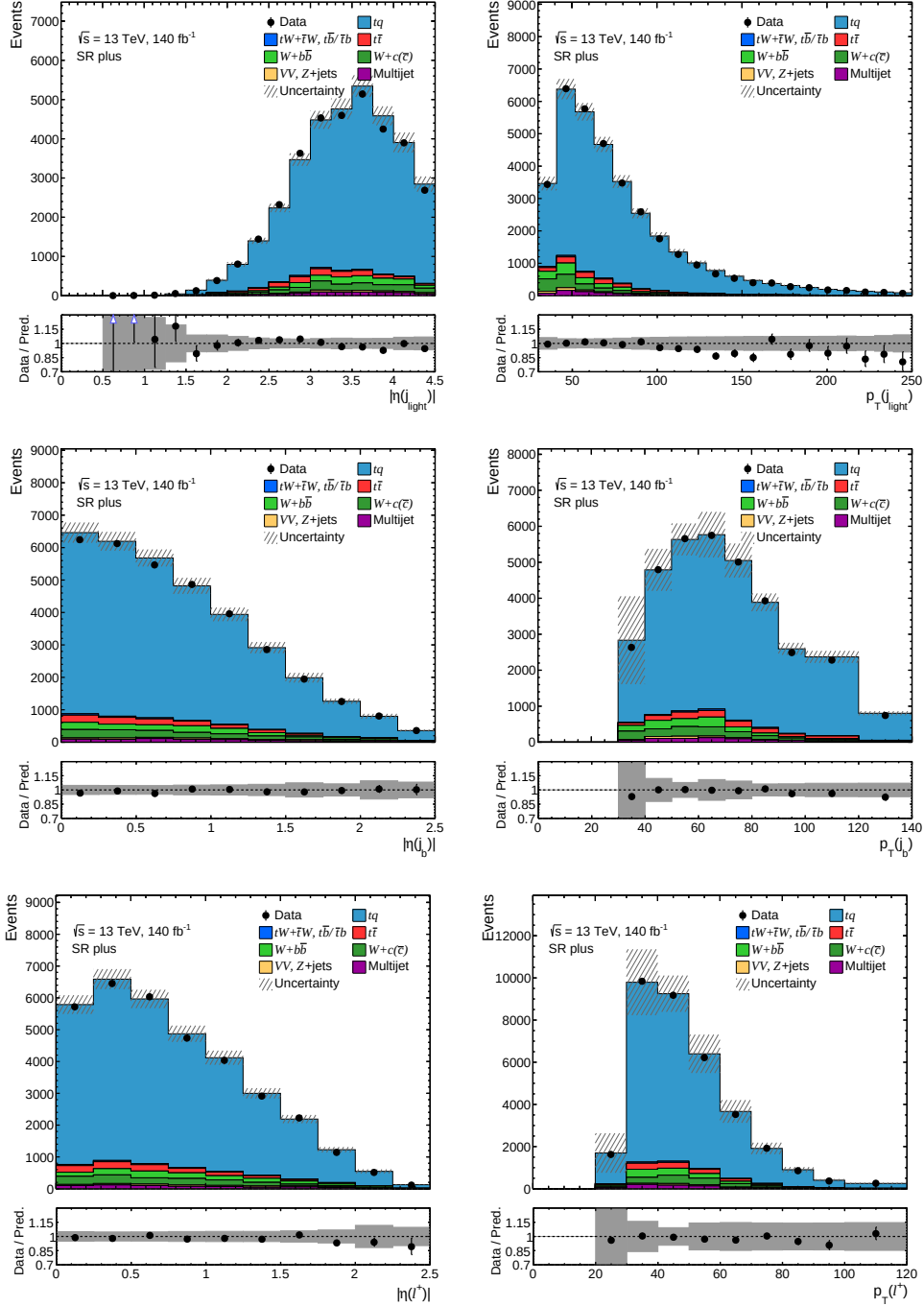


Figure B.6: Comparison between expected and observed distributions in the ℓ^+ SR for the absolute rapidity and transverse momentum of the light jet, the b -jet and the charged lepton.

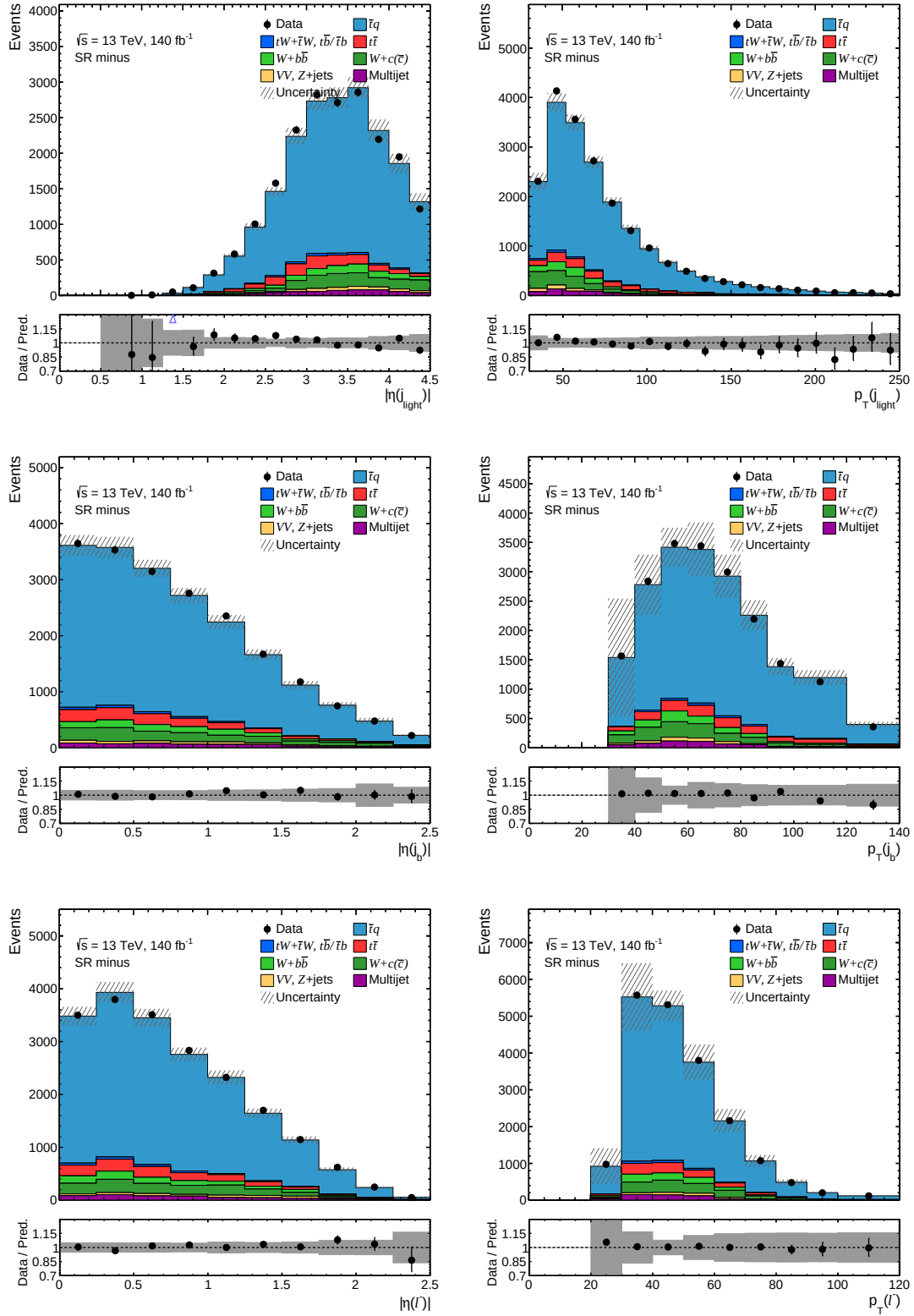


Figure B.7: Comparison between expected and observed distributions in the ℓ^- SR for the absolute rapidity and transverse momentum of the light jet, the b -jet and the charged lepton.

B. Background estimate

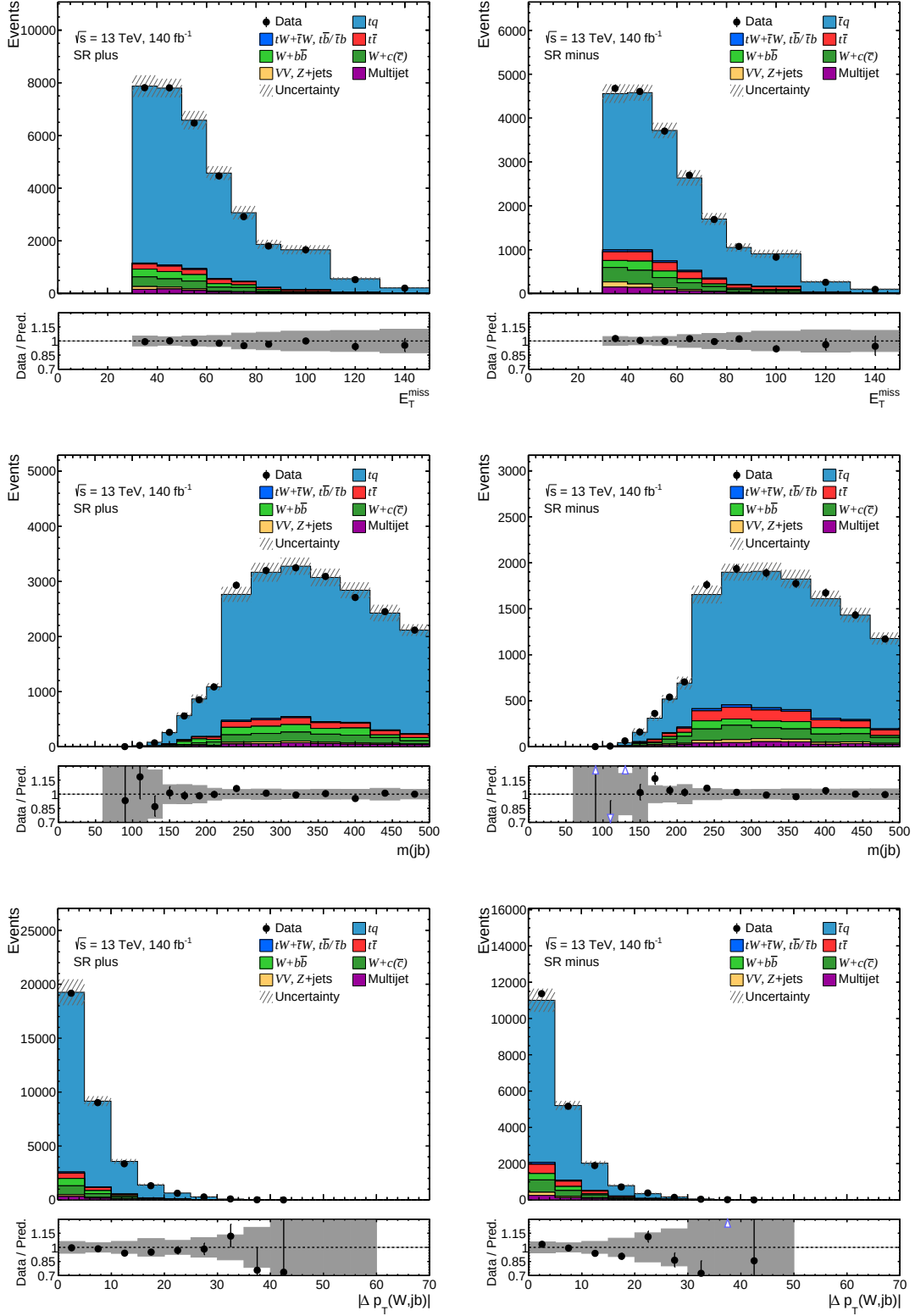


Figure B.8: Comparison between expected and observed distributions in the ℓ^+ SR and the ℓ^- SR for the E_T^{miss} and two NN input variables with the highest and third-highest discriminating power. The second-highest discriminating power stems from the η distribution of the light jet, which is included in the previous figures.



C. Event selection

Supplementary material regarding the event selection described in Chapter 7 is presented in this appendix.

C.1. Angular cut

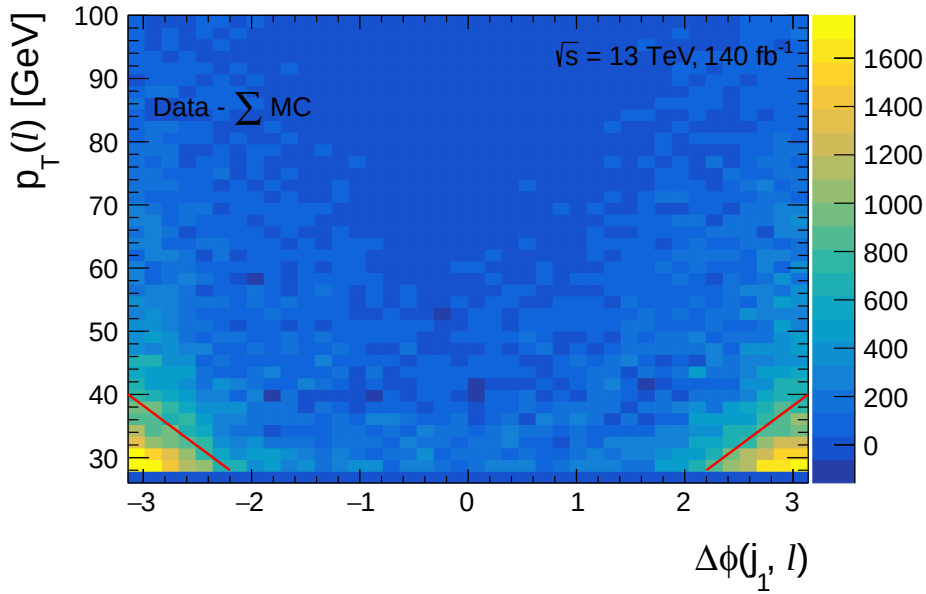


Figure C.1: Distribution in $\Delta\phi(j_1, \ell)$ and $p_T(\ell)$ of events required to contain one lepton, two jets, one b -tag and E_T^{miss} with the p_T and η requirements specified in Section 7 (i.e. all requirements listed in Table 7.1 prior to the $m_T(W)$ criterion are imposed). Data events subtracted by all MC simulated processes are shown, which corresponds to the multijet-background events. Most of these events are dijet events where one jet is misidentified as lepton, therefore the lepton and the p_T -leading jet are emitted back-to-back. The red line indicates the selection requirement $p_T(\ell) > 40 \text{ GeV} \cdot |\Delta\phi(j_1, \ell)|/\pi$, which removes a large fraction of the multijet events.



C.2. NN input variables

Table C.1.: The 17 variables used for the training of the NN ordered by decreasing discriminating power [2]. The sphericity S is defined via the sphericity tensor $S^{\alpha\beta} = \left(\sum_i p_i^\alpha p_i^\beta \right) / \left(\sum_i |\vec{p}_i|^2 \right)$, where α and β correspond to the spatial components x , y and z of the three-momenta $\vec{p}_i$ of the reconstructed jets, charged lepton and neutrino.

Rank	Variable	Description
1	$m(jb)$	Invariant mass of the untagged jet j and the b -tagged jet b
2	$ \eta(j) $	Absolute value of the pseudorapidity of the untagged jet
3	$ \Delta p_T(W, jb) $	Absolute value of the difference in transverse momentum between the reconstructed W -boson and the dijet system
4	$ \Delta\phi(W, jb) $	Absolute value of the difference in the azimuthal angle between the reconstructed W -boson and the dijet system
5	$m(\ell\nu b)$	Invariant mass of the reconstructed top quark
6	$ \Delta\eta(\ell, j) $	Absolute value of the difference in pseudorapidity between the charged lepton ℓ and the untagged jet
7	$\Delta R(\ell, j)$	Angular distance of the charged lepton and the untagged jet, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
8	$ \Delta\eta(b, \ell) $	Absolute value of the difference in pseudorapidity between the b -tagged jet and the charged lepton
9	$m_T(W)$	Transverse mass of the W -boson
10	$m(\ell b)$	Invariant mass of the charged lepton and the b -tagged jet
11	$H_T(\ell, \text{jets}, E_T^{\text{miss}})$	Scalar sum of the transverse momenta of the charged lepton, the jets and the missing transverse momentum E_T^{miss}
12	$ \Delta\eta(b, j) $	Absolute value of the difference in the pseudorapidity of the two jets
13	$ \Delta\phi(j, \ell\nu b) $	Absolute value of the difference in the azimuthal angle between the untagged jet and the reconstructed top quark
14	$\cos\theta^*(\ell, j)$	Cosine of the angle θ^* between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark
15	$ \eta(\ell) $	Absolute value of the pseudorapidity of the charged lepton
16	S	Sphericity defined as the sum of the 2nd and 3rd largest eigenvalues of the sphericity tensor multiplied by $3/2$
17	$ \Delta p_T(\ell, j) $	Absolute value of the difference in transverse momentum of the charged lepton and the untagged jet



C.3. Pseudorapidity of the light jet

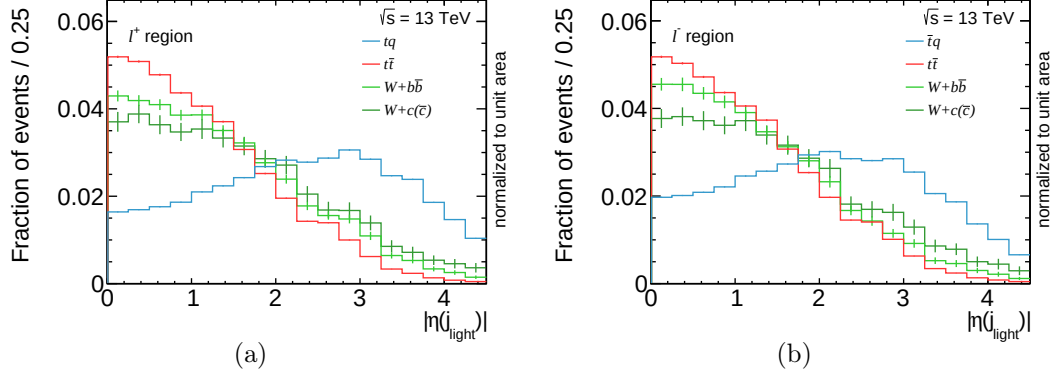


Figure C.2: Shape of the $|\eta|$ -distribution of the light jet for the signal process and the most important background processes in the (a) ℓ^+ region and (b) ℓ^- region. All event selection criteria given in Table 7.1 except for the D_{nn} requirement are applied. The distribution for tq events tends to higher values than for $\bar{t}q$ events because the u -valence quarks have a higher probability to carry a large proton momentum fraction than the d -valence quark.

C.4. Background composition for different D_{nn} requirements

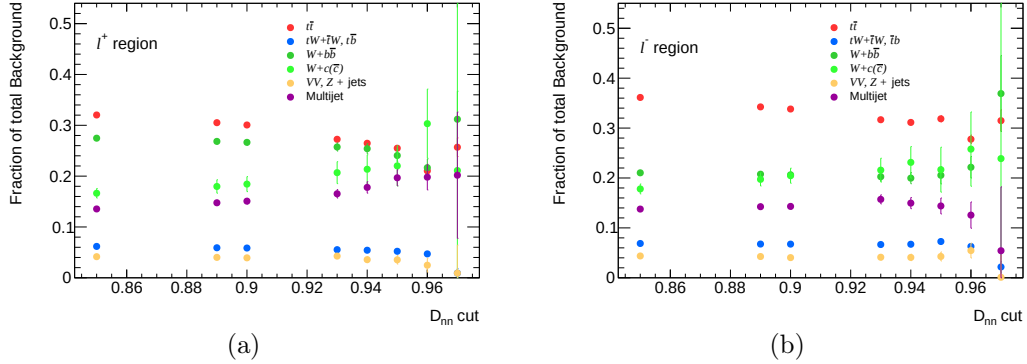


Figure C.3: Background composition in the (a) ℓ^+ region and (b) ℓ^- region as a function of the deployed D_{nn} requirement. All other event selection criteria given in Table 7.1 are applied. The scaling of the background processes described in Chapter 8 is not applied and this study was done at an early stage of the analysis using older versions of the MC samples. The shown fractions therefore differ from the final estimate used in the analysis, but the qualitative statement of this study remains valid. The composition of background events changes gradually between 0.84 and 0.95 which shows that the D_{nn} distribution provides a well-behaved background reduction criterion.



D. Unfolding corrections

The resolution of the observables in the ℓ^- SR, defined as described in Section 9.2, is shown in Appendix D.1. A study of the $p_T(t)$ and $p_T(\bar{t})$ selection efficiencies is presented in Appendix D.2.

D.1. Binning of the observables

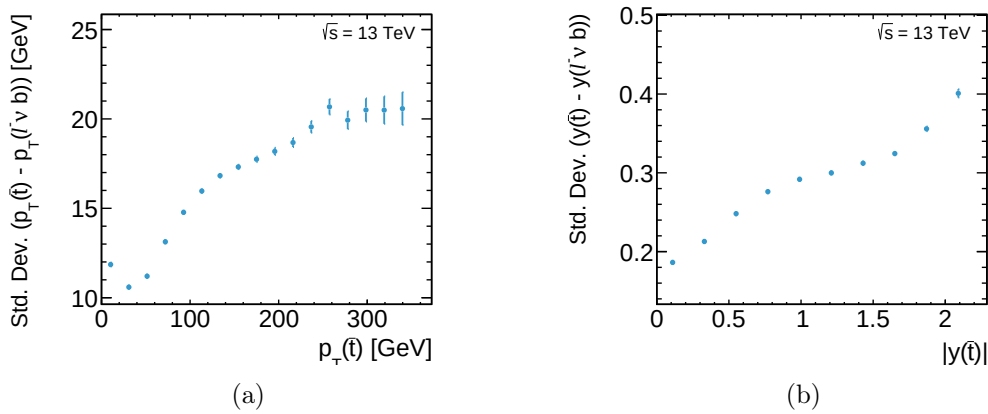


Figure D.1: Resolution of (a) $p_T(\ell^- \nu b)$ and (b) $|y(\ell^- \nu b)|$ as a function of the respective top-antiquark property at parton level. The resolution is defined as the standard deviation of the distribution of the difference between the parton-level and detector-level values.

D.2. Shape of the $p_T(t)$ and $p_T(\bar{t})$ selection efficiencies

As discussed in Section 9.3.2, the selection efficiencies of the $p_T(t)$ and $p_T(\bar{t})$ distributions decrease in the high- p_T region. From considerations about detector limitations and object reconstruction efficiencies, the opposite is expected. Therefore, the impact of individual event selection criteria on the selection efficiency is studied. The selection efficiency is calculated for a very basic event selection requiring one charged lepton. Additional selection criteria are added consecutively as described in Table D.1. The resulting selection efficiencies are presented in Figure D.2. The N^ℓ selection efficiency shows the naively expected behaviour. About one third of the events are reconstructed according to the branching ratio for leptonic W -boson decays and the efficiency increases with increasing $p_T(t)$ and $p_T(\bar{t})$. The shape of the selection efficiency is changed by the requirement of exactly two jets, as most events with a high- p_T top quark contain additional jets radiated off the top quark.

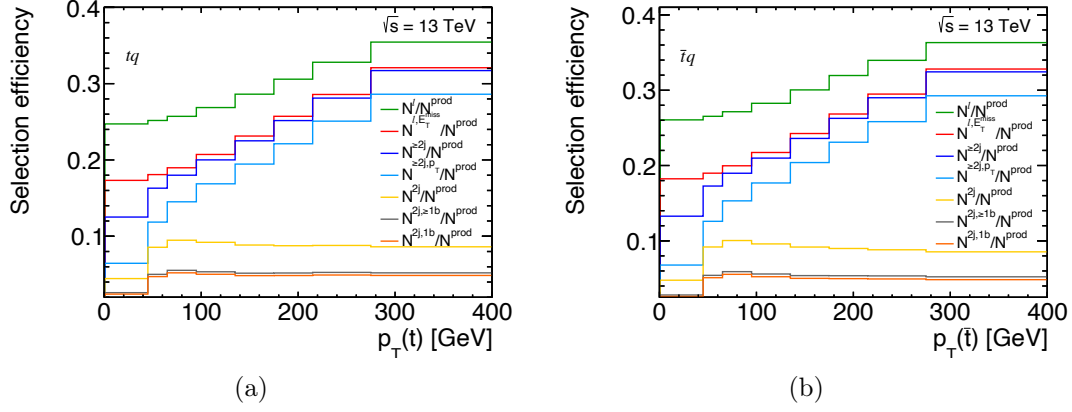


Figure D.2: Selection efficiencies for the (a) $p_T(t)$ and (b) $p_T(\bar{t})$ distributions for different subsets of the full event selection. The nominators of the legend entries specify the selection criteria added in addition to those from earlier entries as summarised in Table D.1.

Table D.1.: Event selection criteria applied in Figure D.2. For any given entry, the listed selection criteria are added to those specified in all rows above.

Legend in Figure D.2	Added selection criterion
N^ℓ	Exactly one charged lepton with $p_T(\ell) > 27$ GeV, veto events with additional leptons with $p_T(\ell) > 10$ GeV
$N^{\ell, E_T^{\text{miss}}}$	$p_T(\ell) > 28$ GeV and $ \eta < 2.5$, $E_T^{\text{miss}} > 30$ GeV
$N^{\geq 2j}$	At least two jets
$N^{\geq 2j, p_T}$	At least two jets with $p_T(j) > 30$ GeV, or $p_T(j) > 35$ GeV if $ \eta(j) > 2.3$
N^{2j}	Exactly two jets with $p_T(j) > 30$ GeV, or $p_T(j) > 35$ GeV if $ \eta(j) > 2.3$
$N^{2j, \geq 1b}$	At least one b -tag
$N^{2j, 1b}$	Exactly one b -tag



E. Unfolding validation

Results of the pull test, which is discussed in Section 9.4.2, for $|y(t)|$ and $|y(\bar{t})|$.

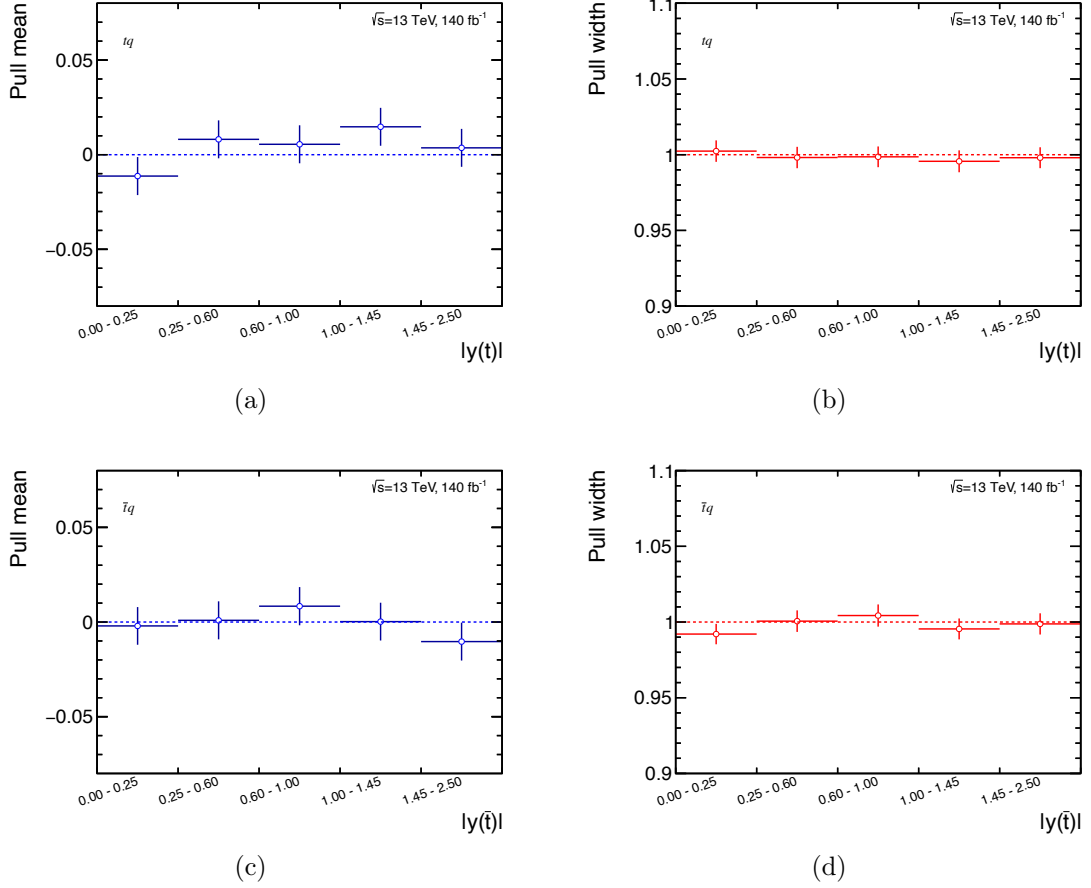


Figure E.1: Results of the pull test for (a), (b) $|y(t)|$ and (c), (d) $|y(\bar{t})|$. The dashed lines show the expected values for the pull distribution of a mean equal to zero and a width equal to one.



F. Systematic uncertainties

This appendix provides supplementary material on the uncertainties in the measurement, which are discussed in Chapter 10. A tabular overview of all considered uncertainties is given in Appendix F.1, followed by the impact of each individual uncertainty on every measured distribution in Appendix F.2. The impact of uncertainties related to the modelling of the signal process is shown graphically in Appendix F.3. In Appendix F.4, the impact of the different categories of experimental uncertainties is shown graphically. Related to the discussion in Section 10.2, the number of jets per event for different signal modelling uncertainties is presented in Appendix F.5 and the statistical uncertainties in systematic uncertainties are listed in Appendix F.6. The covariance and correlation matrices calculated as described in Section 10.3 are presented in Appendices F.7 and F.8.

F.1. Short description of all considered uncertainties

Table F.1.: All considered uncertainties are listed with a short description. Multiple terms are assigned for certain uncertainties; in these cases, the names are numbered in the range given in square brackets. *Twosided* uncertainties are evaluated from up and down variations of simulated samples and *symmetrised* uncertainties are either symmetric by construction or onesided uncertainties that were symmetrised by assigning the full up variation with opposite sign as down variation.

Name	Description	Type
Experimental uncertainties		
JER DataVsMC MC16	Uncertainty in JER applied in phase spaces where $\text{JER}(\text{Data}) < \text{JER}(\text{MC})$	1σ variation, twosided
JER Effective NP [1-12restTerm]	Orthogonal component breakdown of uncertainty in JER applied when $\text{JER}(\text{MC}) < \text{JER}(\text{Data})$	1σ variation, twosided
JES Effective NP Detector[1-2]	Detector modelling related uncertainty in the JES	1σ variation, twosided
JES Effective NP Modelling[1-4]	Uncertainty in the JES related to uncertainties in jet modelling	1σ variation, twosided
JES Effective NP Mixed[1-3]	Collection of various minor uncertainties in the JES	1σ variation, twosided
JES Effective NP Statistical[1-5]	Uncertainty in the JES due to limited statistical power	1σ variation, twosided
JES Flavor Response	Uncertainty in JES related to the response of gluon-initiated jets	1σ variation, twosided
BJES Response	Uncertainty in JES related to the response of b -jets	1σ variation, twosided
JES Flavor Composition $tq, \bar{t}q$	Uncertainty in JES related to the fraction of quark-initiated and gluon-initiated jets, evaluated separately per listed processes	1σ variation, twosided
JES Flavor Composition $t\bar{t}$		
JES Flavor Composition $tW + \bar{t}W, t\bar{b}/\bar{t}b$		
JES pileup OffsetMu	Uncertainty in JES related to the modelling of average pileup	1σ variation, twosided
JES pileup OffsetNPV	Uncertainty in JES related to the modelling of the number of primary vertices	1σ variation, twosided
JES pileup RhoTopology	Uncertainty in JES related to modelling of per-event p_T density	1σ variation, twosided
JES pileup PtTerm	Uncertainty in JES related to the residual p_T dependence of pileup	1σ variation, twosided
JES SingleParticle HighPt	Uncertainty in JES related to high- p_T jets derived from single-particle measurements	1σ variation, twosided
JES PunchThrough MC16	Uncertainty in JES related to the punch-through correction	1σ variation, twosided
JES EtaIntercalibration Modelling	Uncertainty in JES η intercalibration related to generator, pileup and event topology	1σ variation, twosided
JES EtaIntercalibration TotalStat	Statistical uncertainty in the JES η intercalibration	1σ variation, twosided
JES EtaIntercalibration NonClosure highE	Uncertainty in JES due to non-closure at high energies	1σ variation, twosided
JES EtaIntercalibration NonClosure negEta	Uncertainty in JES due to non-closure at $\eta \approx -2.4$	1σ variation, twosided
JES EtaIntercalibration NonClosure posEta	Uncertainty in JES due to non-closure at $\eta \approx 2.4$	1σ variation, twosided
JES EtaIntercalibration NonClosure 2018data	Uncertainty in JES η intercalibration due to non-closure at $\eta \approx \pm 1.5$ due to Tile Calorimeter calibration	1σ variation, twosided
MET SoftTk Scale	Uncertainty in the E_T^{miss} scale arising from the soft term	1σ variation, twosided
MET SoftTk ResoPara	Uncertainty in the E_T^{miss} soft term resolution parallel to the p_T of all reconstructed objects	1σ variation, onesided
MET SoftTk ResoPerp	Uncertainty in the E_T^{miss} soft term resolution perpendicular to the p_T of all reconstructed objects	1σ variation, onesided
JVT	Uncertainty in the JVT efficiency SF	1σ variation, twosided
fJVT	Uncertainty in the fJVT efficiency SF	1σ variation, twosided
b-tag B[0-44]	Orthogonal component breakdown of uncertainties in the tagging efficiency of b -jets	1σ variation, twosided



F. Systematic uncertainties

Name	Description	Type
b-tag C[0-19]	Orthogonal component breakdown of uncertainties in the mistagging rate of c -jets	1σ variation, twosided
b-tag Light[0-19]	Orthogonal component breakdown of uncertainties in the mistagging rate of light jets	1σ variation, twosided
EG RESOLUTION ALL	Uncertainty in the calibration of the electron energy resolution	1σ variation, twosided
EG SCALE ALL	Uncertainty in the calibration of the electron energy scale	1σ variation, twosided
EL ID	Uncertainty in the electron identification SF	1σ variation, twosided
EL Isol	Uncertainty in the electron isolation SF	1σ variation, twosided
EL Reco	Uncertainty in the electron reconstruction SF	1σ variation, twosided
EL Trigger	Uncertainty in the electron trigger SF	1σ variation, twosided
MU ID stat.	Statistical component of the uncertainty in the muon identification SF	1σ variation, twosided
MU ID syst.	Systematic component of the uncertainty in the muon identification SF	1σ variation, twosided
MU Isol stat.	Statistical component of the uncertainty in the muon isolation SF	1σ variation, twosided
MU Isol syst.	Systematic component of the uncertainty in the muon isolation SF	1σ variation, twosided
MU Trigger stat.	Statistical component of the uncertainty in the muon trigger SF	1σ variation, twosided
MU Trigger syst.	Systematic component of the uncertainty in the muon trigger SF	1σ variation, twosided
MU CB	Uncertainty in the CB track resolution	1σ variation, twosided
MU Momentum Scale	Uncertainty in the calibration of the muon momentum scale	1σ variation, twosided
MUON SAGITTA DATASTAT	Statistical uncertainty in the sagitta-bias correction due to the limited number of data events	1σ variation, twosided
MUON SAGITTA RESBIAS	Uncertainty in the muon momentum scale based on the charge-dependent sagitta bias	1σ variation, twosided
pileup	Uncertainty in the pileup reweighting SF	1σ variation, twosided
tq or $\bar{t}q$ charge miss id	Migration between signal regions due to lepton-charge misidentification	Flat factor, symmetrised
Luminosity	Uncertainty in the luminosity measurement	Flat factor, symmetrised
Signal modelling uncertainties		
tq or $\bar{t}q$ μ_R	Uncertainty in tq or $\bar{t}q$ modelling related to the choice of the renormalisation scale	Parameter variation, twosided
tq or $\bar{t}q$ μ_F	Uncertainty in tq or $\bar{t}q$ modelling related to the choice of the factorisation scale	Parameter variation, twosided
tq or $\bar{t}q$ FSR	Uncertainty in tq or $\bar{t}q$ modelling related to the α_S value for FSR modelling	Parameter variation, twosided
tq or $\bar{t}q$ ISR α_S	Uncertainty in tq or $\bar{t}q$ modelling related to the α_S value for ISR modelling	Parameter variation, twosided
tq or $\bar{t}q$ PDF	Uncertainty in the proton PDFs evaluated from eigenvectors	Hessian eigenvectors, twosided
tq or $\bar{t}q$ Parton shower	Uncertainty related to the choice of the parton-shower program	Alternative sample, symmetrised
tq or $\bar{t}q$ NLO matching	Uncertainty related to the NLO-matching procedure	Alternative sample, symmetrised
Background modelling uncertainties		
mj e shape	Uncertainty in the shape of the electron and forward-electron multijet templates, evaluated separately	Alternative sample, twosided
mj f_e shape		
mj μ shape		
$t\bar{t}$ μ_R	Uncertainty in the modelling related to the choice of the renormalisation scale, evaluated separately per listed process	Alternative sample, symmetrised
$tW + \bar{t}W, t\bar{b}/\bar{t}b$ μ_R		
$W + b\bar{b}$ μ_R		
$W + c(\bar{c})$ μ_R		
$t\bar{t}$ μ_F	Uncertainty in the modelling related to the choice of the factorisation scale, evaluated separately per listed process	Parameter variation, twosided
$tW + \bar{t}W, t\bar{b}/\bar{t}b$ μ_F		
$W + b\bar{b}$ μ_F		
$W + c(\bar{c})$ μ_F		
$t\bar{t}$ FSR	Uncertainty in the modelling related to the α_S value for FSR modelling, evaluated separately per listed process	Parameter variation, twosided
$tW + \bar{t}W, t\bar{b}/\bar{t}b$ FSR		
$t\bar{t}$ ISR α_S	Uncertainty in the modelling related to the α_S value for ISR modelling, evaluated separately per listed process	Parameter variation, twosided
$tW + \bar{t}W, t\bar{b}/\bar{t}b$ ISR α_S		
$tW + \bar{t}W$ DS	Uncertainty in the treatment of interference between tW and $t\bar{t}$ production at NLO	Alternative sample, symmetrised
$t\bar{t}$ PDF	Uncertainty in the proton PDFs evaluated from eigenvectors, evaluated separately per listed process	Hessian eigenvectors, twosided
$tW + \bar{t}W, t\bar{b}/\bar{t}b$ PDF		
$t\bar{t}$ Parton shower	Uncertainty related to the choice of the parton-shower program, evaluated separately per listed process	Alternative sample, symmetrised
$tW + \bar{t}W, t\bar{b}/\bar{t}b$ Parton shower		
$t\bar{t}$ NLO matching	Uncertainty related to the NLO-matching procedure, evaluated separately per listed process	Alternative sample, symmetrised
$tW + \bar{t}W$ NLO matching		
$t\bar{t}$ h_{damp}	Uncertainty related to the h_{damp} paramter, evaluated separately per listed process	Alternative sample, symmetrised
$tW + \bar{t}W$ h_{damp}		
Background rate uncertainties		
$t\bar{t}$ rate	Uncertainty in the rate of the respective process, evaluated separately	Flat factor, symmetrised
$tW + \bar{t}W, t\bar{b}/\bar{t}b$ rate		
$W + b\bar{b}$ rate		
$W + c(\bar{c})$ rate		
$VV, Z+\text{jets}$ rate		
mj e rate		
mj f_e rate	Statistical uncertainties	Pseudo-experiments, symmetrised
mj μ rate		
Data stat.	Statistical uncertainty in the data	Pseudo-experiments, symmetrised
MC stat.	Statistical uncertainty in the simulated samples	Pseudo-experiments, symmetrised



F.2. Impact of individual uncertainties

Table F.2.: Contribution of each individual uncertainty on the absolute differential tq cross section binned in $p_T(t)$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]															
	Bin 1		Bin 2		Bin 3		Bin 4		Bin 5		Bin 6		Bin 7		Bin 8	
	Experimental uncertainties															
JER DataVsMC MC16	-1.34 / -0.16	-1.09 / 0.78	0.03 / 0.35	0.12 / -0.28	0.48 / 0.32	-0.57 / -0.51	0.96 / 0.45	-0.94 / 0.09								
JER Effective NP 1	-0.66 / -0.87	1.05 / -1.62	1.48 / -0.6	0.74 / -1.04	1.73 / -0.63	-0.58 / -1.85	0.92 / -0.08	1.16 / -1.05								
JER Effective NP 2	1.21 / -2.8	1.76 / -2.46	1.5 / -0.73	0.33 / -0.91	0.93 / 0.55	-1.62 / -0.61	0.36 / 0.44	0.14 / 0.12								
JER Effective NP 3	-1.26 / 0.43	-1.07 / 0.68	0.08 / 0.16	-0.25 / -0.37	0.07 / 0.96	-0.47 / 0.39	1.07 / 0.82	-1.1 / 0.36								
JER Effective NP 4	-1.33 / -0.43	-0.59 / -0.13	0.0 / 1.03	-0.85 / 0.49	0.01 / 1.07	-1.5 / -0.09	-0.4 / 1.24	-0.2 / -0.32								
JER Effective NP 5	-0.23 / -1.02	-0.48 / -0.18	-0.11 / 0.4	-0.4 / 0.06	0.71 / 0.13	-0.4 / -0.45	0.34 / 1.08	-0.07 / -0.3								
JER Effective NP 6	-0.66 / -0.38	-0.76 / 0.56	-0.31 / 0.66	-0.37 / -0.05	0.75 / 0.33	-0.97 / -0.43	0.96 / -0.1	-0.14 / 0.34								
JER Effective NP 7	-0.98 / -0.99	0.29 / -0.62	0.14 / 0.75	-0.13 / -0.28	0.31 / 0.08	-0.1 / 0.7	0.52 / 0.46	-0.68 / -0.45								
JER Effective NP 8	-0.75 / -0.05	0.41 / -0.19	0.15 / -0.27	-0.03 / -0.08	0.35 / 0.35	0.09 / -0.64	0.69 / 0.57	-1.17 / -0.5								
JER Effective NP 9	-0.55 / -0.7	0.2 / 0.25	0.51 / 0.24	-0.01 / -0.5	0.22 / 0.66	-0.66 / -0.78	0.18 / 0.65	0.5 / 0.04								
JER Effective NP 10	0.4 / -0.07	0.06 / 0.1	0.17 / -0.02	-0.28 / -0.07	-0.04 / 0.44	-0.21 / 0.0	0.26 / 0.5	-0.24 / 0.72								
JER Effective NP 11	-0.67 / 0.55	0.01 / 0.17	0.2 / -0.01	0.04 / -0.35	0.18 / 0.69	-0.38 / -1.45	0.93 / -0.05	-1.25 / 0.8								
JER Effective NP 12restTerm	-0.62 / -0.56	0.09 / -0.03	0.45 / -0.13	-0.18 / 0.09	0.27 / 0.23	0.53 / -0.55	-0.09 / 0.95	0.43 / -0.99								
JES Effective NP Detector1	0.06 / 0.1	0.02 / 0.03	0.03 / 0.02	-0.1 / 0.06	-0.09 / 0.13	-0.07 / 0.09	0.04 / -0.01	-0.2 / 0.09								
JES Effective NP Detector2	-0.01 / -0.03	0.01 / -0.01	0.05 / -0.01	-0.03 / 0.03	-0.01 / -0.02	0.05 / -0.03	-0.04 / 0.08	-0.06 / 0.07								
JES Effective NP Modelling1	0.16 / 1.24	0.07 / 0.28	-0.2 / 0.21	-0.73 / 0.5	-0.82 / 0.94	-1.13 / 1.52	-0.36 / 0.28	0.11 / 0.37								
JES Effective NP Modelling2	0.09 / 0.21	0.01 / -0.02	0.02 / -0.01	-0.13 / 0.12	-0.12 / 0.19	-0.08 / 0.18	-0.22 / 0.22	-0.44 / 0.11								
JES Effective NP Modelling3	0.05 / 0.08	-0.02 / -0.02	0.01 / 0.03	0.21 / -0.24	0.3 / -0.26	0.3 / -0.25	0.3 / -0.17	-0.05 / -0.26								
JES Effective NP Modelling4	0.0 / 0.17	0.0 / 0.01	0.03 / -0.04	-0.04 / 0.02	-0.03 / 0.07	-0.06 / 0.03	-0.02 / 0.04	-0.23 / 0.15								
JES Effective NP Mixed1	0.04 / 0.05	0.09 / -0.1	0.17 / -0.11	-0.23 / 0.17	-0.59 / 0.56	-0.51 / 0.7	-0.5 / 0.41	-0.93 / 0.86								
JES Effective NP Mixed2	0.41 / 0.28	-0.02 / -0.05	-0.08 / 0.02	0.15 / -0.21	0.35 / -0.33	0.43 / -0.18	0.14 / -0.14	0.58 / -0.83								
JES Effective NP Mixed3	0.0 / 0.14	-0.01 / 0.04	0.01 / 0.0	-0.03 / 0.01	0.04 / -0.02	0.03 / -0.09	0.08 / 0.05	-0.11 / 0.02								
JES Effective NP Statistical1	0.02 / -0.01	0.0 / 0.01	0.0 / 0.0	0.0 / 0.0	0.0 / -0.03	0.02 / -0.01	0.0 / 0.04	-0.41 / 0.22								
JES Effective NP Statistical2	0.55 / 0.15	0.05 / -0.04	-0.12 / 0.04	-0.02 / 0.01	-0.05 / 0.07	-0.02 / 0.14	-0.06 / 0.25	-0.08 / -0.05								
JES Effective NP Statistical3	-0.01 / 0.01	0.0 / 0.0	0.0 / 0.0	0.0 / 0.01	0.02 / -0.01	0.07 / 0.03	0.06 / -0.18	0.29 / -0.44								
JES Effective NP Statistical4	0.03 / 0.09	0.01 / 0.0	0.06 / -0.02	-0.06 / 0.05	-0.08 / 0.11	-0.04 / 0.22	-0.27 / 0.2	-0.19 / 0.09								
JES Effective NP Statistical6	-0.01 / 0.16	0.0 / 0.03	0.08 / -0.04	0.0 / 0.02	-0.12 / 0.13	-0.09 / 0.11	0.08 / 0.01	-0.14 / 0.05								
JES Effective NP Statistical5	0.15 / 0.02	0.01 / -0.02	0.02 / 0.01	0.11 / -0.1	0.1 / -0.02	0.05 / 0.09	-0.18 / 0.04	-0.14 / 0.12								
JES Flavor Response	0.52 / 1.68	0.01 / 0.25	0.86 / -0.81	1.46 / -1.48	1.51 / -1.34	2.65 / -1.89	1.76 / -3.24	3.69 / -2.54								
BJES Response	-0.45 / 0.42	-0.03 / 0.26	-0.12 / 0.02	-0.03 / -0.11	0.17 / -0.04	0.16 / -0.06	0.36 / -0.47	0.63 / -0.39								
JES Flavor Composition tq, tq	0.95 / -0.7	0.51 / -0.29	-1.38 / 1.86	-3.89 / 4.09	-3.59 / 4.13	-3.31 / 4.1	-3.39 / 1.79	-1.11 / 2.49								
JES pileup OffsetMu	-0.78 / 1.91	-0.62 / 0.74	-0.34 / 0.76	-0.57 / 0.36	0.1 / 0.66	0.12 / 0.17	0.64 / -1.12	0.25 / -0.75								
JES pileup OffsetNPV	0.27 / 0.74	0.05 / 0.3	0.01 / -0.26	0.17 / -0.24	0.37 / -0.28	0.64 / -0.24	0.8 / -0.94	0.2 / -0.31								
JES pileup RhoTopology	-0.47 / 2.29	0.17 / 0.6	0.0 / -0.09	0.16 / 0.1	0.76 / -0.32	0.78 / -0.75	1.49 / -1.34	1.79 / -1.14								
JES pileup PtTerm	-0.24 / 0.84	-0.02 / 0.08	0.11 / 0.0	-0.32 / 0.01	-0.21 / 0.31	0.62 / 0.49	-0.59 / -0.03	0.09 / 0.59								
JES SingleParticle HighPt	0.01 / 0.01	0.0 / 0.0	-0.01 / -0.01	0.01 / 0.01	0.06 / 0.06	-0.03 / -0.03	0.15 / 0.15	-0.07 / -0.07								
JES PunchThrough MC16	-0.01 / -0.02	0.0 / 0.0	-0.01 / -0.01	0.02 / 0.02	0.05 / 0.03	-0.01 / 0.02	0.16 / 0.19	-0.08 / -0.03								
JES EtaIntercalibration Modelling	-2.83 / 4.03	-0.68 / 1.02	-0.09 / 0.12	-2.0 / 1.89	-2.85 / 2.98	-1.81 / 3.29	-2.49 / 0.46	-1.3 / 2.09								
JES EtaIntercalibration TotalStat	-0.03 / 0.42	-0.18 / 0.24	-0.03 / 0.16	-0.11 / 0.09	-0.08 / 0.1	-0.02 / 0.19	0.12 / 0.0	-0.28 / 0.05								
JES EtaIntercalibration NonClosure highE	0.0 / -0.01	0.0 / 0.0	-0.01 / 0.01	0.02 / -0.01	0.01 / 0.08	0.07 / -0.03	0.16 / 0.04	-0.12 / 0.09								
JES EtaIntercalibration NonClosure negEta	0.03 / -0.01	0.11 / -0.11	-0.03 / 0.0	-0.06 / 0.08	0.09 / -0.04	-0.12 / 0.01	0.19 / 0.15	-0.2 / -0.06								
JES EtaIntercalibration NonClosure posEta	0.0 / -0.08	0.06 / -0.01	-0.02 / -0.02	0.02 / -0.02	-0.08 / 0.1	0.09 / 0.05	-0.04 / 0.07	-0.2 / 0.1								
JES EtaIntercalibration NonClosure 2018data	0.17 / 0.31	0.11 / -0.06	0.12 / -0.16	0.15 / -0.15	0.09 / -0.14	0.07 / 0.02	0.12 / 0.04	-0.17 / 0.41								
MET SoftTrk Scale	0.49 / 0.56	0.06 / -0.3	0.22 / -0.28	0.18 / -0.16	0.41 / -0.13	0.29 / 0.09	0.53 / -0.81	0.73 / 0.2								
MET SoftTrk ResoPara	1.64 / -	-0.16 / -	0.23 / -	0.62 / -	0.16 / -	1.21 / -	0.38 / -	1.88 / -								
MET SoftTrk ResoPerp	1.12 / -	0.71 / -	0.78 / -	0.75 / -	0.87 / -	1.32 / -	0.36 / -	1.49 / -								
JVT	0.02 / 0.04	-0.02 / 0.06	-0.02 / 0.05	0.03 / 0.01	0.07 / -0.04	0.1 / -0.05	0.07 / -0.04	0.15 / -0.11								
fJVT	-1.76 / 1.76	-1.31 / 1.31	-0.78 / 0.78	-0.26 / 0.25	0.61 / -0.63	0.48 / -0.49	0.44 / -0.46	0.5 / -0.51								
b-tag B0	0.8 / -0.8	0.74 / -0.74	0.69 / -0.69	0.66 / -0.66	0.67 / -0.67	0.66 / -0.66	0.58 / -0.58	0.66 / -0.66								
b-tag B1	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.08 / -0.08	0.07 / -0.07	0.07 / -0.07	0.05 / -0.05	0.07 / -0.07								
b-tag B2	0.12 / -0.12	0.11 / -0.11	0.11 / -0.11	0.09 / -0.09	0.08 / -0.08	0.08 / -0.08	0.06 / -0.06	0.12 / -0.12								
b-tag B3	-0.05 / 0.05	-0.06 / 0.06	-0.06 / 0.06	-0.03 / 0.03	-0.01 / 0.01	-0.01 / 0.01	0.0 / 0.0	0.17 / -0.17								
b-tag B4	0.79 / -0.79	0.82 / -0.82	0.78 / -0.78	0.61 / -0.61	0.54 / -0.53	0.5 / -0.5	0.32 / -0.32	0.39 / -0.39								
b-tag B5	-1.05 / 1.05	-1.01 / 1.01	-0.97 / 0.97	-0.91 / 0.91	-0.86 / 0.86	-0.81 / 0.81	-0.8 / 0.79	-0.64 / 0.64								
b-tag B6	-0.23 / 0.23	-0.13 / 0.13	-0.1 / 0.1	-0.18 / 0.18	-0.27 / 0.27	-0.33 / 0.33	-0.37 / 0.37	-0.39 / 0.39								
b-tag B7	0.51 / -0.51	0.4 / -0.4	0.31 / -0.31	0.21 / -0.21	0.13 / -0.13	0.11 / -0.11	0.03 / -0.03	-0.09 / 0.09								
b-tag B8	0.17 / -0.17	0.14 / -0.14	0.1 / -0.1	0.02 / -0.02	-0.07 / 0.07	-0.1 / 0.1	-0.07 / 0.07	-0.03 / 0.03								
b-tag B9	0.01 / -0.01	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.0 / 0.0	-0.02 / 0.02	-0.05 / 0.05								
b-tag B10	0.01 / -0.01	0.01 / -0.01	0.01 / -0.01	0.02 / -0.02	0.03 / -0.03	0.03 / -0.03	-0.03 / 0.03	-0.14 / 0.14								
b-tag B11	0.05 / -0.05	0.04 / -0.04	0.03 / -0.03	0.05 / -0.05	0.07 / -0.07	0.03 / -0.03	-0.01 / 0.01	-0.04 / 0.04								
b-tag B12	-0.05 / 0.05	-0.04 / 0.04	-0.06 / 0.06	-0.07 / 0.07	-0.05 / 0.05	-0.03 / 0.03	-0.03 / 0.03	-0.03 / 0.03								
b-tag B13	0.09 / -0.09	0.03 / -0.03	-0.03 / 0.03	-0.05 / 0.05	-0.03 / 0.03	-0.02 / 0.02	-0.02 / 0.02	-0.01 / 0.01								
b-tag B15	0.01 / -0.01	0.03 / -0.03	0.05 / -0.05	0.06 / -0.06	0.05 / -0.05	0.02 / -0.02	-0.07 / 0.07	-0.18 / 0.18								



F. Systematic uncertainties

b-tag B16	0.01	-0.01	0.01	-0.01	0.02	-0.02	0.02	-0.02	0.0	0.0	-0.04	0.04	-0.02	0.02	0.06	-0.06
b-tag B17	-0.11	0.11	-0.1	0.1	-0.11	0.11	-0.1	0.1	-0.08	0.08	-0.05	0.05	-0.08	0.08	-0.17	0.17
b-tag B18	-0.06	0.06	-0.06	0.06	-0.07	0.07	-0.06	0.06	-0.09	0.09	-0.15	0.15	-0.19	0.19	-0.21	0.21
b-tag B21	-0.03	0.03	-0.03	0.03	-0.04	0.04	-0.06	0.06	-0.09	0.09	-0.09	0.09	-0.08	0.08	-0.09	0.09
b-tag B24	-0.04	0.04	-0.04	0.04	-0.05	0.05	-0.08	0.08	-0.11	0.11	-0.1	0.1	-0.08	0.08	-0.07	0.07
b-tag B25	0.02	-0.02	0.01	-0.01	0.01	-0.01	0.03	-0.03	0.07	-0.07	0.07	-0.07	0.06	-0.06	0.06	-0.06
b-tag B26	0.09	-0.09	0.07	-0.07	0.05	-0.05	0.03	-0.03	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.02	-0.02
b-tag B27	0.02	-0.02	0.03	-0.03	0.05	-0.05	0.06	-0.06	0.05	-0.05	0.05	-0.05	0.04	-0.04	0.03	-0.03
b-tag B28	-0.03	0.03	-0.05	0.05	-0.05	0.05	-0.04	0.04	-0.02	0.02	-0.01	0.01	0.0	0.0	-0.01	0.01
b-tag B29	-0.03	0.03	-0.05	0.05	-0.08	0.08	-0.1	0.1	-0.08	0.08	-0.07	0.07	-0.06	0.06	-0.05	0.05
b-tag B30	-0.07	0.07	-0.06	0.06	-0.05	0.05	-0.04	0.04	-0.03	0.03	-0.03	0.03	-0.02	0.02	-0.02	0.02
b-tag B32	0.05	-0.05	0.03	-0.03	0.02	-0.02	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.0	0.0
b-tag B34	-0.06	0.06	-0.05	0.05	-0.05	0.05	-0.03	0.03	-0.02	0.02	-0.02	0.02	-0.02	0.02	-0.01	0.01
b-tag B35	-0.14	0.14	-0.11	0.11	-0.08	0.08	-0.06	0.06	-0.05	0.05	-0.05	0.05	-0.04	0.04	-0.03	0.03
b-tag B36	0.11	-0.11	0.1	-0.1	0.08	-0.08	0.06	-0.06	0.04	-0.04	0.04	-0.04	0.03	-0.03	0.02	-0.02
b-tag B37	0.04	-0.04	0.07	-0.07	0.09	-0.09	0.08	-0.08	0.05	-0.05	0.03	-0.03	0.02	-0.02	0.01	-0.01
b-tag B39	-0.01	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.01	-0.02	0.02	-0.02	0.02	-0.03	0.03	-0.05	0.05
b-tag C0	0.87	-0.87	0.37	-0.37	0.11	-0.11	0.11	-0.11	0.11	-0.11	0.12	-0.12	0.16	-0.16	0.18	-0.17
b-tag C1	-0.56	0.56	-0.24	0.24	-0.07	0.07	-0.07	0.07	-0.06	0.06	-0.03	0.03	-0.03	0.03	0.01	-0.01
b-tag C2	-0.36	0.36	-0.16	0.16	-0.05	0.05	-0.04	0.04	-0.04	0.04	-0.02	0.02	-0.02	0.02	0.0	0.0
b-tag C3	-0.66	0.66	-0.29	0.29	-0.09	0.09	-0.08	0.08	-0.08	0.08	-0.06	0.06	-0.06	0.06	-0.01	0.01
b-tag C4	-0.34	0.34	-0.15	0.15	-0.05	0.05	-0.05	0.05	-0.04	0.04	-0.03	0.03	-0.03	0.03	-0.02	0.02
b-tag C5	-0.36	0.36	-0.14	0.14	-0.04	0.04	-0.08	0.08	-0.07	0.07	-0.07	0.07	-0.05	0.05	-0.01	0.01
b-tag C6	-0.11	0.11	-0.02	0.02	0.03	-0.03	0.02	-0.02	0.03	-0.03	0.01	-0.01	0.02	-0.02	-0.01	0.01
b-tag C7	0.36	-0.36	0.13	-0.13	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.01	0.0	-0.01	0.01	0.0	0.0
b-tag Light0	0.14	-0.14	0.11	-0.11	0.11	-0.11	0.12	-0.12	0.17	-0.17	0.26	-0.26	0.35	-0.35	0.62	-0.62
b-tag Light2	-0.04	0.04	-0.03	0.03	-0.03	0.03	-0.03	0.03	-0.04	0.04	-0.05	0.05	-0.08	0.08	-0.13	0.13
b-tag Light4	-0.01	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.01	-0.02	0.02	-0.02	0.02	-0.03	0.03	-0.06	0.06
b-tag Light6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.01	0.01	-0.02	0.02	-0.05	0.05
b-tag Light16	-0.02	0.02	-0.02	0.02	-0.02	0.02	-0.02	0.02	-0.02	0.02	-0.03	0.03	-0.04	0.04	-0.05	0.05
EG RESOLUTION ALL	0.62	-0.15	0.01	-0.04	-0.1	0.1	-0.02	0.1	-0.1	0.1	0.07	-0.12	0.18	0.04	0.14	-0.05
EG SCALE ALL	0.35	-0.15	-0.06	-0.02	-0.13	0.02	0.03	-0.03	-0.03	-0.04	0.08	0.1	-0.09	0.16	-0.02	-0.07
EL ID	-0.13	0.13	-0.13	0.13	-0.12	0.12	-0.13	0.13	-0.13	0.13	-0.14	0.14	-0.15	0.15	-0.16	0.16
EL Iscl	-0.94	0.94	-0.84	0.84	-0.78	0.78	-0.76	0.76	-0.78	0.78	-0.83	0.83	-0.82	0.82	-0.84	0.84
EL Reco	-0.23	0.23	-0.19	0.19	-0.16	0.16	-0.16	0.16	-0.17	0.17	-0.17	0.17	-0.16	0.16	-0.14	0.14
EL Trigger	-0.1	0.1	-0.09	0.09	-0.09	0.09	-0.09	0.09	-0.09	0.09	-0.08	0.08	-0.08	0.08	-0.08	0.08
MU ID syst.	-0.09	0.09	-0.08	0.08	-0.07	0.07	-0.07	0.07	-0.08	0.08	-0.08	0.08	-0.09	0.09	-0.11	0.11
MU Iscl stat.	-0.03	0.03	-0.02	0.02	-0.02	0.02	-0.03	0.03	-0.04	0.04	-0.05	0.05	-0.06	0.06	-0.08	0.08
MU Iscl syst.	-0.52	0.52	-0.47	0.47	-0.45	0.45	-0.45	0.45	-0.4	0.4	-0.32	0.32	-0.28	0.28	-0.25	0.25
MU Trigger stat.	-0.19	0.2	-0.17	0.17	-0.16	0.16	-0.16	0.16	-0.15	0.15	-0.15	0.15	-0.15	0.15	-0.15	0.15
MU Trigger syst.	0.42	-0.43	0.36	-0.37	0.33	-0.34	0.34	-0.34	0.33	-0.34	0.31	-0.32	0.32	-0.33	0.32	-0.33
MU CB	0.15	-0.16	-0.01	-0.02	-0.03	0.02	0.09	-0.04	0.08	0.05	0.03	-0.15	0.28	0.03	-0.03	0.04
MU Momentum Scale	0.13	0.13	0.02	-0.04	-0.05	-0.06	0.03	0.02	0.13	0.05	-0.04	0.01	0.11	0.13	-0.1	-0.13
MUON SAGITTA DATASAT	0.13	0.03	0.0	0.02	-0.04	-0.02	0.02	0.01	0.07	0.09	-0.02	-0.04	0.11	0.1	-0.15	-0.06
MUON SAGITTA RESBIAS	0.17	0.1	0.0	-0.04	-0.03	-0.04	0.01	0.01	0.05	0.08	-0.07	-0.01	0.18	0.03	0.02	0.07
pileup	1.45	-1.38	1.33	-1.23	1.46	-1.29	1.41	-1.27	1.25	-1.18	1.06	-1.07	1.12	-1.11	1.3	-1.3
Modelling uncertainties																
$t\bar{t}$ μ_R	-1.57	1.19	-1.47	1.2	-1.3	1.15	-0.77	0.79	0.79	0.01	1.38	-0.55	2.4	-1.49	5.53	-3.16
$t\bar{t}$ μ_F	-0.79	0.59	-0.74	0.51	-1.04	0.72	-1.21	0.72	-0.63	0.32	-0.41	-0.13	-0.28	-0.7	1.31	-1.79
$t\bar{t}$ FSR	-2.17	3.0	-1.91	2.56	-2.11	3.08	-2.34	3.73	-2.81	4.85	-1.78	2.21	-2.56	3.66	-2.4	0.27
$t\bar{t}$ ISR α_S	0.19	-0.14	0.33	-0.25	0.47	-0.35	0.51	-0.5	0.72	-0.52	0.89	-0.89	0.49	-0.99	0.27	-0.74
$t\bar{t}$ PDF	-0.12	0.18	-0.34	0.39	-0.5	0.56	-0.48	0.42	-0.26	0.37	-0.38	0.23	-0.44	-0.16	-0.19	-0.28
$t\bar{t}$ Parton shower	-3.82	(3.82)	-4.45	(4.45)	-1.9	(1.9)	-0.53	(0.53)	-0.66	(0.66)	-3.08	(3.08)	-4.27	(4.27)	-5.07	(5.07)
$t\bar{t}$ NLO matching	-1.12	(1.12)	-3.09	(3.09)	-4.29	(4.29)	-4.68	(4.68)	-4.86	(4.86)	-5.57	(5.57)	-11.03	(11.03)	-14.94	(14.94)
JES Flavor Composition $t\bar{t}$	0.19	-0.15	0.19	-0.2	0.09	-0.21	0.13	-0.17	0.07	-0.15	0.17	0.0	0.36	0.14	0.45	-0.5
JES Flavor Composition $tW + t\bar{W}, t\bar{t}b$	0.01	0.04	0.01	-0.04	0.03	-0.01	-0.03	-0.03	0.02	0.01	0.02	0.02	0.15	-0.04	0.03	0.0
m_j e shape	0.86	-0.66	0.79	0.04	0.83	0.28	0.25	-0.13	0.25	0.13	-0.03	0.02	-0.03	-0.02	0.01	0.0
m_j e shape	0.2	-0.03	-0.03	0.09	0.1	0.07	0.04	0.02	-0.02	-0.01	0.0	0.0	0.0	0.0	0.0	0.0
m_j μ shape	0.25	-0.25	-0.04	0.04	-0.18	0.18	-0.14	0.14	0.46	-0.46	-0.29	0.29	-0.13	0.13	-0.65	0.65
$t\bar{t}$ μ_R	-0.06	0.05	-0.03	0.02	-0.04	0.03	-0.02	0.01	-0.02	0.02	-0.07	0.05	-0.11	0.07	0.14	-0.12
$t\bar{t}$ μ_F	0.0	0.0	-0.02	0.02	-0.04	0.03	-0.06	0.06	-0.11	0.1	-0.08	0.07	-0.06	0.06	-0.14	0.12
$t\bar{t}$ FSR	-0.05	0.09	0.03	-0.24	-0.04	-0.12	-0.06	-0.03	-0.11	-0.24	0.38	-1.07	0.07	-0.41	0.2	1.18
$t\bar{t}$ ISR α_S	0.09	-0.08	0.05	-0.04	0.03	-0.03	0.07	-0.06	0.09	-0.08	0.07	-0.09	0.09	-0.05	0.14	-0.12
$tW + t\bar{W}$ DS	-0.14	(0.14)	-0.04	(0.04)	0.01	(-0.01)	0.03	(-0.03)	0.01	(-0.01)	-0.11	(0.11)	-0.06	(0.06)	0.11	(-0.11)
$tW + t\bar{W}, t\bar{t}b$ FSR	0.02	0.03	-0.01	0.04	-0.04	0.08	0.01	-0.05	0.04	-0.07	0.07	-0.05	0.08	-0.14	-0.09	0.13
$tW + t\bar{W}, t\bar{t}b$ ISR α_S	0.03	-0.02	0.0	0.0	0.01	-0.02	0.0	0.0	0.02	-0.04	0.05	-0.07	-0.05	-0.01	0.01	0.01
$W + b\bar{b}$ μ_F	0.91	-0.91	0.25	-0.25	-0.56	0.56	-0.05	0.05	0.01	-0.01	0.0	0.0	-0.18	0.18	-0.01	0.01
$W + b\bar{b}$ μ_R	0.0	-0.63	0.06	-0.28	0.07	-0.15	0.06	-0.09	0.02	-0.08	0.1	-0.14	0.03	0.02	-0.03	-0.12
$W + c(\bar{c})$ μ_F	-0.37	0.22	0.09	0.15	-0.63	-0.09	-0.03	-0.12	0.06	-0.3	-0.21	0.11	-0.01	-0.14	-0.09	0.1
$W + c(\bar{c})$ μ_R	0.36	-1.29	0.26	-0.33	0.2	-0.05	0.14	-0.39	0.19	0.1	-0.1	-0.48	0.18	-0.1	0.03	-0.11
$t\bar{t}, tW + t\bar{W}, t\bar{t}b$ PDF	-0.05	0.05	-0.07	0.07	-0.11	0.11	-0.13	0.13	-0.14	0.14	-0.13	0.13	-0.16	0.16	-0.32	0.32
$tW + t\bar{W}, t\bar{t}b$ Parton shower	0.05	(-0.05)	0.01	(-0.01)	0.02	(-0.02)	0.09	(-0.09)	0.07	(-0.07)	-0.49	(0.49)	0.05	(-0.05)	0.15	(-0.15)
$t\bar{t}$ Parton shower	0.13	(-0.13)	0.25	(-0.25)	-0.11	(0.11)	0.3	(-0.3)	0.74	(-0.74)	0.23	(-0.23)	-1.68	(1.68)	-0.1	(0.1)
$t\bar{t}$ NLO matching	0.33	(-0.33)	0.02	(-0.02)	-0.01	(0.01)	0.36	(-0.36)	0.12	(-0.12)	0.0	(0.0)	-1.57	(1.57)	-1.14	(1.14)
$tW + t\bar{W}$ NLO matching	0.0	(0.0)	0.04	(-0.04)	0.04	(-0.04)	0.02	(-0.02)	0.06	(-0.06)	-0.2	(0.2)	0.11	(-0.11)	0.34	(-0.34)
$t\bar{t}$ b_{damp}	0.49	(-0.49)	0.01	(-0.01)	0.02	(-0.02)	0.28	(-0.28)	0.07	(-0.07)	-0.7					



Table F.3.: Contribution of each individual uncertainty on the absolute differential $\bar{t}q$ cross section binned in $p_T(\bar{t})$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]															
	Bin 1		Bin 2		Bin 3		Bin 4		Bin 5		Bin 6		Bin 7		Bin 8	
Experimental uncertainties																
JER DataVsMC MC16	0.97 / -0.04	0.58 / -0.06	-0.93 / 0.72	-0.13 / -0.16	-0.12 / -0.45	0.1 / 0.88	0.9 / -0.11	-0.19 / 1.33								
JER Effective NP 1	-2.47 / 3.93	-0.14 / 0.24	1.47 / -1.41	0.39 / -1.17	0.78 / -1.63	-0.57 / -0.35	1.57 / 0.31	0.66 / -3.28								
JER Effective NP 2	1.43 / 1.45	0.33 / -1.08	1.52 / -2.56	0.54 / -0.78	-0.65 / 1.73	-2.4 / 1.67	1.38 / -0.04	-0.77 / -0.59								
JER Effective NP 3	2.25 / -0.11	0.69 / 0.32	-1.39 / 1.5	-0.67 / -0.09	-0.56 / -0.29	0.97 / 0.26	-1.9 / 1.23	-1.62 / -0.29								
JER Effective NP 4	0.63 / 2.38	-0.4 / 0.01	-0.21 / 0.17	-1.2 / 0.23	-0.55 / 0.4	-1.68 / 1.29	1.66 / 0.43	-2.6 / 0.75								
JER Effective NP 5	2.3 / -1.09	-0.18 / 0.67	-0.76 / 1.19	-0.37 / -0.08	-0.3 / -0.68	1.69 / -1.23	-0.42 / 0.6	-0.26 / -1.39								
JER Effective NP 6	-0.63 / 3.32	0.34 / -0.11	0.7 / 0.62	-0.69 / 0.19	-0.53 / 0.02	1.53 / -1.79	-0.01 / 0.11	-0.49 / -0.57								
JER Effective NP 7	1.46 / 0.75	0.07 / 0.23	-0.68 / 0.01	0.61 / -1.04	0.04 / 0.26	-0.13 / 0.72	0.56 / 0.34	-1.5 / -0.7								
JER Effective NP 8	-1.06 / 0.76	0.31 / 0.61	0.24 / -0.56	-0.57 / 0.07	-0.66 / 0.28	0.97 / 0.22	0.02 / 0.35	-1.09 / 0.21								
JER Effective NP 9	1.14 / 0.3	-0.04 / 0.12	0.3 / 0.26	0.14 / -0.85	0.33 / -0.04	-0.86 / 1.42	0.36 / -1.0	0.29 / -0.53								
JER Effective NP 10	1.15 / 0.08	-0.26 / 0.65	-0.47 / -0.45	-0.22 / -0.28	0.51 / -0.31	-0.34 / -0.22	-0.54 / 0.53	0.53 / -1.06								
JER Effective NP 11	-0.51 / 1.0	0.01 / 0.11	0.63 / -0.61	-0.54 / 0.03	-0.53 / 0.73	0.64 / -0.65	0.03 / -0.7	-0.53 / -1.32								
JER Effective NP 12restTerm	1.25 / 0.2	0.41 / 0.38	0.11 / -0.65	-0.11 / -0.47	0.27 / -0.12	-0.7 / 1.35	0.47 / -1.27	-0.45 / -1.58								
JES Effective NP Detector1	0.07 / 0.03	0.01 / 0.02	-0.36 / 0.05	-0.14 / 0.09	0.03 / 0.18	-0.22 / -0.07	-0.1 / 0.26	0.03 / -0.12								
JES Effective NP Detector2	0.0 / 0.08	0.02 / 0.0	0.0 / -0.01	-0.05 / 0.0	0.07 / 0.05	-0.08 / -0.05	0.0 / 0.14	-0.1 / -0.03								
JES Effective NP Modelling1	-0.63 / 1.25	-0.34 / 0.14	0.12 / -0.27	-0.34 / 1.34	-1.2 / 1.4	-1.37 / 0.4	0.06 / 1.14	0.37 / 0.09								
JES Effective NP Modelling2	0.04 / -0.03	-0.03 / -0.02	-0.36 / 0.07	-0.13 / 0.05	-0.11 / 0.33	-0.29 / -0.05	0.07 / 0.37	-0.76 / 0.25								
JES Effective NP Modelling3	0.12 / 0.14	0.01 / -0.02	0.1 / -0.4	0.19 / -0.22	0.4 / -0.25	0.22 / -0.35	0.4 / -0.07	-0.05 / -0.53								
JES Effective NP Modelling4	0.05 / 0.15	0.04 / 0.04	0.01 / -0.01	-0.11 / -0.07	0.06 / 0.19	-0.11 / -0.09	-0.28 / 0.01	-0.48 / -0.36								
JES Effective NP Mixed1	0.23 / 0.14	0.18 / 0.0	-0.29 / -0.12	-0.3 / 0.14	-0.36 / 0.86	-0.65 / 0.08	-0.52 / 0.93	-1.38 / 0.54								
JES Effective NP Mixed2	0.21 / -0.25	0.08 / 0.1	-0.04 / -0.29	0.15 / -0.24	0.6 / -0.18	-0.09 / -0.34	0.57 / -0.34	0.01 / -0.52								
JES Effective NP Mixed3	-0.03 / 0.14	-0.02 / 0.1	-0.38 / 0.04	-0.06 / -0.01	0.14 / 0.0	-0.07 / -0.04	0.08 / 0.12	0.01 / -0.06								
JES Effective NP Statistical1	-0.01 / 0.13	-0.01 / 0.0	0.0 / -0.01	0.0 / -0.02	0.04 / 0.08	-0.04 / -0.01	-0.03 / 0.1	-0.19 / 0.12								
JES Effective NP Statistical2	0.22 / -0.31	0.02 / 0.05	0.11 / -0.27	0.02 / -0.08	-0.09 / 0.16	-0.07 / -0.1	-0.15 / 0.27	-0.03 / 0.5								
JES Effective NP Statistical3	0.0 / 0.02	-0.02 / -0.01	0.0 / 0.0	-0.03 / -0.01	0.14 / 0.04	-0.13 / -0.1	0.2 / 0.04	0.34 / -0.58								
JES Effective NP Statistical4	0.15 / 0.1	0.03 / 0.0	-0.36 / -0.01	-0.05 / 0.01	-0.06 / 0.33	-0.16 / 0.04	-0.04 / 0.38	-0.35 / -0.14								
JES Effective NP Statistical6	-0.02 / 0.14	0.0 / 0.02	0.02 / -0.06	-0.04 / -0.02	-0.07 / 0.23	-0.04 / 0.15	-0.18 / -0.01	0.06 / -0.02								
JES Effective NP Statistical5	0.19 / 0.22	0.04 / 0.0	0.07 / -0.42	0.08 / -0.13	0.13 / 0.09	-0.02 / 0.09	-0.23 / 0.19	0.04 / 0.12								
JES Flavor Response	0.25 / -0.33	0.18 / 0.25	1.61 / -0.44	1.5 / -1.66	2.54 / -2.16	2.83 / -2.06	3.26 / -2.82	4.32 / -2.0								
BJES Response	-0.23 / 0.25	-0.36 / 0.24	-0.53 / 0.26	0.13 / 0.11	0.66 / 0.15	-0.22 / -0.58	0.2 / -0.33	0.72 / -0.55								
JES Flavor Composition $tq, \bar{t}q$	0.0 / 0.51	-0.3 / 0.69	-2.02 / 2.76	-4.04 / 4.04	-4.03 / 4.12	-3.73 / 4.27	-2.74 / 3.26	-1.44 / 2.5								
JES pileup OffsetMu	-5.72 / 2.98	0.02 / 1.18	-0.35 / 0.26	-0.62 / 1.23	-0.06 / 0.15	0.3 / -0.53	0.39 / -0.54	0.22 / -0.04								
JES pileup OffsetNPV	-0.74 / 0.83	0.0 / 0.26	0.18 / -0.61	0.17 / 0.43	0.04 / -0.37	0.42 / -0.71	1.15 / -0.59	1.48 / -0.33								
JES pileup RhoTopology	-1.78 / 1.77	-0.58 / 0.31	0.41 / 0.04	0.27 / 0.16	0.26 / -0.11	0.82 / -1.12	2.62 / -1.75	2.51 / -1.98								
JES pileup PtTerm	-0.12 / 0.34	-0.13 / 0.3	-0.36 / 0.24	0.11 / -0.2	-0.47 / 0.6	-0.49 / -0.3	-0.95 / 0.58	-0.21 / -0.33								
JES SingleParticle HighPt	0.08 / 0.08	0.01 / 0.01	0.02 / 0.02	-0.04 / -0.04	-0.06 / -0.06	0.03 / 0.03	-0.1 / -0.1	-0.38 / -0.38								
JES PunchThrough MC16	0.05 / 0.05	-0.02 / -0.02	-0.01 / -0.01	-0.01 / -0.01	-0.01 / -0.02	0.04 / 0.07	-0.13 / -0.1	0.02 / 0.0								
JES EtaIntercalibration Modelling	-5.29 / 4.33	-1.68 / 1.37	0.51 / 0.39	-1.24 / 1.63	-3.46 / 3.51	-2.37 / 1.9	-1.22 / 2.39	-1.11 / 2.44								
JES EtaIntercalibration TotalStat	-0.92 / 0.61	-0.19 / 0.28	0.15 / -0.34	-0.21 / 0.75	-0.13 / 0.2	-0.14 / 0.0	0.62 / -0.13	0.47 / -0.12								
JES EtaIntercalibration NonClosure highE	0.02 / 0.02	-0.03 / -0.02	0.01 / 0.02	0.0 / -0.02	-0.02 / 0.01	0.05 / 0.08	0.01 / -0.06	0.39 / 0.13								
JES EtaIntercalibration NonClosure negEta	0.22 / 0.01	0.11 / -0.17	-0.46 / 0.1	-0.03 / 0.13	0.2 / -0.16	0.03 / 0.16	-0.31 / 0.25	0.25 / -0.33								
JES EtaIntercalibration NonClosure posEta	0.04 / 0.03	0.03 / -0.11	0.05 / -0.03	0.04 / -0.04	-0.15 / -0.01	-0.03 / 0.2	0.18 / -0.21	-0.17 / 0.35								
JES EtaIntercalibration NonClosure 2018data	0.16 / -0.18	0.21 / 0.03	0.17 / -0.1	0.15 / -0.21	0.28 / -0.1	-0.09 / -0.12	0.23 / 0.17	0.57 / 0.35								
MET SoftTrk Scale	0.11 / 0.56	0.21 / -0.11	0.35 / -0.68	0.44 / -0.25	0.79 / -0.61	-0.25 / 0.18	-0.64 / -0.18	0.65 / -1.63								
MET SoftTrk ResoPara	1.42 / -	0.91 / -	0.33 / -	0.29 / -	2.45 / -	1.04 / -	-0.98 / -	0.42 / -								
MET SoftTrk ResoPerp	0.98 / -	1.23 / -	1.06 / -	0.73 / -	1.31 / -	0.94 / -	0.11 / -	1.43 / -								
JVT	0.12 / -0.02	0.02 / 0.04	0.04 / 0.01	0.05 / -0.01	0.12 / -0.07	0.18 / -0.13	0.12 / -0.09	0.22 / -0.17								
IJVT	-1.58 / 1.59	-1.29 / 1.29	-0.62 / 0.61	-0.22 / 0.21	0.72 / -0.75	0.61 / -0.63	0.48 / -0.5	0.68 / -0.69								
b-tag B0	0.84 / -0.84	0.78 / -0.78	0.72 / -0.72	0.7 / -0.7	0.7 / -0.7	0.69 / -0.69	0.63 / -0.63	0.56 / -0.56								
b-tag B1	0.1 / -0.1	0.1 / -0.1	0.09 / -0.09	0.08 / -0.08	0.07 / -0.07	0.07 / -0.07	0.06 / -0.06	0.06 / -0.06								
b-tag B2	0.13 / -0.13	0.12 / -0.12	0.11 / -0.11	0.1 / -0.1	0.08 / -0.08	0.08 / -0.08	0.07 / -0.07	0.1 / -0.1								
b-tag B3	-0.06 / 0.06	-0.07 / 0.07	-0.06 / 0.06	-0.04 / 0.04	-0.01 / 0.01	0.0 / 0.0	-0.02 / 0.02	0.11 / -0.11								
b-tag B4	0.85 / -0.85	0.86 / -0.85	0.79 / -0.79	0.67 / -0.67	0.54 / -0.54	0.47 / -0.47	0.44 / -0.44	0.38 / -0.39								
b-tag B5	-1.09 / 1.09	-1.07 / 1.07	-1.02 / 1.01	-0.95 / 0.95	-0.91 / 0.91	-0.85 / 0.85	-0.82 / 0.82	-0.75 / 0.75								
b-tag B6	-0.24 / 0.24	-0.14 / 0.14	-0.12 / 0.12	-0.19 / 0.19	-0.29 / 0.29	-0.35 / 0.35	-0.43 / 0.43	-0.44 / 0.44								
b-tag B7	0.53 / -0.53	0.43 / -0.43	0.33 / -0.33	0.22 / -0.22	0.13 / -0.13	0.13 / -0.13	0.04 / -0.04	-0.1 / 0.1								
b-tag B8	0.17 / -0.17	0.15 / -0.15	0.11 / -0.11	0.03 / -0.03	-0.08 / 0.08	-0.11 / 0.11	-0.09 / 0.09	-0.03 / 0.03								
b-tag B9	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.01 / -0.01	-0.02 / 0.02	-0.05 / 0.05								
b-tag B10	0.01 / -0.01	0.01 / -0.01	0.01 / -0.01	0.02 / -0.02	0.03 / -0.03	0.04 / -0.04	-0.02 / 0.02	-0.17 / 0.17								
b-tag B11	0.06 / -0.06	0.04 / -0.04	0.03 / -0.03	0.05 / -0.05	0.09 / -0.09	0.03 / -0.03	-0.01 / 0.01	-0.03 / 0.03								
b-tag B12	-0.05 / 0.05	-0.04 / 0.04	-0.06 / 0.06	-0.08 / 0.08	-0.06 / 0.06	-0.04 / 0.04	-0.03 / 0.03	-0.03 / 0.03								
b-tag B13	0.1 / -0.1	0.03 / -0.03	-0.03 / 0.03	-0.05 / 0.05	-0.04 / 0.04	-0.02 / 0.02	-0.01 / 0.01	-0.01 / 0.01								
b-tag B14	0.04 / -0.04	0.02 / -0.02	0.01 / -0.01	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.0 / 0.0	-0.01 / 0.01								
b-tag B15	0.01 / -0.01	0.03 / -0.03	0.05 / -0.05	0.06 / -0.06	0.05 / -0.05	0.03 / -0.03	-0.08 / 0.08	-0.21 / 0.21								
b-tag B16	0.01 / -0.01	0.01 / -0.01	0.02 / -0.02	0.03 / -0.03	0.01 / -0.01	-0.04 / 0.04	-0.03 / 0.03	0.07 / -0.07								
b-tag B17	-0.11 / 0.11	-0.11 / 0.11	-0.11 / 0.11	-0.11 / 0.11	-0.09 / 0.09	-0.05 / 0.05	-0.07 / 0.07	-0.2 / 0.2								
b-tag B18	-0.06 / 0.06	-0.07 / 0.07	-0.07 / 0.07	-0.07 / 0.07	-0.08 / 0.08	-0.16 / 0.16	-0.21 / 0.21	-0.22 / 0.22								

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Table F.4.: Contribution of each individual uncertainty on the absolute differential tq cross section binned in $|y(t)|$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]									
	Bin 1		Bin 2		Bin 3		Bin 4		Bin 5	
	Experimental uncertainties									
JER DataVsMC MC16	-0.4 / 0.02	0.54 / 0.42	-0.78 / -0.06	-0.4 / 0.07	-2.73 / 1.42					
JER Effective NP 1	0.22 / -1.32	1.78 / -0.31	1.13 / -1.11	-0.54 / -1.0	1.32 / -2.12					
JER Effective NP 2	0.57 / -1.54	1.59 / -1.36	1.53 / -1.09	-0.02 / -0.84	2.76 / -3.75					
JER Effective NP 3	-0.31 / -0.3	-0.22 / 1.0	-0.73 / 0.14	-0.34 / -0.75	-1.6 / 2.24					
JER Effective NP 4	-0.48 / -0.15	-0.48 / 1.5	-1.18 / 0.14	0.5 / -0.08	-1.45 / -0.42					
JER Effective NP 5	-0.53 / -0.2	0.55 / 0.32	-0.39 / -0.08	-0.77 / -0.27	-0.32 / -0.65					
JER Effective NP 6	-0.22 / -0.6	-0.07 / 1.33	-0.76 / 0.19	-1.03 / 0.05	0.03 / -0.13					
JER Effective NP 7	-0.85 / 0.36	0.53 / 0.22	-0.18 / -0.43	0.06 / -0.45	0.13 / -0.82					
JER Effective NP 8	-0.02 / 0.32	0.19 / 0.13	0.31 / -0.64	-0.35 / -0.69	-0.17 / 0.4					
JER Effective NP 9	-0.04 / -0.14	0.51 / 0.45	0.05 / -0.02	-0.58 / -0.44	0.74 / -0.42					
JER Effective NP 10	0.09 / -0.01	0.2 / 0.12	-0.24 / 0.4	-0.22 / -0.24	1.15 / -0.57					
JER Effective NP 11	-0.55 / 0.18	0.37 / 0.14	0.56 / -0.25	-0.54 / -0.27	-0.71 / 1.3					
JER Effective NP 12restTerm	-0.03 / 0.0	0.43 / -0.1	-0.36 / 0.05	-0.37 / -0.13	0.97 / -0.9					
JES Effective NP Detector1	0.07 / 0.0	-0.06 / 0.01	-0.04 / 0.0	0.05 / 0.17	0.03 / 0.14					
JES Effective NP Detector2	0.07 / -0.01	-0.01 / -0.01	0.0 / 0.01	0.01 / -0.01	-0.01 / -0.02					
JES Effective NP Modelling1	-0.15 / 0.41	-0.27 / 0.45	-0.13 / 0.29	-0.18 / 0.44	-0.44 / 1.79					
JES Effective NP Modelling2	0.03 / 0.06	-0.04 / -0.02	-0.07 / 0.11	-0.02 / 0.18	0.12 / 0.0					
JES Effective NP Modelling3	0.02 / 0.03	0.03 / -0.08	0.07 / -0.08	0.2 / -0.05	0.02 / -0.02					
JES Effective NP Modelling4	0.03 / -0.02	-0.03 / -0.02	-0.02 / 0.01	0.02 / 0.14	0.01 / 0.1					
JES Effective NP Mixed1	0.07 / -0.09	-0.04 / 0.01	-0.05 / 0.05	-0.08 / 0.18	0.02 / 0.13					
JES Effective NP Mixed2	-0.07 / 0.06	0.07 / -0.09	0.02 / -0.07	0.11 / 0.01	0.73 / -0.02					
JES Effective NP Mixed3	0.06 / 0.0	-0.02 / 0.0	-0.02 / 0.0	0.0 / 0.13	0.0 / 0.14					
JES Effective NP Statistical2	-0.05 / 0.09	0.07 / -0.06	-0.02 / 0.09	-0.01 / 0.06	0.65 / 0.01					
JES Effective NP Statistical4	0.05 / 0.0	-0.02 / -0.02	-0.02 / 0.04	0.03 / 0.17	0.03 / -0.01					
JES Effective NP Statistical6	0.07 / -0.01	-0.02 / -0.01	0.01 / 0.02	0.0 / 0.15	0.04 / 0.11					
JES Effective NP Statistical5	0.01 / 0.04	0.01 / -0.05	0.04 / -0.03	0.15 / 0.01	0.13 / 0.01					
JES Flavor Response	0.57 / -0.29	0.59 / -0.23	0.54 / -0.27	0.9 / -0.6	2.22 / -0.23					
BJES Response	0.05 / 0.11	-0.15 / 0.17	-0.18 / 0.0	-0.07 / 0.22	-0.09 / 0.07					
JES Flavor Composition tq, tq	-0.68 / 1.29	-0.8 / 1.28	-1.22 / 1.07	-1.22 / 1.63	-2.11 / 2.36					
JES pileup OffsetMu	-0.5 / 0.94	-0.47 / 0.62	0.0 / 0.51	-1.18 / 1.02	-0.3 / 1.62					
JES pileup OffsetNPV	0.12 / 0.3	0.3 / -0.23	0.12 / -0.19	0.03 / 0.13	-0.01 / 0.81					
JES pileup RhoTopology	-0.06 / 0.15	0.22 / 0.31	0.42 / 0.61	-0.4 / 0.09	0.14 / 1.97					
JES pileup PtTerm	-0.26 / 0.32	0.01 / 0.1	-0.14 / 0.01	0.09 / 0.08	-0.01 / 0.97					
JES EtaIntercalibration Modelling	-0.55 / 1.33	-1.38 / 1.17	-0.83 / 1.19	-1.97 / 1.74	-2.37 / 3.94					
JES EtaIntercalibration TotalStat	-0.01 / 0.22	-0.13 / 0.22	0.16 / 0.01	-0.38 / 0.05	-0.22 / 0.97					
JES EtaIntercalibration NonClosure posEta	0.0 / -0.07	0.0 / 0.0	0.03 / 0.01	-0.02 / -0.07	0.08 / 0.09					
JES EtaIntercalibration NonClosure 2018data	0.17 / -0.11	0.14 / -0.07	0.07 / 0.03	0.13 / -0.08	0.12 / 0.11					
MET SoftTrk Scale	-0.02 / -0.13	0.13 / -0.07	0.2 / -0.09	0.59 / 0.03	0.57 / -0.47					
MET SoftTrk ResoPara	-0.39 / -	0.51 / -	0.43 / -	0.61 / -	1.99 / -					
MET SoftTrk ResoPerp	-0.23 / -	0.89 / -	0.8 / -	1.01 / -	2.7 / -					
JVT	0.02 / 0.03	0.0 / 0.04	-0.01 / 0.05	0.02 / 0.03	0.04 / 0.0					
fJVT	-0.88 / 0.87	-0.91 / 0.91	-0.85 / 0.85	-0.82 / 0.82	-0.82 / 0.82					
b-tag B0	0.71 / -0.71	0.71 / -0.71	0.71 / -0.71	0.72 / -0.72	0.74 / -0.74					
b-tag B1	0.09 / -0.09	0.09 / -0.09	0.08 / -0.08	0.08 / -0.08	0.08 / -0.08					
b-tag B2	0.1 / -0.1	0.11 / -0.11	0.1 / -0.1	0.11 / -0.11	0.11 / -0.11					
b-tag B3	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.04 / 0.04					
b-tag B4	0.74 / -0.74	0.75 / -0.74	0.72 / -0.72	0.74 / -0.74	0.72 / -0.72					
b-tag B5	-0.98 / 0.98	-0.97 / 0.97	-0.97 / 0.97	-0.96 / 0.96	-0.93 / 0.93					
b-tag B6	-0.14 / 0.14	-0.15 / 0.15	-0.16 / 0.16	-0.18 / 0.18	-0.25 / 0.25					
b-tag B7	0.32 / -0.32	0.32 / -0.32	0.33 / -0.33	0.34 / -0.34	0.35 / -0.35					
b-tag B8	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09					
b-tag B12	-0.04 / 0.04	-0.05 / 0.05	-0.05 / 0.05	-0.06 / 0.06	-0.08 / 0.08					
b-tag B17	-0.11 / 0.11	-0.1 / 0.1	-0.1 / 0.1	-0.1 / 0.1	-0.09 / 0.09					
b-tag B18	-0.08 / 0.08	-0.07 / 0.07	-0.07 / 0.07	-0.07 / 0.07	-0.06 / 0.06					
b-tag B21	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.04 / 0.04	-0.04 / 0.04					
b-tag B24	-0.06 / 0.06	-0.06 / 0.06	-0.06 / 0.06	-0.06 / 0.06	-0.05 / 0.05					
b-tag B26	0.05 / -0.05	0.05 / -0.05	0.05 / -0.05	0.05 / -0.05	0.06 / -0.06					
b-tag B27	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04					
b-tag B28	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.03 / 0.03					
b-tag B29	-0.06 / 0.06	-0.06 / 0.06	-0.06 / 0.06	-0.06 / 0.06	-0.07 / 0.07					



F. Systematic uncertainties

b-tag B30	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05
b-tag B34	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.04 / 0.04
b-tag B35	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09	-0.1 / 0.1
b-tag B36	0.09 / -0.09	0.08 / -0.08	0.08 / -0.08	0.08 / -0.08	0.08 / -0.08	0.08 / -0.08	0.07 / -0.07
b-tag B37	0.08 / -0.08	0.07 / -0.07	0.07 / -0.07	0.07 / -0.07	0.07 / -0.07	0.07 / -0.07	0.05 / -0.05
b-tag C0	0.33 / -0.33	0.32 / -0.32	0.32 / -0.32	0.32 / -0.32	0.23 / -0.23	0.38 / -0.38	
b-tag C1	-0.21 / 0.21	-0.2 / 0.2	-0.2 / 0.2	-0.2 / 0.2	-0.15 / 0.15	-0.25 / 0.25	
b-tag C2	-0.14 / 0.14	-0.13 / 0.13	-0.14 / 0.14	-0.14 / 0.14	-0.09 / 0.09	-0.16 / 0.16	
b-tag C3	-0.25 / 0.25	-0.24 / 0.24	-0.25 / 0.25	-0.25 / 0.25	-0.17 / 0.17	-0.29 / 0.29	
b-tag C4	-0.13 / 0.13	-0.13 / 0.13	-0.13 / 0.13	-0.13 / 0.13	-0.09 / 0.09	-0.15 / 0.15	
b-tag C5	-0.14 / 0.14	-0.15 / 0.15	-0.1 / 0.1	-0.09 / 0.09	-0.09 / 0.09	-0.19 / 0.19	
b-tag C7	0.1 / -0.1	0.12 / -0.12	0.1 / -0.1	0.1 / -0.1	0.08 / -0.08	0.09 / -0.09	
b-tag Light0	0.12 / -0.12	0.14 / -0.14	0.13 / -0.13	0.14 / -0.14	0.14 / -0.14	0.14 / -0.14	
EG RESOLUTION ALL	-0.09 / 0.09	0.1 / 0.0	0.01 / -0.06	0.05 / -0.17	0.58 / 0.02		
EG SCALE ALL	-0.01 / -0.04	0.02 / 0.02	-0.06 / 0.01	-0.13 / 0.1	0.45 / 0.05		
EL ID	-0.13 / 0.13	-0.14 / 0.14	-0.13 / 0.13	-0.11 / 0.11	-0.13 / 0.13		
EL Isol	-0.9 / 0.9	-0.88 / 0.88	-0.8 / 0.8	-0.71 / 0.71	-0.76 / 0.76		
EL Reco	-0.2 / 0.2	-0.19 / 0.19	-0.17 / 0.17	-0.17 / 0.17	-0.19 / 0.19		
EL Trigger	-0.08 / 0.08	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09	-0.11 / 0.11		
MU ID syst.	-0.08 / 0.07	-0.07 / 0.07	-0.07 / 0.07	-0.08 / 0.08	-0.12 / 0.12		
MU Isol syst.	-0.41 / 0.41	-0.42 / 0.42	-0.46 / 0.46	-0.51 / 0.51	-0.54 / 0.54		
MU Trigger stat.	-0.16 / 0.17	-0.17 / 0.17	-0.18 / 0.18	-0.16 / 0.17	-0.14 / 0.14		
MU Trigger syst.	0.36 / -0.37	0.36 / -0.36	0.35 / -0.36	0.35 / -0.36	0.36 / -0.36		
MU CB	-0.04 / -0.11	-0.02 / 0.09	0.09 / -0.13	0.21 / 0.08	-0.07 / -0.18		
MU Momentum Scale	-0.07 / -0.04	0.02 / -0.01	0.03 / 0.07	0.14 / 0.03	0.03 / -0.1		
MUON SAGITTA DATASTAT	-0.04 / -0.02	0.0 / 0.01	0.09 / 0.01	0.05 / 0.04	-0.04 / 0.01		
MUON SAGITTA RESBIAS	-0.03 / -0.09	0.03 / 0.07	-0.02 / 0.06	0.17 / 0.03	-0.01 / -0.16		
pileup	1.34 / -1.16	1.28 / -1.19	1.38 / -1.28	1.31 / -1.27	1.96 / -1.73		
Modelling uncertainties							
$tq \mu_R$	-0.79 / 0.75	-0.66 / 0.78	-0.69 / 0.73	-1.02 / 0.79	-1.53 / 1.18		
$tq \mu_F$	-0.96 / 0.55	-0.86 / 0.59	-0.98 / 0.6	-1.26 / 0.64	-1.53 / 1.02		
tq FSR	-2.21 / 2.63	-2.02 / 2.87	-2.11 / 3.61	-2.28 / 3.06	-2.4 / 3.68		
tq ISR α_S	0.33 / -0.3	0.47 / -0.3	0.43 / -0.36	0.36 / -0.49	0.33 / -0.37		
tq PDF	-0.15 / 0.12	-0.05 / 0.16	-0.09 / 0.12	-0.25 / 0.09	-0.13 / 0.05		
tq Parton shower	-3.26 / (3.26)	-2.34 / (2.34)	-2.47 / (2.47)	-1.95 / (1.95)	-3.46 / (3.46)		
tq NLO matching	-3.37 / (3.37)	-4.21 / (4.21)	-3.92 / (3.92)	-3.42 / (3.42)	-3.72 / (3.72)		
JES Flavor Composition $t\bar{t}$	0.21 / -0.26	0.15 / -0.19	0.14 / -0.11	0.17 / -0.19	0.01 / -0.12		
mj e shape	0.77 / -0.13	0.73 / 0.02	0.8 / -0.15	0.42 / 0.19	0.28 / -0.1		
mj fe shape	0.0 / 0.0	-0.01 / -0.01	-0.03 / -0.01	0.17 / 0.07	0.41 / 0.37		
mj μ shape	-0.15 / 0.15	-0.03 / 0.03	-0.16 / 0.16	0.07 / -0.07	0.31 / -0.31		
$t\bar{t} \mu_R$	-0.07 / 0.05	-0.06 / 0.04	-0.03 / 0.02	-0.02 / 0.02	0.01 / -0.01		
$t\bar{t} \mu_F$	-0.06 / 0.05	-0.04 / 0.03	-0.03 / 0.03	-0.04 / 0.03	-0.02 / 0.02		
$t\bar{t}$ FSR	-0.09 / 0.34	0.04 / -0.38	0.02 / -0.25	-0.07 / 0.05	-0.02 / -0.19		
$t\bar{t}$ ISR α_S	0.08 / -0.07	0.07 / -0.07	0.06 / -0.05	0.02 / -0.01	0.06 / -0.05		
$tW + tW$ DS	0.07 / (-0.07)	-0.04 / (0.04)	-0.1 / (0.1)	-0.07 / (0.07)	0.05 / (-0.05)		
$tW + tW, tb/tb$ FSR	0.01 / 0.0	-0.02 / 0.03	-0.02 / 0.08	0.03 / -0.04	-0.05 / 0.04		
$W + b\bar{b} \mu_F$	0.12 / -0.12	0.12 / -0.12	-0.15 / 0.15	0.35 / -0.35	-0.35 / 0.35		
$W + b\bar{b} \mu_R$	0.05 / -0.18	0.01 / -0.2	0.19 / -0.27	0.08 / -0.68	-0.23 / 0.32		
$W + c(\bar{c}) \mu_F$	-0.06 / -0.1	-0.08 / -0.1	0.06 / 0.47	0.59 / -0.28	-1.46 / 0.01		
$W + c(\bar{c}) \mu_R$	0.34 / -0.35	0.3 / -0.03	0.16 / -0.85	0.38 / -0.16	-0.35 / -0.78		
$t\bar{t}, tW + tW, tb/tb$ PDF	-0.08 / 0.08	-0.08 / 0.08	-0.1 / 0.1	-0.11 / 0.11	-0.11 / 0.11		
$tW + tW, tb/tb$ Parton shower	0.12 / (-0.12)	0.05 / (-0.05)	-0.1 / (0.1)	0.07 / (-0.07)	0.0 / (0.0)		
$t\bar{t}$ Parton shower	0.08 / (-0.08)	0.09 / (-0.09)	0.22 / (-0.22)	0.28 / (-0.28)	-0.18 / (0.18)		
$t\bar{t}$ NLO matching	0.08 / (-0.08)	0.09 / (-0.09)	0.16 / (-0.16)	0.08 / (-0.08)	-0.05 / (0.05)		
$tW + tW$ NLO matching	0.17 / (-0.17)	-0.02 / (0.02)	-0.02 / (0.02)	0.05 / (-0.05)	-0.05 / (0.05)		
$t\bar{t} h_{damp}$	0.13 / (-0.13)	0.16 / (-0.16)	0.16 / (-0.16)	0.07 / (-0.07)	-0.02 / (0.02)		
Luminosity	0.83 / -0.83	0.83 / -0.83	0.83 / -0.83	0.83 / -0.83	0.83 / -0.83		
Background rate uncertainties							
$t\bar{t}$ rate	-0.16 / 0.16	-0.15 / 0.15	-0.14 / 0.14	-0.12 / 0.12	-0.08 / 0.08		
$tW + tW, tb/tb$ rate	-0.08 / 0.08	-0.07 / 0.07	-0.06 / 0.06	-0.07 / 0.07	-0.07 / 0.07		
$W + b\bar{b}$ rate	-0.4 / 0.4	-0.47 / 0.47	-0.51 / 0.51	-0.55 / 0.55	-0.72 / 0.72		
$W + c(\bar{c})$ rate	-0.95 / 0.95	-0.96 / 0.96	-0.9 / 0.9	-0.67 / 0.67	-1.07 / 1.07		
$VV, +jets$ rate	-0.11 / 0.11	-0.13 / 0.13	-0.17 / 0.17	-0.27 / 0.27	-0.4 / 0.4		
mj e rate	-0.21 / 0.21	-0.22 / 0.22	-0.24 / 0.24	-0.12 / 0.12	-0.08 / 0.08		
mj fe rate	-0.23 / 0.23	-0.23 / 0.23	-0.24 / 0.24	-0.15 / 0.15	-0.43 / 0.43		
mj μ rate	-0.37 / 0.37	-0.34 / 0.34	-0.32 / 0.32	-0.42 / 0.42	-0.51 / 0.51		
Statistical uncertainties							
Data stat.	1.64 / -1.64	1.32 / -1.32	1.51 / -1.51	1.8 / -1.8	2.58 / -2.58		
MC stat.	0.43 / -0.43	0.39 / -0.39	0.42 / -0.42	0.51 / -0.51	0.65 / -0.65		
Total uncertainty	6.9 / -6.9	7.8 / -6.6	7.5 / -6.9	6.9 / -7.0	11.6 / -10.1		



Table F.5.: Contribution of each individual uncertainty on the absolute differential $\bar{t}q$ cross section binned in $|\mathbf{y}(\bar{t})|$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]									
	Bin 1		Bin 2		Bin 3		Bin 4		Bin 5	
	Experimental uncertainties									
JER DataVsMC MC16	-1.79 / 0.48	0.73 / -0.25	1.67 / 0.49	-0.56 / -0.34	-0.74 / 0.75					
JER Effective NP 1	1.48 / -2.53	-1.26 / 0.91	-0.42 / 1.52	1.57 / -0.48	-1.42 / 1.67					
JER Effective NP 2	2.14 / -3.24	0.16 / 0.7	0.47 / 0.26	0.54 / -0.82	1.33 / -2.06					
JER Effective NP 3	-1.54 / 1.78	1.33 / -0.34	0.42 / 0.38	-0.19 / 0.71	-0.11 / -0.08					
JER Effective NP 4	-1.76 / 0.64	0.47 / 0.08	-0.71 / 1.97	0.16 / 0.32	1.29 / -1.04					
JER Effective NP 5	-0.75 / 0.49	0.02 / 0.26	0.97 / 0.11	-0.12 / -0.5	0.89 / 1.45					
JER Effective NP 6	-1.25 / 1.08	-0.06 / 0.32	1.12 / 1.34	0.07 / 0.94	0.74 / -0.22					
JER Effective NP 7	-0.2 / -0.19	-0.17 / 0.1	1.16 / 0.01	-0.02 / 0.28	-0.05 / 0.63					
JER Effective NP 8	-0.73 / -0.94	0.49 / 0.92	0.27 / -0.23	-0.7 / 0.78	-0.89 / 0.7					
JER Effective NP 9	-0.03 / -0.33	0.83 / -0.41	0.11 / 0.53	0.16 / 0.15	0.55 / 0.95					
JER Effective NP 10	0.0 / -0.45	-0.24 / 0.4	-0.04 / -0.42	0.68 / 0.0	-0.46 / 1.11					
JER Effective NP 11	-0.79 / -0.43	-0.04 / 0.47	0.39 / -0.49	0.2 / 0.7	0.41 / 0.32					
JER Effective NP 12restTerm	0.18 / -0.05	0.22 / 0.21	0.41 / -0.92	0.85 / -0.34	0.37 / 1.44					
JES Effective NP Detector1	0.11 / 0.12	-0.38 / 0.04	-0.13 / 0.17	0.05 / -0.04	-0.06 / -0.3					
JES Effective NP Detector2	0.0 / 0.08	0.0 / 0.01	0.01 / -0.01	0.0 / 0.0	-0.01 / 0.02					
JES Effective NP Modelling1	-0.16 / 1.12	-0.37 / 0.34	-0.02 / 0.18	-0.31 / 0.45	-1.35 / 0.39					
JES Effective NP Modelling2	0.01 / 0.09	-0.27 / 0.0	-0.09 / 0.02	-0.08 / 0.08	-0.36 / -0.03					
JES Effective NP Modelling3	0.12 / 0.08	0.04 / -0.33	0.19 / -0.16	0.13 / -0.03	0.03 / -0.32					
JES Effective NP Modelling4	-0.02 / 0.08	0.03 / 0.05	-0.01 / 0.0	0.0 / -0.01	0.05 / 0.06					
JES Effective NP Mixed1	0.1 / 0.1	-0.35 / 0.11	-0.02 / 0.19	0.05 / -0.13	-0.07 / -0.03					
JES Effective NP Mixed2	0.12 / -0.09	0.21 / -0.41	0.17 / -0.05	-0.01 / 0.0	-0.17 / -0.21					
JES Effective NP Mixed3	0.08 / 0.09	-0.4 / 0.04	-0.11 / 0.2	0.0 / -0.08	-0.04 / -0.04					
JES Effective NP Statistical1	0.0 / 0.09	-0.01 / 0.03	0.0 / 0.0	-0.02 / -0.02	-0.01 / 0.01					
JES Effective NP Statistical2	0.06 / -0.04	0.15 / -0.38	0.21 / -0.02	-0.03 / 0.03	-0.26 / -0.15					
JES Effective NP Statistical4	0.07 / 0.13	-0.31 / 0.0	-0.05 / 0.03	0.04 / 0.02	-0.07 / 0.0					
JES Effective NP Statistical6	-0.01 / 0.13	-0.04 / 0.01	0.02 / 0.0	0.01 / -0.03	-0.06 / 0.02					
JES Effective NP Statistical5	0.12 / 0.09	-0.01 / -0.32	0.19 / -0.08	0.09 / 0.03	0.0 / -0.08					
JES Flavor Response	1.22 / -0.58	0.48 / -0.76	1.46 / -0.3	0.92 / 0.27	1.23 / -2.14					
BJES Response	-0.34 / 0.27	-0.43 / -0.05	-0.1 / 0.25	0.1 / 0.48	-0.5 / 0.09					
JES Flavor Composition $tq, \bar{t}q$	-1.27 / 1.84	-1.46 / 1.74	-1.43 / 2.33	-1.59 / 2.04	-2.88 / 2.33					
JES pileup OffsetMu	-1.34 / 1.57	-2.1 / 1.14	-0.61 / 0.71	-0.52 / 1.24	-2.21 / 1.33					
JES pileup OffsetNPV	0.28 / -0.37	-0.05 / 0.12	-0.01 / 0.39	-0.09 / 0.23	-0.76 / -0.14					
JES pileup RhoTopology	0.04 / 0.93	-0.08 / 0.19	-0.14 / 0.7	-0.19 / 0.04	-2.25 / -0.18					
JES pileup PtTerm	0.18 / 0.42	-0.68 / 0.15	0.1 / 0.24	-0.01 / 0.2	-0.78 / -0.07					
JES EtaIntercalibration Modelling	-1.57 / 2.28	-1.9 / 1.03	-1.09 / 1.53	-1.72 / 2.81	-4.02 / 2.26					
JES EtaIntercalibration TotalStat	-0.15 / 0.43	-0.39 / 0.15	0.0 / 0.21	-0.27 / 0.18	-0.39 / 0.0					
JES EtaIntercalibration NonClosure negEta	0.09 / 0.03	0.07 / -0.08	-0.36 / 0.03	0.03 / 0.05	-0.06 / -0.04					
JES EtaIntercalibration NonClosure posEta	-0.02 / -0.02	0.05 / -0.03	0.04 / -0.04	0.04 / -0.06	0.01 / -0.08					
JES EtaIntercalibration NonClosure 2018data	0.37 / 0.0	0.14 / -0.26	0.17 / -0.06	0.02 / -0.13	0.18 / 0.19					
MET SoftTrk Scale	0.32 / 0.15	-0.08 / -0.48	0.69 / -0.25	0.07 / 0.32	0.49 / -0.95					
MET SoftTrk ResoPara	1.23 / -	0.14 / -	0.82 / -	1.46 / -	0.56 / -					
MET SoftTrk ResoPerp	1.08 / -	0.44 / -	1.13 / -	1.53 / -	1.67 / -					
JVT	0.04 / 0.01	0.05 / 0.01	0.11 / -0.04	0.02 / 0.03	0.06 / 0.0					
fJVT	-0.78 / 0.77	-0.94 / 0.93	-0.81 / 0.81	-0.83 / 0.83	-0.67 / 0.67					
b-tag B0	0.75 / -0.75	0.75 / -0.75	0.75 / -0.75	0.76 / -0.76	0.77 / -0.77					
b-tag B1	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09					
b-tag B2	0.11 / -0.11	0.11 / -0.11	0.11 / -0.11	0.11 / -0.11	0.12 / -0.12					
b-tag B3	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.06 / 0.06					
b-tag B4	0.78 / -0.77	0.78 / -0.78	0.77 / -0.77	0.76 / -0.76	0.84 / -0.84					
b-tag B5	-1.04 / 1.04	-1.03 / 1.03	-1.03 / 1.03	-1.03 / 1.03	-0.93 / 0.93					
b-tag B6	-0.16 / 0.16	-0.16 / 0.16	-0.17 / 0.17	-0.19 / 0.19	-0.26 / 0.26					
b-tag B7	0.36 / -0.36	0.36 / -0.36	0.36 / -0.36	0.36 / -0.36	0.39 / -0.39					
b-tag B8	0.11 / -0.11	0.1 / -0.1	0.1 / -0.1	0.11 / -0.11	0.1 / -0.1					
b-tag B11	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04	0.05 / -0.05					
b-tag B12	-0.04 / 0.04	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.09 / 0.09					
b-tag B17	-0.11 / 0.11	-0.11 / 0.11	-0.11 / 0.11	-0.1 / 0.1	-0.09 / 0.09					
b-tag B18	-0.08 / 0.08	-0.07 / 0.07	-0.07 / 0.07	-0.07 / 0.07	-0.06 / 0.06					
b-tag B21	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.04 / 0.04					
b-tag B24	-0.06 / 0.06	-0.06 / 0.06	-0.06 / 0.06	-0.06 / 0.06	-0.05 / 0.05					
b-tag B26	0.05 / -0.05	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06					
b-tag B27	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04					
b-tag B28	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.03 / 0.03					
b-tag B29	-0.07 / 0.07	-0.06 / 0.06	-0.06 / 0.06	-0.06 / 0.06	-0.07 / 0.07					



F. Systematic uncertainties

b-tag B30	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.06 / 0.06
b-tag B34	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.04 / 0.04
b-tag B35	-0.1 / 0.1	-0.1 / 0.1	-0.1 / 0.1	-0.1 / 0.1	-0.1 / 0.1	-0.11 / 0.11
b-tag B36	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.09 / -0.09	0.08 / -0.08
b-tag B37	0.08 / -0.08	0.08 / -0.08	0.07 / -0.07	0.07 / -0.07	0.07 / -0.07	0.04 / -0.04
b-tag C0	0.47 / -0.47	0.48 / -0.48	0.44 / -0.44	0.46 / -0.46	0.53 / -0.53	0.53 / -0.53
b-tag C1	-0.29 / 0.29	-0.3 / 0.3	-0.27 / 0.27	-0.29 / 0.29	-0.34 / 0.34	-0.34 / 0.34
b-tag C2	-0.19 / 0.19	-0.19 / 0.19	-0.17 / 0.17	-0.18 / 0.18	-0.2 / 0.2	-0.2 / 0.2
b-tag C3	-0.35 / 0.35	-0.36 / 0.36	-0.32 / 0.32	-0.33 / 0.33	-0.4 / 0.4	-0.4 / 0.4
b-tag C4	-0.18 / 0.18	-0.19 / 0.19	-0.17 / 0.17	-0.18 / 0.18	-0.21 / 0.21	-0.21 / 0.21
b-tag C5	-0.16 / 0.16	-0.23 / 0.23	-0.23 / 0.23	-0.27 / 0.27	-0.33 / 0.33	-0.33 / 0.33
b-tag C6	-0.02 / 0.02	-0.02 / 0.02	-0.05 / 0.05	-0.07 / 0.07	0.03 / -0.03	0.03 / -0.03
b-tag C7	0.15 / -0.15	0.15 / -0.15	0.18 / -0.18	0.19 / -0.19	0.12 / -0.12	0.12 / -0.12
b-tag Light0	0.16 / -0.16	0.17 / -0.17	0.15 / -0.15	0.2 / -0.2	0.14 / -0.14	0.14 / -0.14
b-tag Light2	-0.04 / 0.04	-0.04 / 0.04	-0.03 / 0.03	-0.06 / 0.06	-0.03 / 0.03	-0.03 / 0.03
b-tag Light3	0.02 / -0.02	0.0 / 0.0	0.01 / -0.01	0.05 / -0.05	0.01 / -0.01	0.01 / -0.01
EG RESOLUTION ALL	0.45 / 0.08	-0.08 / -0.12	0.26 / -0.01	-0.52 / -0.07	-0.23 / 0.15	-0.23 / 0.15
EG SCALE ALL	-0.02 / 0.07	0.02 / -0.06	0.3 / 0.1	-0.7 / 0.0	-0.36 / 0.07	-0.36 / 0.07
EL ID	-0.14 / 0.14	-0.14 / 0.14	-0.14 / 0.14	-0.12 / 0.12	-0.13 / 0.13	-0.13 / 0.13
EL Isol	-0.98 / 0.98	-0.93 / 0.93	-0.88 / 0.88	-0.77 / 0.77	-0.8 / 0.8	-0.8 / 0.8
EL Reco	-0.21 / 0.21	-0.2 / 0.2	-0.19 / 0.19	-0.18 / 0.18	-0.24 / 0.24	-0.24 / 0.24
EL Trigger	-0.09 / 0.09	-0.09 / 0.09	-0.1 / 0.1	-0.09 / 0.09	-0.11 / 0.11	-0.11 / 0.11
MU ID syst.	-0.08 / 0.08	-0.08 / 0.08	-0.07 / 0.07	-0.09 / 0.09	-0.12 / 0.12	-0.12 / 0.12
MU Isol syst.	-0.45 / 0.45	-0.46 / 0.46	-0.49 / 0.49	-0.55 / 0.55	-0.54 / 0.54	-0.54 / 0.54
MU Trigger stat.	-0.17 / 0.17	-0.18 / 0.19	-0.2 / 0.21	-0.18 / 0.18	-0.14 / 0.14	-0.14 / 0.14
MU Trigger syst.	0.4 / -0.41	0.39 / -0.4	0.38 / -0.39	0.38 / -0.38	0.35 / -0.36	0.35 / -0.36
MU CB	-0.05 / 0.02	0.17 / -0.2	0.42 / -0.3	0.23 / 0.22	0.31 / -0.05	0.31 / -0.05
MU Momentum Scale	0.04 / -0.01	-0.33 / 0.04	-0.04 / 0.01	0.06 / 0.04	0.19 / -0.09	0.19 / -0.09
MUON SAGITTA DATASTAT	0.0 / -0.01	-0.01 / 0.04	0.03 / 0.02	0.0 / 0.05	0.09 / -0.02	0.09 / -0.02
MUON SAGITTA RESBIAS	0.12 / 0.06	-0.05 / -0.36	-0.09 / 0.05	0.18 / 0.1	0.06 / 0.17	0.06 / 0.17
pileup	1.42 / -1.42	1.44 / -1.28	1.23 / -1.24	1.21 / -1.18	1.52 / -1.49	1.52 / -1.49
Modelling uncertainties						
$\bar{t}q \mu_R$	-1.37 / 0.79	-1.07 / 1.1	-1.23 / 1.03	-1.32 / 0.85	-1.12 / 1.52	-1.12 / 1.52
$\bar{t}q \mu_F$	-1.43 / 0.54	-1.19 / 0.91	-1.4 / 0.9	-1.69 / 0.86	-1.78 / 1.89	-1.78 / 1.89
$\bar{t}q$ FSR	-2.14 / 3.13	-1.74 / 2.84	-2.33 / 2.79	-2.77 / 2.74	-1.29 / 3.56	-1.29 / 3.56
$\bar{t}q$ ISR α_S	0.21 / -0.62	0.5 / -0.28	0.39 / -0.42	0.15 / -0.42	0.89 / -0.12	0.89 / -0.12
$\bar{t}q$ PDF	-0.88 / 0.44	-0.58 / 0.76	-0.76 / 0.73	-0.91 / 0.58	-0.03 / 0.68	-0.03 / 0.68
$\bar{t}q$ Parton shower	-3.7 / (3.7)	-2.61 / (2.61)	-1.23 / (1.23)	-1.65 / (1.65)	-3.67 / (3.67)	-3.67 / (3.67)
$\bar{t}q$ NLO matching	-5.46 / (5.46)	-4.04 / (4.04)	-2.26 / (2.26)	-2.26 / (2.26)	-6.41 / (6.41)	-6.41 / (6.41)
JES Flavor Composition $t\bar{t}$	0.18 / -0.34	0.3 / -0.36	0.44 / -0.25	0.29 / -0.21	-0.05 / -0.14	-0.05 / -0.14
mj e shape	0.0 / -0.16	1.52 / -0.24	1.11 / -0.13	0.06 / 0.73	0.2 / -0.02	0.2 / -0.02
mj fe shape	-0.03 / -0.01	0.01 / 0.0	0.22 / 0.05	-0.1 / -0.01	-3.36 / -0.28	-3.36 / -0.28
mj μ shape	0.0 / 0.0	-0.04 / 0.04	0.34 / -0.34	0.03 / -0.03	-0.54 / 0.54	-0.54 / 0.54
$t\bar{t} \mu_R$	-0.11 / 0.08	-0.12 / 0.08	-0.12 / 0.09	-0.09 / 0.07	-0.07 / 0.05	-0.07 / 0.05
$t\bar{t} \mu_F$	-0.07 / 0.08	-0.1 / 0.09	-0.15 / 0.13	-0.1 / 0.09	0.02 / -0.01	0.02 / -0.01
$t\bar{t}$ FSR	-0.19 / -0.53	-0.06 / -0.09	0.23 / -0.42	-0.02 / -0.32	-0.25 / 0.62	-0.25 / 0.62
$t\bar{t}$ ISR α_S	0.09 / -0.08	0.1 / -0.08	0.11 / -0.1	0.11 / -0.09	0.01 / -0.02	0.01 / -0.02
$t\bar{t}W + t\bar{t}W$ DS	0.0 / (0.0)	-0.06 / (0.06)	0.09 / (-0.09)	-0.32 / (0.32)	0.05 / (-0.05)	0.05 / (-0.05)
$t\bar{t}W + t\bar{t}W, tb/tb$ FSR	-0.07 / -0.09	-0.05 / 0.11	0.04 / 0.08	0.0 / 0.04	-0.1 / 0.37	-0.1 / 0.37
$t\bar{t}W + t\bar{t}W, tb/tb$ ISR α_S	0.04 / -0.03	0.07 / -0.06	0.02 / -0.05	0.03 / -0.02	0.01 / -0.01	0.01 / -0.01
$W + b\bar{b} \mu_F$	-1.8 / 1.8	0.1 / -0.1	0.21 / -0.21	0.77 / -0.77	0.43 / -0.43	0.43 / -0.43
$W + b\bar{b} \mu_R$	-0.09 / -0.5	-0.05 / -0.59	0.51 / 0.12	0.41 / 0.35	-0.87 / -1.55	-0.87 / -1.55
$W + c(\bar{c}) \mu_F$	-0.42 / -1.05	0.16 / -0.55	-0.01 / -0.6	-0.31 / 0.34	0.44 / -0.88	0.44 / -0.88
$W + c(\bar{c}) \mu_R$	0.59 / 0.06	0.05 / -0.77	-0.25 / -1.48	0.24 / -0.94	1.05 / 0.66	1.05 / 0.66
$t\bar{t}, t\bar{t}W + t\bar{t}W, tb/tb$ PDF	-0.14 / 0.14	-0.16 / 0.16	-0.2 / 0.2	-0.24 / 0.24	-0.19 / 0.19	-0.19 / 0.19
$t\bar{t}W + t\bar{t}W, tb/tb$ Parton shower	-0.02 / (0.02)	0.07 / (-0.07)	0.08 / (-0.08)	-0.01 / (0.01)	0.19 / (-0.19)	0.19 / (-0.19)
$t\bar{t}$ Parton shower	0.01 / (-0.01)	-0.14 / (0.14)	0.52 / (-0.52)	0.41 / (-0.41)	-0.21 / (0.21)	-0.21 / (0.21)
$t\bar{t}$ NLO matching	-0.01 / (0.01)	-0.07 / (0.07)	0.32 / (-0.32)	0.44 / (-0.44)	-0.81 / (0.81)	-0.81 / (0.81)
$t\bar{t}W + t\bar{t}W$ NLO matching	-0.03 / (0.03)	-0.04 / (0.04)	0.1 / (-0.1)	0.0 / (0.0)	0.12 / (-0.12)	0.12 / (-0.12)
$t\bar{t} h_{damp}$	0.3 / (-0.3)	0.21 / (-0.21)	0.17 / (-0.17)	0.33 / (-0.33)	-0.26 / (0.26)	-0.26 / (0.26)
$\bar{t}q$ charge miss id	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06
Luminosity	0.83 / -0.83	0.83 / -0.83	0.83 / -0.83	0.83 / -0.83	0.83 / -0.83	0.83 / -0.83
Background rate uncertainties						
$t\bar{t}$ rate	-0.31 / 0.31	-0.29 / 0.29	-0.27 / 0.27	-0.25 / 0.25	-0.16 / 0.16	-0.16 / 0.16
$t\bar{t}W + t\bar{t}W, tb/tb$ rate	-0.14 / 0.14	-0.13 / 0.13	-0.14 / 0.14	-0.13 / 0.13	-0.13 / 0.13	-0.13 / 0.13
$W + b\bar{b}$ rate	-0.57 / 0.57	-0.59 / 0.59	-0.65 / 0.65	-0.61 / 0.61	-0.59 / 0.59	-0.59 / 0.59
$W + c(\bar{c})$ rate	-1.08 / 1.08	-1.13 / 1.13	-1.05 / 1.05	-1.15 / 1.15	-1.22 / 1.22	-1.22 / 1.22
$VV, +jets$ rate	-0.21 / 0.21	-0.24 / 0.24	-0.38 / 0.38	-0.57 / 0.57	-0.73 / 0.73	-0.73 / 0.73
mj e rate	-0.36 / 0.36	-0.42 / 0.42	-0.37 / 0.37	-0.22 / 0.22	-0.07 / 0.07	-0.07 / 0.07
mj fe rate	-0.39 / 0.39	-0.45 / 0.45	-0.39 / 0.39	-0.21 / 0.21	-0.52 / 0.52	-0.52 / 0.52
mj μ rate	-0.42 / 0.42	-0.61 / 0.61	-0.56 / 0.56	-0.44 / 0.44	-1.04 / 1.04	-1.04 / 1.04
Statistical uncertainties						
Data stat.	2.26 / -2.26	1.86 / -1.86	2.11 / -2.11	2.49 / -2.49	3.65 / -3.65	3.65 / -3.65
MC stat.	0.48 / -0.48	0.45 / -0.45	0.47 / -0.47	0.58 / -0.58	0.76 / -0.76	0.76 / -0.76
Total uncertainty	10.2 / -10.5	7.9 / -7.7	7.9 / -6.3	7.9 / -7.0	11.6 / -12.5	11.6 / -12.5



Table F.6.: Contribution of each individual uncertainty on the normalised differential tq cross section binned in $p_T(t)$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]															
	Bin 1	Bin 2		Bin 3		Bin 4		Bin 5		Bin 6		Bin 7		Bin 8		
	Experimental uncertainties															
ER DataVsMC MC16	-0.73 / -0.31	-0.48 / 0.64	0.63 / 0.21	0.72 / -0.43	1.07 / 0.17	0.04 / -0.65	1.55 / 0.3	-0.33 / -0.05								
JER Effective NP 1	-1.18 / 0.11	0.53 / -0.63	0.96 / 0.37	0.22 / -0.06	1.21 / 0.35	-1.11 / -0.86	0.4 / 0.89	0.64 / -0.07								
JER Effective NP 2	0.1 / -1.14	0.66 / -0.81	0.4 / 0.9	-0.79 / 0.72	-0.17 / 2.16	-2.76 / 1.02	-0.75 / 2.05	-0.98 / 1.73								
JER Effective NP 3	-0.61 / 0.08	-0.42 / 0.34	0.72 / -0.19	0.39 / -0.72	0.71 / 0.61	0.17 / 0.04	1.7 / 0.47	-0.45 / 0.01								
JER Effective NP 4	-0.59 / -0.64	0.14 / -0.34	0.74 / 0.82	-0.11 / 0.28	0.74 / 0.86	-0.75 / -0.31	0.34 / 1.03	0.53 / -0.53								
JER Effective NP 5	-0.03 / -0.74	-0.28 / 0.1	0.09 / 0.68	-0.2 / 0.34	0.91 / 0.41	-0.19 / -0.17	0.54 / 1.36	0.14 / -0.02								
JER Effective NP 6	-0.21 / -0.5	-0.31 / 0.44	0.14 / 0.54	0.07 / -0.17	1.19 / 0.21	-0.52 / -0.54	1.41 / -0.21	0.31 / 0.23								
JER Effective NP 7	-0.73 / -0.68	0.54 / -0.32	0.38 / 1.05	0.11 / 0.03	0.55 / 0.39	0.14 / 1.0	0.76 / 0.76	-0.44 / -0.14								
JER Effective NP 8	-0.64 / 0.06	0.53 / -0.08	0.27 / -0.15	0.08 / 0.04	0.47 / 0.46	0.2 / -0.53	0.81 / 0.69	-1.05 / -0.39								
JER Effective NP 9	-0.51 / -0.52	0.24 / 0.43	0.56 / 0.41	0.04 / -0.32	0.26 / 0.83	-0.62 / -0.6	0.23 / 0.83	0.54 / 0.21								
JER Effective NP 10	0.27 / -0.09	-0.07 / 0.08	0.03 / -0.04	-0.41 / -0.09	-0.17 / 0.42	-0.34 / -0.02	0.13 / 0.48	-0.37 / 0.71								
JER Effective NP 11	-0.49 / 0.39	0.18 / 0.0	0.38 / -0.17	0.21 / -0.52	0.36 / 0.52	-0.2 / -1.62	1.1 / -0.22	-1.08 / 0.63								
JER Effective NP 12restTerm	-0.53 / -0.36	0.18 / 0.18	0.54 / 0.07	-0.08 / 0.3	0.37 / 0.43	0.63 / -0.34	0.01 / 1.15	0.52 / -0.78								
JES Effective NP Detector1	0.06 / 0.04	0.01 / -0.04	0.03 / -0.05	-0.11 / -0.01	-0.1 / 0.07	-0.08 / 0.03	0.04 / -0.08	-0.21 / 0.03								
JES Effective NP Detector2	-0.01 / -0.02	0.01 / 0.0	0.05 / 0.0	-0.04 / 0.04	-0.02 / -0.01	0.05 / -0.02	-0.05 / 0.09	-0.07 / 0.08								
JES Effective NP Modelling1	0.33 / 0.54	0.24 / -0.43	-0.03 / -0.49	-0.56 / -0.2	-0.65 / 0.24	-0.96 / 0.82	-0.19 / -0.42	0.28 / -0.34								
JES Effective NP Modelling2	0.09 / 0.11	0.01 / -0.12	0.03 / -0.12	-0.13 / 0.01	-0.11 / 0.09	-0.08 / 0.07	-0.21 / 0.12	-0.44 / 0.01								
JES Effective NP Modelling3	-0.03 / 0.11	-0.1 / 0.02	-0.07 / 0.07	0.13 / -0.2	0.22 / -0.23	0.22 / -0.21	0.22 / -0.13	-0.13 / -0.23								
JES Effective NP Modelling4	0.0 / 0.11	0.01 / -0.05	0.04 / -0.1	-0.03 / -0.04	-0.02 / 0.01	-0.05 / -0.03	-0.01 / -0.02	-0.23 / 0.09								
JES Effective NP Mixed1	0.08 / -0.03	0.14 / -0.18	0.21 / -0.19	-0.19 / 0.09	-0.54 / 0.48	-0.47 / 0.62	-0.45 / 0.33	-0.88 / 0.78								
JES Effective NP Mixed2	0.22 / 0.27	-0.21 / -0.07	-0.26 / 0.0	-0.03 / -0.23	0.16 / -0.35	0.25 / -0.19	-0.05 / -0.15	0.4 / -0.84								
JES Effective NP Mixed3	0.0 / 0.09	-0.01 / -0.02	0.01 / -0.05	-0.03 / -0.04	0.04 / -0.07	0.03 / -0.15	0.08 / -0.01	-0.11 / -0.04								
JES Effective NP Statistical1	0.02 / -0.01	0.0 / 0.01	-0.01 / 0.0	0.0 / 0.0	-0.03 / 0.02	-0.01 / -0.01	0.04 / -0.01	0.41 / 0.22								
JES Effective NP Statistical2	0.39 / 0.08	-0.11 / -0.1	-0.28 / -0.02	-0.18 / -0.05	-0.21 / 0.01	-0.18 / 0.08	-0.22 / 0.19	-0.24 / -0.11								
JES Effective NP Statistical3	-0.02 / 0.01	0.0 / 0.0	-0.01 / 0.0	0.0 / 0.02	0.01 / -0.01	0.07 / 0.04	0.05 / -0.18	0.29 / -0.43								
JES Effective NP Statistical4	0.03 / 0.04	0.01 / -0.05	0.06 / -0.08	-0.06 / 0.0	-0.09 / 0.06	-0.04 / 0.17	-0.27 / 0.15	-0.2 / 0.03								
JES Effective NP Statistical6	-0.01 / 0.09	0.0 / -0.04	0.08 / -0.11	-0.01 / -0.04	-0.12 / 0.06	-0.09 / 0.05	0.07 / -0.05	-0.15 / -0.01								
JES Effective NP Statistical5	0.08 / 0.03	-0.07 / -0.01	-0.06 / 0.02	0.03 / -0.1	0.03 / -0.02	-0.03 / 0.09	-0.25 / 0.04	-0.22 / 0.12								
JES Flavor Response	-0.3 / 1.69	-0.82 / 0.26	0.04 / -0.8	0.64 / -1.46	0.69 / -1.33	1.84 / -1.88	0.94 / -3.22	2.89 / -2.53								
BJES Response	-0.3 / 0.26	0.12 / 0.1	0.03 / -0.14	0.12 / -0.27	0.32 / -0.2	0.31 / -0.22	0.51 / -0.63	0.78 / -0.55								
JES Flavor Composition $tq, \bar{t}q$	1.77 / -1.87	1.34 / -1.46	-0.53 / 0.72	-3.02 / 2.97	-2.72 / 3.02	-2.45 / 2.99	-2.53 / 0.64	-0.26 / 1.35								
JES pileup OffsetMu	-0.28 / 0.92	-0.12 / -0.26	0.16 / -0.24	-0.07 / -0.65	0.6 / -0.34	0.62 / -0.84	1.14 / -2.15	0.75 / -1.77								
JES pileup OffsetNPV	0.08 / 0.57	-0.14 / 0.13	-0.18 / -0.42	-0.02 / -0.41	0.19 / -0.45	0.45 / -0.41	0.62 / -1.11	0.02 / -0.48								
JES pileup RhoTopology	-0.5 / 1.51	0.14 / -0.19	-0.03 / -0.89	0.13 / -0.69	0.73 / -1.12	0.75 / -1.56	1.46 / -2.14	1.76 / -1.94								
JES pileup PtTerm	-0.13 / 0.5	0.1 / -0.26	0.22 / -0.34	-0.2 / -0.33	-0.09 / -0.03	0.74 / 0.15	-0.47 / -0.37	0.21 / 0.25								
JES SingleParticle HighPt	0.0 / 0.0	-0.01 / -0.01	-0.02 / -0.02	0.01 / 0.01	0.05 / 0.05	-0.04 / -0.04	0.15 / 0.15	-0.08 / -0.08								
JES PunchThrough MC16	-0.01 / -0.02	0.0 / 0.0	-0.01 / -0.01	0.01 / 0.02	0.04 / 0.03	-0.02 / 0.02	0.16 / 0.19	-0.09 / -0.04								
JES EtaIntercalibration Modelling	-1.12 / 1.9	0.99 / -1.17	1.57 / -2.1	-0.31 / -0.29	-1.14 / 0.83	-0.12 / 1.15	-0.79 / -1.75	0.38 / -0.08								
JES EtaIntercalibration TotalStat	0.04 / 0.18	-0.11 / 0.0	0.04 / -0.08	-0.03 / -0.16	0.0 / -0.15	0.05 / -0.06	0.19 / -0.24	-0.21 / -0.2								
JES EtaIntercalibration NonClosure highE	0.0 / -0.01	0.0 / 0.0	-0.02 / 0.0	0.01 / -0.02	0.0 / 0.08	0.06 / -0.03	0.15 / 0.03	-0.13 / 0.08								
JES EtaIntercalibration NonClosure negEta	0.01 / 0.01	0.09 / -0.09	-0.05 / 0.01	-0.07 / 0.09	0.08 / -0.03	-0.14 / 0.02	0.17 / 0.16	-0.22 / -0.05								
JES EtaIntercalibration NonClosure posEta	-0.01 / -0.06	0.06 / 0.02	-0.02 / 0.01	0.02 / 0.0	-0.08 / 0.12	0.08 / 0.08	-0.04 / 0.09	-0.21 / 0.13								
JES EtaIntercalibration NonClosure 2018data	0.04 / 0.27	-0.02 / -0.09	-0.01 / -0.19	0.01 / -0.18	-0.05 / -0.17	-0.06 / -0.02	-0.02 / 0.01	-0.3 / 0.38								
MET SoftTrk Scale	0.19 / 0.53	-0.24 / -0.33	-0.08 / -0.32	-0.12 / -0.2	0.11 / -0.17	-0.01 / 0.05	0.23 / -0.84	0.43 / 0.17								
MET SoftTrk ResoPara	0.92 / -	-0.9 / -	-0.51 / -	-0.11 / -	-0.57 / -	0.48 / -	-0.35 / -	1.16 / -								
MET SoftTrk ResoPerp	0.23 / -	-0.19 / -	-0.12 / -	-0.15 / -	-0.03 / -	0.42 / -	-0.54 / -	0.59 / -								
JVT	0.0 / 0.01	-0.03 / 0.03	-0.03 / 0.02	0.01 / -0.02	0.05 / -0.07	0.08 / -0.08	0.05 / -0.07	0.13 / -0.14								
lJVT	-0.79 / 0.81	-0.35 / 0.36	0.18 / -0.18	0.7 / -0.71	1.55 / -1.6	1.43 / -1.46	1.39 / -1.43	1.45 / -1.48								
b-tag B0	0.07 / -0.07	0.01 / -0.01	-0.04 / 0.04	-0.07 / 0.07	-0.06 / 0.06	-0.07 / 0.07	-0.14 / 0.14	-0.07 / 0.07								
b-tag B2	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	-0.02 / 0.02	-0.03 / 0.03	-0.03 / 0.03	-0.05 / 0.05	0.02 / -0.02								
b-tag B3	-0.01 / 0.01	-0.02 / 0.02	-0.02 / 0.02	0.01 / -0.01	0.03 / -0.03	0.03 / -0.03	0.05 / -0.05	0.21 / -0.21								
b-tag B4	0.07 / -0.06	0.09 / -0.09	0.05 / -0.05	-0.12 / 0.12	-0.19 / 0.19	-0.23 / 0.22	-0.41 / 0.41	-0.34 / 0.34								
b-tag B5	-0.08 / 0.08	-0.03 / 0.03	0.01 / -0.01	0.06 / -0.06	0.11 / -0.12	0.16 / -0.17	0.18 / -0.18	0.33 / -0.33								
b-tag B6	-0.04 / 0.04	0.05 / -0.05	0.09 / -0.09	0.01 / -0.01	-0.08 / 0.08	-0.14 / 0.14	-0.19 / 0.19	-0.2 / 0.21								
b-tag B7	0.16 / -0.16	0.06 / -0.05	-0.04 / 0.04	-0.14 / 0.14	-0.22 / 0.22	-0.24 / 0.24	-0.32 / 0.32	-0.44 / 0.44								
b-tag B8	0.07 / -0.07	0.04 / -0.04	0.01 / -0.01	-0.07 / 0.07	-0.17 / 0.17	-0.19 / 0.19	-0.17 / 0.17	-0.12 / 0.12								
b-tag B9	0.01 / -0.01	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	-0.02 / 0.02	-0.05 / 0.05								
b-tag B10	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.02 / -0.02	0.02 / -0.02	-0.04 / 0.04	-0.15 / 0.15								
b-tag B11	0.01 / -0.01	-0.01 / 0.01	-0.02 / 0.02	0.0 / 0.0	0.03 / -0.03	-0.01 / -0.01	-0.05 / 0.05	-0.08 / 0.08								
b-tag B13	0.07 / -0.07	0.01 / -0.01	-0.05 / 0.05	-0.07 / 0.07	-0.05 / 0.05	-0.04 / 0.04	-0.04 / 0.04	-0.03 / 0.03								
b-tag B15	-0.01 / 0.01	0.0 / 0.0	0.02 / -0.02	0.03 / -0.03	0.02 / -0.02	-0.01 / 0.01	-0.09 / 0.09	-0.21 / 0.21								
b-tag B16	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.01 / -0.01	0.01 / -0.01	0.01 / -0.05	0.05 / -0.03	0.03 / 0.04	-0.04 / -0.04							
b-tag B17	0.0 / 0.0	0.0 / 0.0	-0.01 / 0.01	0.0 / 0.0	0.02 / -0.02	0.05 / -0.05	0.03 / -0.03	-0.07 / 0.07								
b-tag B18	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	0.01 / -0.01	-0.01 / 0.01	-0.08 / 0.08	-0.11 / 0.11	-0.13 / 0.14								
b-tag B21	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	-0.02 / 0.02	-0.04 / 0.04	-0.04 / 0.04	-0.03 / 0.03	-0.04 / 0.04								
b-tag B24	0.01 / -0.01	0.01 / -0.01	0.01 / -0.01	-0.02 / 0.02	-0.05 / 0.05	-0.04 / 0.04	-0.03 / 0.03	-0.01 / 0.01								



F. Systematic uncertainties

b-tag B25	-0.01 / 0.01	-0.01 / 0.01	-0.01 / 0.01	-0.01 / 0.01	-0.01 / 0.01	-0.01 / 0.01	-0.01 / 0.01	0.05 / -0.05	0.05 / -0.05	0.05 / -0.05	0.04 / -0.04	0.04 / -0.04	0.04 / -0.04
b-tag B26	0.03 / -0.03	0.01 / -0.01	-0.01 / 0.01	-0.01 / 0.01	-0.01 / 0.01	-0.03 / 0.03	-0.03 / 0.03	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.04 / 0.04	-0.04 / 0.04
b-tag B35	-0.04 / 0.04	-0.01 / 0.01	0.01 / -0.01	0.02 / -0.02	0.03 / -0.03	0.03 / -0.03	0.05 / -0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.06 / 0.06	-0.06 / 0.06	-0.07 / -0.07
b-tag B36	0.03 / -0.03	0.01 / -0.01	-0.01 / 0.01	0.0 / 0.0	0.0 / 0.0	-0.03 / 0.03	-0.03 / 0.03	-0.04 / 0.04	-0.05 / 0.05	-0.05 / 0.05	-0.06 / 0.06	-0.06 / 0.06	-0.07 / -0.07
b-tag B37	-0.02 / 0.02	0.01 / -0.01	-0.01 / 0.01	0.03 / -0.03	0.02 / -0.02	-0.01 / 0.01	-0.03 / 0.03	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.05 / 0.05	-0.05 / 0.05
b-tag C0	0.45 / -0.45	-0.04 / 0.04	-0.3 / 0.3	-0.31 / 0.3	-0.31 / 0.3	-0.3 / 0.3	-0.3 / 0.3	-0.3 / 0.3	-0.3 / 0.3	-0.25 / 0.25	-0.25 / 0.25	-0.24 / 0.24	-0.24 / 0.24
b-tag C1	-0.3 / 0.3	0.02 / -0.02	-0.02 / 0.02	0.19 / -0.19	0.19 / -0.19	0.19 / -0.19	0.2 / -0.2	0.23 / -0.23	0.23 / -0.23	0.23 / -0.23	0.23 / -0.23	0.27 / -0.27	0.27 / -0.27
b-tag C2	-0.19 / 0.19	0.01 / -0.01	-0.01 / 0.01	0.12 / -0.12	0.13 / -0.13	0.13 / -0.13	0.13 / -0.13	0.15 / -0.15	0.15 / -0.15	0.15 / -0.15	0.15 / -0.15	0.17 / -0.17	0.17 / -0.17
b-tag C3	-0.34 / 0.34	0.02 / -0.02	-0.02 / 0.02	0.22 / -0.22	0.23 / -0.23	0.23 / -0.23	0.23 / -0.23	0.26 / -0.26	0.26 / -0.26	0.25 / -0.25	0.3 / -0.3	0.3 / -0.3	0.3 / -0.3
b-tag C4	-0.18 / 0.18	0.01 / -0.01	-0.01 / 0.01	0.11 / -0.11	0.12 / -0.12	0.12 / -0.12	0.12 / -0.12	0.12 / -0.12	0.13 / -0.13	0.13 / -0.13	0.13 / -0.13	0.14 / -0.14	0.14 / -0.14
b-tag C5	-0.19 / 0.19	0.04 / -0.04	-0.04 / 0.04	0.14 / -0.14	0.09 / -0.09	0.1 / -0.1	0.1 / -0.1	0.1 / -0.1	0.1 / -0.1	0.12 / -0.12	0.12 / -0.12	0.17 / -0.17	0.17 / -0.17
b-tag C6	-0.09 / 0.09	0.01 / -0.01	-0.01 / 0.01	0.06 / -0.06	0.05 / -0.05	-0.05 / 0.05	-0.06 / 0.06	-0.06 / 0.06	0.04 / -0.04	0.05 / -0.05	0.05 / -0.05	0.02 / -0.02	0.02 / -0.02
b-tag C7	0.21 / -0.21	-0.02 / 0.02	-0.02 / 0.02	-0.14 / 0.14	-0.13 / 0.13	-0.13 / 0.13	-0.16 / 0.16	-0.16 / 0.16	-0.15 / 0.15	-0.15 / 0.15	-0.15 / 0.15	-0.15 / 0.15	-0.15 / 0.15
b-tag Light0	0.0 / 0.0	-0.04 / 0.04	-0.03 / 0.03	-0.02 / 0.02	0.03 / -0.03	0.03 / -0.03	-0.02 / 0.02	0.03 / -0.03	-0.02 / 0.02	0.12 / -0.12	0.21 / -0.21	0.47 / -0.47	0.47 / -0.47
b-tag Light2	0.0 / 0.0	0.01 / -0.01	-0.01 / 0.01	0.01 / -0.01	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	0.0 / 0.0	-0.02 / 0.02	0.02 / -0.02	-0.05 / 0.05	-0.1 / 0.1	-0.1 / 0.1
b-tag Light3	0.01 / -0.01	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	-0.02 / 0.02	0.02 / -0.02	-0.03 / 0.03	-0.05 / 0.05	-0.05 / 0.05
b-tag Light4	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	-0.01 / 0.01	-0.01 / 0.01	-0.01 / 0.01	-0.02 / 0.02	-0.02 / 0.02	-0.05 / 0.05	-0.05 / 0.05
b-tag Light6	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	-0.01 / 0.01	0.01 / -0.01	-0.02 / 0.02	-0.04 / 0.04	-0.04 / 0.04
EG RESOLUTION ALL	0.44 / -0.1	-0.18 / 0.01	-0.29 / 0.05	-0.2 / 0.15	-0.29 / -0.05	-0.12 / -0.07	-0.01 / 0.09	-0.01 / 0.09	-0.01 / 0.09	-0.01 / 0.09	-0.01 / 0.09	-0.04 / 0.04	-0.04 / 0.04
EG SCALE ALL	0.27 / 0.1	-0.15 / -0.07	-0.21 / -0.03	-0.05 / -0.08	-0.11 / -0.09	0.0 / 0.05	-0.17 / 0.11	-0.1 / -0.1	-0.1 / -0.1	-0.1 / -0.1	-0.1 / -0.1	-0.1 / -0.1	-0.1 / -0.1
EL Isol	-0.09 / 0.09	0.0 / 0.0	0.07 / -0.07	-0.08 / -0.09	0.06 / -0.06	0.01 / -0.01	0.02 / -0.02	0.03 / -0.03	0.03 / -0.03	0.03 / -0.03	0.05 / -0.05	0.05 / -0.05	0.05 / -0.05
EL Reco	-0.04 / 0.04	0.0 / 0.0	0.03 / -0.03	0.03 / -0.03	0.02 / -0.02	0.02 / -0.02	0.02 / -0.02	0.03 / -0.03	0.03 / -0.03	0.03 / -0.03	0.05 / -0.05	0.05 / -0.05	0.05 / -0.05
MU Isol stat.	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	-0.01 / 0.01	-0.02 / 0.02	0.03 / -0.03	0.03 / -0.03	0.03 / -0.03	0.03 / -0.03	0.05 / -0.05	0.05 / -0.05
MU Isol syst.	-0.06 / 0.06	-0.01 / 0.01	0.02 / -0.02	0.01 / -0.01	0.06 / -0.06	0.14 / -0.14	0.18 / -0.18	0.21 / -0.21	0.22 / -0.22	0.22 / -0.22	0.22 / -0.22	0.22 / -0.22	0.22 / -0.22
MU Trigger syst.	0.05 / -0.05	-0.01 / 0.01	-0.03 / 0.03	-0.03 / 0.03	-0.04 / 0.04	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.05 / 0.05	-0.04 / 0.04	-0.04 / 0.04
MU CB	0.08 / -0.1	-0.08 / 0.04	-0.09 / 0.08	0.02 / 0.02	0.02 / 0.11	-0.03 / -0.09	0.22 / 0.09	-0.09 / 0.1	-0.09 / 0.1	-0.09 / 0.1	-0.09 / 0.1	-0.09 / 0.1	-0.09 / 0.1
MU Momentum Scale	0.08 / 0.1	-0.03 / -0.07	-0.1 / -0.09	-0.02 / -0.01	0.07 / 0.02	-0.09 / -0.03	0.06 / 0.1	-0.15 / -0.16	-0.15 / -0.16	-0.15 / -0.16	-0.15 / -0.16	-0.15 / -0.16	-0.15 / -0.16
MU'ON SAGITTA DATA'AT	0.09 / 0.01	-0.04 / 0.0	-0.08 / -0.04	-0.02 / -0.01	0.02 / 0.08	-0.06 / -0.06	0.07 / 0.09	-0.19 / -0.08	-0.19 / -0.08	-0.19 / -0.08	-0.19 / -0.08	-0.19 / -0.08	-0.19 / -0.08
MU'ON SAGITTA RESBIAS	0.11 / 0.07	-0.05 / -0.06	-0.09 / -0.07	-0.05 / -0.01	0.0 / 0.06	-0.12 / -0.03	0.12 / 0.01	-0.04 / 0.05	-0.04 / 0.05	-0.04 / 0.05	-0.04 / 0.05	-0.04 / 0.05	-0.04 / 0.05
pileup	0.06 / -0.09	-0.06 / 0.06	0.07 / 0.0	0.02 / 0.02	-0.14 / 0.11	-0.34 / 0.21	-0.17 / 0.17	-0.09 / -0.01	-0.09 / -0.01	-0.09 / -0.01	-0.09 / -0.01	-0.09 / -0.01	-0.09 / -0.01
Modelling uncertainties													
$tq \mu_R$	-0.6 / 0.32	-0.5 / 0.33	-0.34 / 0.28	0.19 / -0.08	1.73 / -0.87	2.32 / -1.43	3.33 / -2.38	6.43 / -4.07	6.43 / -4.07	6.43 / -4.07	6.43 / -4.07	6.43 / -4.07	6.43 / -4.07
$tq \mu_F$	0.04 / 0.07	0.09 / 0.0	-0.22 / 0.2	-0.38 / 0.2	0.19 / -0.2	0.41 / -0.65	0.54 / -1.22	2.12 / -2.32	2.12 / -2.32	2.12 / -2.32	2.12 / -2.32	2.12 / -2.32	2.12 / -2.32
tq FSR	0.0 / -0.11	0.26 / -0.56	0.06 / -0.03	-0.16 / 0.64	-0.62 / 1.8	0.38 / -0.93	-0.38 / 0.57	-0.22 / -2.94	-0.22 / -2.94	-0.22 / -2.94	-0.22 / -2.94	-0.22 / -2.94	-0.22 / -2.94
tq ISR α_S	-0.2 / 0.19	-0.05 / 0.08	0.09 / -0.02	0.12 / -0.17	0.34 / -0.19	0.51 / -0.56	0.11 / -0.66	-0.12 / -0.41	-0.12 / -0.41	-0.12 / -0.41	-0.12 / -0.41	-0.12 / -0.41	-0.12 / -0.41
tq PDF	0.2 / -0.16	-0.03 / 0.06	-0.18 / 0.23	-0.16 / 0.09	0.06 / 0.04	-0.06 / -0.11	-0.12 / -0.49	0.13 / -0.61	0.13 / -0.61	0.13 / -0.61	0.13 / -0.61	0.13 / -0.61	0.13 / -0.61
tq Parton shower	-0.94 / (0.94)	-1.55 / (1.55)	0.93 / (-0.93)	2.26 / (-2.26)	2.14 / (-2.14)	-0.21 / (0.21)	-1.38 / (1.38)	-2.15 / (2.15)	-2.15 / (2.15)	-2.15 / (2.15)	-2.15 / (2.15)	-2.15 / (2.15)	-2.15 / (2.15)
tq NLO matching	2.23 / (-2.23)	0.32 / (-0.32)	-0.83 / (0.83)	-1.21 / (1.21)	-1.39 / (1.39)	-2.08 / (2.08)	-7.35 / (7.35)	-11.14 / (11.14)	-11.14 / (11.14)	-11.14 / (11.14)	-11.14 / (11.14)	-11.14 / (11.14)	-11.14 / (11.14)
JES Flavor Composition tt	0.03 / 0.02	0.03 / -0.03	-0.07 / -0.04	-0.03 / 0.0	-0.09 / 0.02	0.01 / 0.16	0.2 / 0.3	0.29 / -0.34	0.29 / -0.34	0.29 / -0.34	0.29 / -0.34	0.29 / -0.34	0.29 / -0.34
JES Flavor Composition $tW + tW, tb/tb$	0.0 / 0.04	0.0 / -0.04	0.02 / -0.01	-0.04 / -0.03	0.01 / 0.01	0.01 / 0.02	0.14 / -0.04	0.02 / 0.0	0.02 / 0.0	0.02 / 0.0	0.02 / 0.0	0.02 / 0.0	0.02 / 0.0
$m_j e$ shape	0.2 / -0.49	0.14 / 0.2	0.17 / 0.44	-0.41 / 0.04	-0.41 / 0.29	-0.69 / 0.18	-0.69 / 0.14	-0.65 / 0.17	-0.65 / 0.17	-0.65 / 0.17	-0.65 / 0.17	-0.65 / 0.17	-0.65 / 0.17
$m_j e$ shape	0.12 / -0.05	-0.12 / 0.06	0.01 / 0.05	-0.04 / 0.0	-0.1 / -0.03	-0.09 / -0.03	-0.08 / -0.02	-0.09 / -0.03	-0.09 / -0.03	-0.09 / -0.03	-0.09 / -0.03	-0.09 / -0.03	-0.09 / -0.03
$m_j \mu$ shape	0.22 / -0.22	-0.07 / 0.07	-0.21 / 0.21	-0.17 / 0.17	0.43 / -0.43	-0.32 / 0.32	-0.16 / 0.16	-0.68 / 0.68	-0.68 / 0.68	-0.68 / 0.68	-0.68 / 0.68	-0.68 / 0.68	-0.68 / 0.68
$tt \mu_R$	-0.02 / 0.02	0.01 / -0.01	0.0 / 0.0	0.02 / -0.02	0.02 / -0.02	0.01 / -0.07	0.04 / 0.18	-0.15 / -0.15	-0.15 / -0.15	-0.15 / -0.15	-0.15 / -0.15	-0.15 / -0.15	-0.15 / -0.15
$tt \mu_F$	0.04 / -0.03	0.01 / -0.01	0.0 / 0.0	-0.03 / 0.03	-0.08 / 0.07	-0.05 / 0.04	-0.02 / 0.03	-0.11 / 0.09	-0.11 / 0.09	-0.11 / 0.09	-0.11 / 0.09	-0.11 / 0.09	-0.11 / 0.09
tt FSR	-0.03 / 0.1	0.05 / -0.23	-0.02 / -0.11	-0.04 / -0.02	-0.09 / -0.23	0.4 / -1.06	0.09 / -0.4	0.22 / 1.19	0.22 / 1.19	0.22 / 1.19	0.22 / 1.19	0.22 / 1.19	0.22 / 1.19
tt ISR α_S	0.02 / -0.02	-0.02 / 0.02	-0.04 / 0.04	0.0 / 0.0	0.02 / -0.02	0.0 / -0.03	0.02 / 0.01	0.07 / -0.05	0.07 / -0.05	0.07 / -0.05	0.07 / -0.05	0.07 / -0.05	0.07 / -0.05
$tW + tW$ DS	-0.09 / (0.09)	0.01 / (-0.01)	0.06 / (-0.06)	0.08 / (-0.08)	0.06 / (-0.06)	-0.06 / (0.06)	-0.01 / (0.01)	0.16 / (-0.16)	0.16 / (-0.16)	0.16 / (-0.16)	0.16 / (-0.16)	0.16 / (-0.16)	0.16 / (-0.16)
$tW + tW, tb/tb$ FSR	0.01 / 0.01	-0.01 / 0.02	-0.05 / 0.06	0.01 / -0.07	0.04 / -0.09	0.07 / -0.07	0.08 / -0.16	-0.09 / 0.11	-0.09 / 0.11	-0.09 / 0.11	-0.09 / 0.11	-0.09 / 0.11	-0.09 / 0.11
$W + bb \mu_F$	0.69 / -0.69	0.03 / -0.03	-0.79 / 0.79	-0.28 / 0.28	-0.22 / 0.22	-0.23 / 0.23	-0.41 / 0.41	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23
$W + bb \mu_R$	-0.04 / -0.31	0.02 / 0.04	0.03 / 0.16	0.02 / 0.23	-0.02 / 0.24	0.06 / 0.18	-0.01 / 0.33	-0.07 / 0.19	-0.07 / 0.19	-0.07 / 0.19	-0.07 / 0.19	-0.07 / 0.19	-0.07 / 0.19
$W + c(c) \mu_F$	-0.25 / 0.17	0.21 / 0.1	0.09 / -0.14	0.09 / -0.17	0.18 / -0.35	-0.09 / 0.06	0.11 / -0.19	0.03 / 0.05	0.03 / 0.05	0.03 / 0.05	0.03 / 0.05	0.03 / 0.05	0.03 / 0.05
$W + c(c) \mu_R$	0.12 / -0.72	0.02 / 0.24	-0.05 / 0.52	-0.1 / 0.18	-0.06 / 0.67	-0.35 / 0.09	-0.06 / 0.47	-0.21 / 0.46	-0.21 / 0.46	-0.21 / 0.46	-0.21 / 0.46	-0.21 / 0.46	-0.21 / 0.46
$tt, tW + tW, tb/tb$ PDF	0.04 / -0.04	0.03 / -0.03	-0.01 / 0.01	-0.04 / 0.04	-0.05 / 0.05	-0.04 / 0.04	-0.07 / 0.07	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23	-0.23 / 0.23
$tW + tW, tb/tb$ Parton shower	0.02 / (-0.02)	-0.02 / (0.02)	0.0 / (0.0)	0.06 / (-0.06)	0.05 / (-0.05)	-0.52 / (0.52)	0.03 / (-0.03)	0.12 / (-0.12)	0.12 / (-0.12)	0.12 / (-0.12)	0.12 / (-0.12)	0.12 / (-0.12)	0.12 / (-0.12)
tt Parton shower	-0.01 / (0.01)	0.11 / (-0.11)	-0.25 / (0.25)	0.16 / (-0.16)	0.6 / (-0.6)	0.09 / (-0.09)	-1.83 / (1.83)	-0.24 / (0.24)	-0.24 / (0.24)	-0.24 / (0.24)	-0.24 / (0.24)	-0.24 / (0.24)	-0.24 / (0.24)
tt NLO matching	0.2 / (-0.2)	-0.1 / (0.1)	-0.13 / (0.13)	0.23 / (-0.23)	-0.01 / (0.01)	-0.12 / (0.12)	-1.69 / (1.69)	-1.27 / (1.27)	-1.27 / (1.27)	-1.27 / (1.27)	-1.27 / (1.27)	-1.27 / (1.27)	-1.27 / (1.27)
$tW + tW$ NLO matching	-0.02 / (0.02)	0.02 / (-0.02)	0.02 / (-0.02)	0.0 / (0.0)	0.03 / (-0.03)	-0.22 / (0.22)	0.09 / (-0.09)	0.32 / (-0.32)	0.32 / (-0.32)	0.32 / (-0.32)	0.32 / (-0.32)	0.32 / (-0.32)	0.32 / (-0.32)
$tt h_{damp}$	0.31 / (-0.31)	-											



Table F.7.: Contribution of each individual uncertainty on the normalised differential $\bar{t}q$ cross section binned in $p_T(\bar{t})$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]															
	Bin 1		Bin 2		Bin 3		Bin 4		Bin 5		Bin 6		Bin 7		Bin 8	
	Experimental uncertainties															
JER DataVsMC MC16	0.71 / -0.15	0.32 / -0.17	-1.2 / 0.62	-0.39 / -0.27	-0.38 / -0.56	-0.17 / 0.77	0.64 / -0.22	-0.45 / 1.22								
JER Effective NP 1	-1.99 / 3.1	0.33 / -0.63	1.94 / -2.28	0.86 / -2.05	1.25 / -2.51	-0.1 / -1.22	2.03 / -0.55	1.13 / -4.18								
JER Effective NP 2	0.56 / 1.63	-0.55 / -0.9	0.65 / -2.37	-0.34 / -0.6	-1.54 / 1.91	-3.31 / 1.85	0.5 / 0.14	-1.66 / -0.41								
JER Effective NP 3	1.75 / -0.44	0.19 / -0.01	-1.91 / 1.18	-1.18 / -0.42	-1.07 / -0.62	0.47 / -0.06	-2.42 / 0.91	-2.14 / -0.62								
JER Effective NP 4	0.76 / 1.41	-0.26 / -0.98	-0.07 / -0.82	-1.07 / -0.76	-0.42 / -0.59	-1.55 / 0.32	1.8 / -0.56	-2.47 / -0.24								
JER Effective NP 5	1.72 / -1.0	-0.78 / 0.76	-1.36 / 1.28	-0.97 / 0.02	-0.9 / -0.58	1.1 / -1.14	-1.02 / 0.7	-0.86 / -1.29								
JER Effective NP 6	-0.52 / 2.09	0.45 / -1.38	0.8 / -0.65	-0.58 / -1.09	-0.42 / -1.26	1.64 / -3.09	0.1 / -1.17	-0.38 / -1.86								
JER Effective NP 7	1.0 / 0.54	-0.41 / 0.02	-1.16 / -0.2	0.14 / -1.25	-0.43 / 0.05	-0.6 / 0.51	0.09 / 0.13	-1.98 / -0.91								
JER Effective NP 8	-0.69 / 0.44	0.68 / 0.3	0.61 / -0.88	-0.19 / -0.25	-0.29 / -0.04	1.33 / -0.1	0.38 / 0.03	-0.72 / -0.1								
JER Effective NP 9	0.66 / 0.22	-0.52 / 0.04	-0.18 / 0.18	-0.34 / -0.93	-0.15 / -0.12	-1.34 / 1.34	-0.13 / -1.08	-0.19 / -0.61								
JER Effective NP 10	0.9 / 0.08	-0.51 / 0.65	-0.72 / -0.45	-0.47 / -0.28	0.26 / -0.31	-0.59 / -0.22	-0.79 / 0.54	0.28 / -1.06								
JER Effective NP 11	-0.36 / 0.74	0.16 / -0.16	0.78 / -0.88	-0.39 / -0.24	-0.38 / 0.47	0.79 / -0.92	0.18 / -0.97	-0.38 / -1.59								
JER Effective NP 12restTerm	0.71 / 0.26	-0.13 / 0.44	-0.43 / -0.59	-0.65 / -0.41	-0.27 / -0.06	-1.24 / 1.41	-0.07 / -1.21	-0.99 / -1.51								
JES Effective NP Detector1	0.14 / -0.02	0.08 / -0.03	-0.29 / 0.0	-0.07 / 0.04	0.1 / 0.14	-0.15 / -0.12	-0.02 / 0.22	0.1 / -0.17								
JES Effective NP Detector2	0.0 / 0.05	0.02 / -0.03	0.0 / -0.04	-0.05 / -0.03	0.07 / 0.02	-0.08 / -0.08	0.0 / 0.11	-0.1 / -0.06								
JES Effective NP Modelling1	-0.21 / 0.54	0.07 / -0.58	0.53 / -0.99	0.08 / 0.63	-0.79 / 0.69	-0.95 / -0.31	0.47 / 0.43	0.78 / -0.62								
JES Effective NP Modelling2	0.14 / -0.07	0.07 / -0.06	-0.26 / 0.03	-0.02 / 0.02	-0.01 / 0.29	-0.18 / -0.08	0.17 / 0.33	-0.65 / 0.22								
JES Effective NP Modelling3	-0.01 / 0.23	-0.12 / 0.07	-0.02 / -0.3	0.07 / -0.12	0.28 / -0.15	0.1 / -0.26	0.27 / 0.02	-0.17 / -0.44								
JES Effective NP Modelling4	0.05 / 0.09	0.04 / -0.01	0.01 / -0.06	-0.12 / -0.12	0.06 / 0.14	-0.12 / -0.14	-0.29 / -0.05	-0.48 / -0.41								
JES Effective NP Mixed1	0.27 / 0.02	0.22 / -0.12	-0.25 / -0.24	-0.26 / 0.02	-0.32 / 0.74	-0.6 / -0.04	-0.47 / 0.81	-1.33 / 0.41								
JES Effective NP Mixed2	0.07 / -0.06	-0.07 / 0.29	-0.18 / -0.1	0.01 / -0.05	0.46 / 0.01	-0.24 / -0.15	0.43 / -0.15	-0.13 / -0.33								
JES Effective NP Mixed3	0.06 / 0.07	0.07 / 0.02	-0.28 / -0.04	0.03 / -0.09	0.23 / -0.07	0.02 / -0.12	0.18 / 0.04	0.1 / -0.14								
JES Effective NP Statistical1	0.0 / 0.08	-0.01 / -0.05	0.01 / -0.06	0.0 / -0.07	0.05 / 0.04	-0.04 / -0.06	-0.02 / 0.05	-0.19 / 0.07								
JES Effective NP Statistical2	0.13 / -0.16	-0.08 / 0.2	0.01 / -0.12	-0.08 / 0.07	-0.19 / 0.31	-0.17 / 0.05	-0.25 / 0.42	-0.12 / 0.65								
JES Effective NP Statistical3	0.0 / 0.02	-0.03 / -0.01	0.0 / 0.01	-0.03 / -0.01	0.14 / 0.05	-0.14 / -0.1	0.2 / 0.04	0.34 / -0.58								
JES Effective NP Statistical4	0.18 / 0.04	0.06 / -0.06	-0.33 / -0.07	-0.02 / -0.05	-0.03 / 0.27	-0.13 / -0.02	-0.01 / 0.32	-0.32 / -0.2								
JES Effective NP Statistical6	0.0 / 0.09	0.01 / -0.04	0.03 / -0.12	-0.02 / -0.08	-0.06 / 0.17	-0.02 / 0.09	-0.17 / -0.07	0.07 / -0.08								
JES Effective NP Statistical5	0.08 / 0.23	-0.06 / 0.01	-0.03 / -0.41	-0.02 / -0.11	0.03 / 0.1	-0.12 / 0.11	-0.33 / 0.21	-0.07 / 0.13								
JES Flavor Response	-0.73 / 0.3	-0.8 / 0.87	0.64 / 0.18	0.53 / -1.02	1.58 / -1.53	1.87 / -1.43	2.31 / -2.18	3.38 / -1.36								
BJES Response	-0.03 / 0.06	-0.16 / 0.06	-0.33 / 0.07	0.32 / -0.08	0.86 / -0.04	-0.02 / -0.77	0.4 / -0.52	0.91 / -0.74								
JES Flavor Composition $tq, t\bar{q}$	1.4 / -1.38	1.1 / -1.19	-0.6 / 0.91	-2.59 / 2.22	-2.58 / 2.3	-2.28 / 2.46	-1.31 / 1.42	-0.03 / 0.65								
JES pileup OffsetMu	-3.48 / 1.51	2.14 / -0.31	1.78 / -1.25	1.51 / -0.27	2.06 / -1.36	2.41 / -2.05	2.49 / -2.06	2.34 / -1.55								
JES pileup OffsetNPV	-0.58 / 0.6	0.16 / 0.04	0.34 / -0.84	0.33 / 0.2	0.2 / -0.6	0.58 / -0.94	1.31 / -0.82	1.64 / -0.56								
JES pileup RhoTopology	-1.25 / 1.14	-0.05 / -0.33	0.93 / -0.6	0.79 / -0.47	0.78 / -0.75	1.34 / -1.77	3.13 / -2.4	3.02 / -2.63								
JES pileup PtTerm	0.06 / 0.11	0.05 / 0.06	-0.18 / 0.01	0.29 / -0.43	-0.29 / 0.37	-0.31 / -0.53	-0.72 / 0.35	-0.03 / -0.56								
JES SingleParticle HighPt	0.06 / 0.06	-0.01 / -0.01	0.0 / 0.0	-0.06 / -0.06	-0.07 / -0.07	0.01 / 0.01	-0.11 / -0.11	0.4 / -0.4								
JES PunchThrough MC16	0.04 / 0.04	-0.04 / -0.03	-0.02 / -0.02	-0.02 / -0.02	0.0 / -0.03	0.03 / 0.06	-0.14 / -0.11	0.01 / -0.01								
JES EtaIntercalibration Modelling	-2.66 / 1.95	0.86 / -1.08	3.0 / -2.09	1.29 / -0.82	-0.87 / 1.11	0.19 / -0.54	1.31 / -0.04	1.42 / 0.02								
JES EtaIntercalibration TotalStat	-0.56 / 0.29	0.16 / -0.03	0.51 / -0.66	0.14 / 0.44	0.22 / -0.11	0.22 / -0.31	0.97 / -0.44	0.82 / -0.43								
JES EtaIntercalibration NonClosure highE	0.02 / 0.01	-0.03 / -0.03	0.0 / 0.01	0.0 / -0.02	-0.02 / 0.0	0.04 / 0.08	0.0 / -0.06	0.38 / 0.12								
JES EtaIntercalibration NonClosure negEta	0.21 / 0.01	0.1 / -0.18	-0.47 / 0.1	-0.04 / 0.13	0.19 / -0.17	0.02 / 0.15	-0.32 / 0.24	0.23 / -0.34								
JES EtaIntercalibration NonClosure posEta	0.01 / 0.05	0.0 / -0.09	0.02 / -0.01	0.02 / -0.02	-0.17 / 0.01	-0.06 / 0.22	0.16 / -0.19	-0.19 / 0.37								
JES EtaIntercalibration NonClosure 2018data	-0.01 / -0.07	0.03 / 0.14	-0.01 / 0.01	-0.03 / -0.09	0.1 / 0.01	-0.27 / -0.01	0.05 / 0.29	0.4 / 0.46								
MET SoftTrk Scale	-0.14 / 0.6	-0.04 / -0.06	0.1 / -0.64	0.19 / -0.2	0.54 / -0.56	-0.5 / 0.23	-0.89 / -0.14	0.4 / -1.59								
MET SoftTrk ResoPara	0.48 / -	-0.04 / -	-0.62 / -	-0.66 / -	1.51 / -	0.09 / -	-1.95 / -	-0.54 / -								
MET SoftTrk ResoPerp	-0.05 / -	0.2 / -	0.04 / -	-0.3 / -	0.29 / -	-0.09 / -	-0.93 / -	0.41 / -								
JVT	0.04 / -0.01	-0.05 / 0.05	-0.04 / 0.02	-0.03 / 0.0	0.04 / -0.06	0.1 / -0.12	0.05 / -0.08	0.15 / -0.17								
fJVT	-0.68 / 0.7	-0.4 / 0.41	0.27 / -0.28	0.67 / -0.69	1.6 / -1.66	1.49 / -1.54	1.36 / -1.41	1.56 / -1.59								
b-tag B0	0.07 / -0.07	0.01 / -0.01	-0.04 / 0.04	-0.07 / 0.07	-0.06 / 0.06	-0.08 / 0.08	-0.14 / 0.14	-0.2 / 0.2								
b-tag B2	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	-0.02 / 0.02	-0.03 / 0.03	-0.04 / 0.04	-0.04 / 0.04	-0.01 / 0.01								
b-tag B3	-0.01 / 0.01	-0.02 / 0.02	-0.01 / 0.01	0.01 / -0.01	0.04 / -0.04	0.05 / -0.05	0.03 / -0.03	0.16 / -0.16								
b-tag B4	0.07 / -0.07	0.08 / -0.08	0.01 / -0.01	-0.1 / 0.1	-0.24 / 0.23	-0.31 / 0.3	-0.34 / 0.33	-0.39 / 0.38								
b-tag B5	-0.06 / 0.06	-0.04 / 0.04	0.01 / -0.01	0.08 / -0.08	0.11 / -0.11	0.17 / -0.18	0.21 / -0.21	0.27 / -0.28								
b-tag B6	-0.04 / 0.04	0.06 / -0.06	0.08 / -0.08	0.01 / -0.01	-0.08 / 0.09	-0.15 / 0.15	-0.22 / 0.23	-0.24 / 0.24								
b-tag B7	0.15 / -0.15	0.05 / -0.05	-0.05 / 0.05	-0.16 / 0.16	-0.25 / 0.25	-0.25 / 0.25	-0.34 / 0.34	-0.49 / 0.48								
b-tag B8	0.07 / -0.07	0.04 / -0.04	0.0 / 0.0	-0.08 / 0.08	-0.19 / 0.19	-0.22 / 0.21	-0.2 / 0.2	-0.14 / 0.14								
b-tag B9	0.01 / -0.01	0.0 / 0.0	-0.01 / 0.01	0.0 / 0.0	0.01 / -0.01	0.01 / -0.01	-0.03 / 0.03	-0.06 / 0.06								
b-tag B10	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.02 / -0.02	0.03 / -0.03	0.03 / -0.03								
b-tag B11	0.01 / -0.01	-0.01 / 0.01	-0.02 / 0.02	0.0 / 0.0	0.04 / -0.04	-0.01 / 0.01	-0.06 / 0.06	-0.07 / 0.07								
b-tag B13	0.07 / -0.07	0.01 / -0.01	-0.05 / 0.05	-0.08 / 0.08	-0.06 / 0.06	-0.04 / 0.04	-0.04 / 0.04	-0.03 / 0.03								
b-tag B15	-0.02 / 0.02	0.0 / 0.0	0.02 / -0.02	0.03 / -0.03	0.02 / -0.02	0.0 / 0.0	-0.1 / 0.1	-0.24 / 0.24								
b-tag B16	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.01 / -0.01	-0.01 / 0.01	-0.06 / 0.06	-0.04 / 0.04	0.06 / -0.06								
b-tag B17	0.0 / 0.0	0.0 / 0.0	-0.01 / 0.01	0.0 / 0.0	0.02 / -0.02	0.06 / -0.06	0.04 / -0.04	-0.09 / 0.09								
b-tag B18	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	0.01 / -0.01	-0.01 / 0.01	-0.09 / 0.09	-0.14 / 0.14	-0.15 / 0.15								
b-tag B21	0.01 / -0.01	0.01 / -0.01	0.0 / 0.0	-0.02 / 0.02	-0.05 / 0.05	-0.04 / 0.04	-0.04 / 0.04	-0.05 / 0.05								
b-tag B24	0.01 / -0.01	0.01 / -0.01	0.01 / -0.01	-0.02 / 0.02	-0.06 / 0.06	-0.05 / 0.05	-0.03 / 0.03	-0.03 / 0.03								
b-tag B25	0.0 / 0.0	-0.01 / 0.01	-0.01 / 0.01	0.01 / -0.01	0.05 / -0.05	0.05 / -0.05	0.05 / -0.05	0.05 / -0.05								



F. Systematic uncertainties

b-tag B26	0.03	-0.03	0.01	-0.01	-0.01	0.01	-0.03	0.03	-0.06	0.06	-0.05	0.05	-0.05	0.05	-0.05	0.05
b-tag B29	0.03	-0.03	0.01	-0.01	-0.02	0.02	-0.04	0.04	-0.03	0.03	-0.01	0.01	0.0	0.0	0.01	-0.01
b-tag B35	-0.04	0.04	-0.01	0.01	0.02	-0.02	0.04	-0.04	0.05	-0.05	0.05	-0.05	0.06	-0.06	0.08	-0.08
b-tag B36	0.02	-0.02	0.01	-0.01	-0.01	0.0	-0.03	0.03	-0.05	0.05	-0.06	0.06	-0.06	0.06	-0.07	0.07
b-tag B37	-0.02	0.02	0.01	-0.01	0.03	-0.03	0.02	-0.02	-0.01	0.01	-0.03	0.03	-0.05	0.05	-0.05	0.05
b-tag B39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.01	0.01	-0.01	0.01	-0.02	0.02	-0.05	0.05
b-tag C0	0.45	-0.44	-0.04	0.04	-0.32	0.32	-0.38	0.37	-0.36	0.35	-0.3	0.3	-0.14	0.14	-0.25	0.25
b-tag C1	-0.29	0.29	0.02	-0.02	0.19	-0.19	0.23	-0.23	0.24	-0.24	0.28	-0.28	0.32	-0.32	0.33	-0.33
b-tag C2	-0.17	0.17	0.0	0.0	0.11	-0.11	0.14	-0.15	0.15	-0.15	0.17	-0.17	0.2	-0.2	0.21	-0.21
b-tag C3	-0.33	0.33	0.02	-0.02	0.21	-0.21	0.27	-0.27	0.27	-0.27	0.29	-0.29	0.32	-0.32	0.36	-0.36
b-tag C4	-0.17	0.17	0.01	-0.01	0.11	-0.11	0.14	-0.14	0.14	-0.14	0.15	-0.15	0.16	-0.16	0.17	-0.17
b-tag C5	-0.3	0.3	0.08	-0.08	0.23	-0.23	0.18	-0.18	0.15	-0.15	0.19	-0.19	0.2	-0.2	0.29	-0.29
b-tag C6	-0.09	0.09	-0.04	0.04	0.07	-0.07	0.11	-0.11	0.11	-0.11	0.09	-0.09	0.09	-0.09	0.03	-0.03
b-tag C7	0.2	-0.2	0.04	-0.04	-0.13	0.13	-0.2	0.2	-0.22	0.22	-0.19	0.19	-0.21	0.2	-0.23	0.23
b-tag C8	0.0	0.0	0.0	0.0	-0.01	0.01	-0.01	0.01	0.02	-0.02	0.04	-0.04	0.05	-0.05	0.06	-0.06
b-tag Light0	-0.02	0.02	-0.01	0.01	-0.06	0.06	0.07	-0.07	0.03	-0.03	0.08	-0.08	0.22	-0.22	0.68	-0.68
b-tag Light2	0.0	0.0	0.0	0.0	0.02	-0.02	-0.02	0.02	-0.01	0.01	0.0	0.0	-0.05	0.05	-0.14	0.14
b-tag Light3	0.01	-0.01	0.01	-0.01	-0.01	0.01	-0.01	0.01	0.0	0.0	-0.03	0.03	-0.03	0.03	-0.06	0.06
b-tag Light4	0.01	-0.01	0.0	0.0	0.0	0.0	-0.02	0.02	0.0	0.0	-0.01	0.01	-0.04	0.04	-0.06	0.06
b-tag Light6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.01	0.01	-0.02	0.02	-0.06	0.06
EG RESOLUTION ALL	-0.22	0.08	0.05	0.01	0.25	-0.04	0.02	-0.09	0.27	-0.06	0.02	0.11	-0.28	-0.12	0.35	-0.59
EG SCALE ALL	-0.3	0.02	0.16	-0.01	0.27	0.0	0.02	-0.04	0.19	0.15	0.3	-0.15	0.01	-0.18	0.02	-0.27
EL ID	0.0	0.0	0.0	0.0	0.01	-0.01	0.0	0.0	-0.01	0.01	-0.01	0.01	-0.02	0.02	-0.05	0.05
EL Isol	-0.08	0.08	-0.02	0.02	0.07	-0.07	0.1	-0.1	0.06	-0.07	0.03	-0.03	-0.01	0.01	-0.05	0.05
MU Isol stat.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.01	0.01	-0.02	0.02	-0.04	0.04	-0.05	0.05
MU Isol syst.	-0.05	0.05	-0.01	0.01	0.01	-0.01	0.02	-0.02	0.07	-0.07	0.15	-0.15	0.18	-0.18	0.2	-0.21
MU Trigger syst.	0.04	-0.04	0.0	0.0	-0.02	0.02	-0.04	0.04	-0.04	0.04	-0.05	0.05	-0.04	0.04	-0.04	0.04
MU CB	0.14	0.0	0.14	0.23	0.0	-0.21	-0.23	-0.11	-0.38	0.24	-0.31	0.09	-0.38	0.0	-0.53	-0.48
MU Momentum Scale	0.14	0.02	0.07	0.07	-0.28	-0.01	-0.03	-0.09	0.05	0.0	-0.01	0.02	-0.02	-0.18	-0.32	-0.42
MUON SAGITTA DATASAT	0.07	0.04	0.01	0.05	-0.01	0.01	-0.08	-0.1	-0.06	-0.07	-0.02	0.03	-0.19	-0.17	-0.36	-0.44
MUON SAGITTA RESBIAS	-0.01	0.2	0.14	-0.01	-0.01	-0.27	-0.09	-0.05	0.05	0.02	-0.13	-0.08	-0.1	-0.12	-0.56	-0.37
pileup	-0.36	0.11	0.03	0.03	0.37	-0.22	0.24	-0.06	0.14	0.09	0.38	-0.23	-0.31	0.52	0.23	-0.07
Modelling uncertainties																
$t\bar{t} \mu_R$	-0.59	0.34	-0.59	0.38	-0.51	-0.05	0.5	-0.23	2.04	-1.01	3.63	-0.64	3.73	-1.98	8.64	-4.37
$t\bar{t} \mu_F$	-0.01	0.13	0.06	0.01	-0.43	-0.11	-0.2	0.11	0.05	-0.08	1.61	0.15	1.16	-0.96	3.96	-2.58
$t\bar{t}$ FSR	-0.07	0.81	0.2	-0.03	-0.35	-0.86	-0.05	-1.73	0.27	-0.48	1.52	2.89	0.52	1.54	-0.58	5.75
$t\bar{t}$ ISR α_S	-0.07	0.13	-0.02	0.02	-0.11	-0.35	-0.01	-0.02	0.12	0.09	1.17	0.7	0.46	-0.2	0.71	0.42
$t\bar{t}$ PDF	0.34	-0.27	-0.01	0.03	-0.46	-0.04	-0.26	0.26	-0.15	0.34	0.76	1.05	-0.07	0.29	0.1	0.81
$t\bar{t}$ Parton shower	-0.12	(0.12)	-0.82	(0.82)	0.33	(-0.33)	0.85	(-0.85)	1.44	(-1.44)	0.58	(-0.58)	-5.31	(5.31)	0.15	(-0.15)
$t\bar{t}$ NLO matching	2.55	(-2.55)	0.22	(-0.22)	-0.32	(0.32)	-0.43	(0.43)	-7.83	(7.83)	-4.73	(4.73)	-6.16	(6.16)	-16.49	(16.49)
JES Flavor Composition $t\bar{t}$	0.07	0.07	-0.17	0.04	-0.02	-0.07	0.13	-0.2	0.02	0.23	-0.06	-0.15	-0.29	-0.39	0.09	0.57
JES Flavor Composition $tW + t\bar{W}, t\bar{b}/t\bar{b}$	-0.04	0.1	0.01	-0.12	0.01	-0.09	0.03	0.01	-0.12	0.05	0.24	0.09	0.1	-0.07	0.4	0.09
mj e shape	0.51	0.49	-0.5	-0.04	0.19	-0.97	-0.18	0.28	-0.95	0.02	-0.8	-0.18	-0.8	-0.16	-0.82	-0.15
mj $\bar{e}$ shape	-0.18	0.15	-0.07	-0.05	0.54	-0.19	-0.5	-0.03	0.31	-0.01	0.47	-0.03	0.3	-0.03	0.32	-0.03
mj μ shape	0.3	-0.3	-0.07	0.07	-0.26	0.26	-0.06	0.06	-0.34	0.34	-0.08	0.08	-0.03	0.03	-0.86	0.86
$t\bar{t} \mu_R$	0.0	0.0	0.0	0.0	0.01	-0.01	0.0	0.0	-0.04	0.03	-0.01	0.0	0.06	-0.06	-0.05	-0.01
$t\bar{t} \mu_F$	0.06	-0.05	0.04	-0.03	-0.04	0.03	-0.06	0.06	-0.09	0.08	-0.08	0.06	-0.12	0.13	0.06	0.04
$t\bar{t}$ FSR	0.17	-0.07	-0.14	-0.11	-0.04	0.08	-0.05	0.06	-0.13	0.0	-0.1	-0.43	0.49	-0.16	-0.7	3.58
$t\bar{t}$ ISR α_S	0.03	-0.02	-0.06	0.05	-0.02	0.03	-0.03	0.03	0.0	-0.06	0.26	-0.29	0.04	-0.07	-0.14	0.25
$tW + t\bar{W}, t\bar{b}/t\bar{b} \mu_R$	0.01	-0.01	0.0	0.0	-0.01	0.0	-0.01	0.0	-0.01	0.01	-0.03	0.02	0.03	-0.02	-0.13	0.1
$tW + t\bar{W}$ DS	0.1	(-0.1)	-0.06	(0.06)	-0.03	(0.03)	0.0	(0.0)	0.02	(-0.02)	0.36	(-0.36)	-0.96	(0.96)	-0.14	(0.14)
$tW + t\bar{W}, t\bar{b}/t\bar{b} \mu_F$	0.02	-0.01	0.0	0.0	-0.01	0.01	-0.02	0.01	0.0	0.0	-0.03	0.02	-0.03	0.02	-0.11	0.1
$tW + t\bar{W}, t\bar{b}/t\bar{b}$ FSR	-0.01	0.0	0.01	0.04	-0.01	-0.03	-0.1	0.18	0.13	-0.22	0.34	-0.59	0.02	0.33	0.09	-0.39
$tW + t\bar{W}, t\bar{b}/t\bar{b}$ ISR α_S	0.01	-0.01	-0.02	-0.01	0.01	0.0	-0.01	0.03	-0.02	0.03	0.09	-0.06	-0.12	0.11	-0.07	0.01
$W + b\bar{b} \mu_F$	0.43	-0.43	-0.09	0.09	-0.57	0.57	-0.09	0.09	-0.33	0.33	0.19	-0.19	0.34	-0.34	0.06	-0.06
$W + b\bar{b} \mu_R$	0.04	0.49	-0.1	-0.7	0.02	-0.15	0.08	-0.07	-0.13	-0.01	0.08	0.36	-0.31	-0.25	-0.01	-0.16
$W + c(\bar{c}) \mu_F$	0.43	-1.55	-0.16	0.65	-0.31	0.96	-0.28	0.97	-0.09	0.86	-0.53	1.12	0.0	0.44	-0.21	0.82
$W + c(\bar{c}) \mu_R$	-0.06	-0.62	-0.18	0.02	0.39	0.71	-0.04	0.38	-0.12	0.12	-0.38	-0.05	-0.08	0.33	-0.1	1.0
$t\bar{t}, tW + t\bar{W}, t\bar{b}/t\bar{b}$ PDF	0.1	-0.1	0.06	-0.06	-0.02	0.02	-0.1	0.1	-0.19	0.19	-0.34	0.34	-0.16	0.16	-0.49	0.5
$tW + t\bar{W}, t\bar{b}/t\bar{b}$ Parton shower	0.19	(-0.19)	-0.09	(0.09)	-0.15	(0.15)	-0.12	(0.12)	0.13	(-0.13)	0.49	(-0.49)	-1.37	(1.37)	0.18	(-0.18)
$t\bar{t}$ Parton shower	-0.04	(0.04)	-0.2	(0.2)	-0.64	(0.64)	0.32	(-0.32)	1.43	(-1.43)	-0.02	(0.02)	3.89	(-3.89)	-0.75	(0.75)
$t\bar{t}$ NLO matching	0.33	(-0.33)	0.16	(-0.16)	-0.19	(0.19)	-0.23	(0.23)	-0.56	(0.56)	-2.25	(2.25)	1.39	(-1.39)	-1.18	(1.18)
$tW + t\bar{W}$ NLO matching	0.05	(-0.05)	-0.05	(0.05)	0.0	(0.0)	0.05	(-0.05)	-0.01	(0.01)	-0.05	(0.05)	-1.13	(1.13)	0.37	(-0.37)
$t\bar{t} h_{\text{damp}}$	0.23	(-0.23)	0.17	(-0.17)	-0.35	(0.35)	-0.08	(0.08)	-0.06	(0.06)	-1.35	(1.35)	-0.07	(0.07)	0.92	(-0.92)
Background rate uncertainties																
$t\bar{t}$ rate	0.01	-0.01	0.03	-0.03	0.01	-0.01	-0.01	0.01	-0.04	0.04	-0.03	0.03	-0.13	0.14	-0.26	0.26
$tW + t\bar{W}, t\bar{b}/t\bar{b}$ rate	-0.05	0.05	0.01	-0.01	0.04	-0.04	0.05	-0.05	0.0	0.0	-0.01	0.01	0.04	-0.04	-0.12	0.12
$W + b\bar{b}$ rate	-0.34	0.34	-0.13	0.13	0.23	-0.23	0.41	-0.41	0.34	-0.34	0.46	-0.47	0.44	-0.45	0.41	-0.41
$W + c(\bar{c})$ rate	-1.08	1.11	0.04	-0.04	0.73	-0.75	0.92	-0.94	0.9	-0.93	0.87	-0.89	0.83	-0.85	1.08	-1.11
VV, γ jets rate	-0.41	0.41	0.0	0.0	0.28	-0.28	0.35	-0.35	0.34	-0.34	0.33	-0.34	0.39	-0.39	0.42	-0.42
mj e rate	-0.19	0.19	-0.01	0.01	-0.01	0.01	0.21	-0.21	0.39	-0.39	0.34	-0.34	0.34	-0.35	0.35	-0.35
mj $\bar{$																



Table F.8.: Contribution of each individual uncertainty on the normalised differential tq cross section binned in $|y(t)|$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
Experimental uncertainties					
JER DataVsMC MC16	0.69 / -0.53	1.61 / -0.13	0.3 / -0.61	0.68 / -0.48	-1.62 / 0.87
JER Effective NP 1	-0.73 / -0.01	0.84 / 0.99	0.19 / 0.2	-1.5 / 0.31	0.38 / -0.79
JER Effective NP 2	-1.05 / 0.5	-0.01 / 0.67	-0.06 / 0.94	-1.65 / 1.19	1.18 / -1.66
JER Effective NP 3	0.5 / -1.11	0.59 / 0.2	0.08 / -0.68	0.47 / -1.57	-0.78 / 1.45
JER Effective NP 4	0.33 / -0.27	0.32 / 1.38	-0.37 / 0.01	1.3 / -0.21	-0.64 / -0.55
JER Effective NP 5	-0.26 / 0.04	0.82 / 0.56	-0.11 / 0.16	-0.5 / -0.03	-0.05 / -0.41
JER Effective NP 6	0.12 / -0.76	0.27 / 1.17	-0.41 / 0.03	-0.68 / -0.11	0.37 / -0.29
JER Effective NP 7	-0.85 / 0.7	0.53 / 0.56	-0.17 / -0.09	0.06 / -0.11	0.14 / -0.47
JER Effective NP 8	-0.01 / 0.35	0.2 / 0.17	0.32 / -0.61	-0.34 / -0.66	-0.15 / 0.43
JER Effective NP 9	-0.3 / 0.01	0.25 / 0.59	-0.21 / 0.13	-0.84 / -0.29	0.48 / -0.27
JER Effective NP 10	-0.26 / 0.11	-0.15 / 0.24	-0.59 / 0.52	-0.57 / -0.12	0.8 / -0.45
JER Effective NP 11	-0.34 / -0.21	0.58 / -0.25	0.76 / -0.65	-0.33 / -0.67	-0.5 / 0.91
JER Effective NP 12restTerm	-0.3 / 0.32	0.16 / 0.23	-0.63 / 0.38	-0.64 / 0.19	0.7 / -0.57
JES Effective NP Detector1	0.06 / -0.07	-0.07 / -0.06	-0.05 / -0.08	0.04 / 0.1	0.02 / 0.07
JES Effective NP Detector2	0.06 / -0.01	-0.01 / 0.0	-0.01 / 0.02	0.0 / 0.0	-0.02 / -0.01
JES Effective NP Modelling1	0.12 / -0.46	0.0 / -0.42	0.14 / -0.57	0.09 / -0.42	-0.17 / 0.95
JES Effective NP Modelling2	0.01 / 0.0	-0.05 / -0.07	-0.09 / 0.06	-0.04 / 0.12	0.1 / -0.06
JES Effective NP Modelling3	-0.04 / 0.07	-0.03 / -0.04	0.01 / -0.04	0.14 / -0.01	-0.04 / 0.02
JES Effective NP Modelling4	0.03 / -0.07	-0.03 / -0.07	-0.02 / -0.04	0.02 / 0.09	0.01 / 0.05
JES Effective NP Mixed1	0.09 / -0.16	-0.02 / -0.06	-0.04 / -0.02	-0.06 / 0.11	0.03 / 0.06
JES Effective NP Mixed2	-0.34 / 0.09	-0.19 / -0.06	-0.25 / -0.04	-0.16 / 0.04	0.46 / 0.01
JES Effective NP Mixed3	0.06 / -0.06	-0.02 / -0.07	-0.02 / -0.07	0.0 / 0.06	0.0 / 0.07
JES Effective NP Statistical2	-0.27 / 0.06	-0.15 / -0.1	-0.23 / 0.06	-0.22 / 0.03	0.43 / -0.02
JES Effective NP Statistical4	0.04 / -0.02	-0.04 / -0.04	-0.04 / 0.01	0.02 / 0.14	0.02 / -0.04
JES Effective NP Statistical6	0.05 / -0.07	-0.04 / -0.07	-0.01 / -0.04	-0.02 / 0.09	0.02 / 0.05
JES Effective NP Statistical5	-0.07 / 0.04	-0.06 / -0.05	-0.04 / -0.02	0.07 / 0.02	0.05 / 0.01
JES Flavor Response	-0.6 / 0.01	-0.58 / 0.07	-0.64 / 0.03	-0.27 / -0.3	1.07 / 0.07
BJES Response	0.14 / 0.01	-0.05 / 0.07	-0.08 / -0.1	0.03 / 0.12	0.01 / -0.03
JES Flavor Composition $tq, \bar{t}q$	0.68 / -0.36	0.56 / -0.37	0.15 / -0.59	0.14 / -0.02	-0.73 / 0.72
JES pileup OffsetMu	-0.08 / -0.09	-0.05 / -0.42	0.42 / -0.53	-0.76 / -0.01	0.12 / 0.59
JES pileup OffsetNPV	0.02 / 0.05	0.21 / -0.48	0.03 / -0.44	-0.07 / -0.12	-0.11 / 0.56
JES pileup RhoTopology	-0.17 / -0.73	0.11 / -0.57	0.31 / -0.27	-0.51 / -0.79	0.03 / 1.11
JES pileup PtTerm	-0.21 / -0.08	0.07 / -0.3	-0.09 / -0.39	0.14 / -0.32	0.04 / 0.58
JES EtaIntercalibration Modelling	1.01 / -0.89	0.19 / -1.06	0.72 / -1.03	-0.4 / -0.47	-0.79 / 1.78
JES EtaIntercalibration TotalStat	0.11 / -0.18	-0.01 / -0.19	0.28 / -0.39	-0.26 / -0.36	-0.1 / 0.57
JES EtaIntercalibration NonClosure posEta	-0.03 / -0.08	-0.03 / -0.02	0.0 / 0.0	-0.05 / -0.08	0.05 / 0.08
JES EtaIntercalibration NonClosure 2018data	0.05 / -0.12	0.02 / -0.08	-0.05 / 0.03	0.01 / -0.08	0.0 / 0.11
MET SoftTrk Scale	-0.36 / 0.07	-0.21 / 0.13	-0.14 / 0.11	0.25 / 0.23	0.23 / -0.27
MET SoftTrk ResoPara	-1.28 / -	-0.38 / -	-0.46 / -	-0.27 / -	1.12 / -
MET SoftTrk ResoPerp	-1.6 / -	-0.46 / -	-0.55 / -	-0.33 / -	1.38 / -
fJVT	-0.03 / 0.02	-0.06 / 0.06	0.0 / 0.0	0.03 / -0.03	0.03 / -0.03
b-tag B6	0.05 / -0.05	0.04 / -0.04	0.03 / -0.03	0.01 / -0.01	-0.06 / 0.06
b-tag C0	0.0 / 0.0	-0.01 / 0.01	-0.01 / 0.01	-0.1 / 0.1	0.05 / -0.05
b-tag C1	0.0 / 0.0	0.01 / -0.01	0.01 / -0.01	0.06 / -0.06	-0.04 / 0.04
b-tag C2	0.0 / 0.0	0.01 / -0.01	0.0 / 0.0	0.04 / -0.04	-0.02 / 0.02
b-tag C3	0.0 / 0.0	0.01 / -0.01	0.0 / 0.0	0.08 / -0.08	-0.04 / 0.04
b-tag C5	0.01 / -0.01	-0.01 / 0.01	0.04 / -0.04	0.05 / -0.05	-0.05 / 0.05



F. Systematic uncertainties

EG RESOLUTION ALL	-0.3 / 0.11	-0.11 / 0.02	-0.2 / -0.04	-0.16 / -0.16	0.37 / 0.04
EG SCALE ALL	-0.13 / -0.07	-0.1 / -0.01	-0.18 / -0.02	-0.25 / 0.07	0.33 / 0.02
EL Isol	-0.1 / 0.1	-0.08 / 0.08	0.0 / 0.0	0.09 / -0.1	0.04 / -0.04
MU Isol syst.	0.07 / -0.07	0.06 / -0.06	0.02 / -0.02	-0.03 / 0.03	-0.06 / 0.06
MU CB	-0.06 / -0.03	-0.03 / 0.16	0.07 / -0.05	0.2 / 0.16	-0.09 / -0.11
MU Momentum Scale	-0.1 / -0.02	-0.01 / 0.01	-0.01 / 0.09	0.11 / 0.05	0.0 / -0.08
MUON SAGITTA DATASTAT	-0.04 / -0.03	-0.01 / 0.0	0.08 / 0.0	0.04 / 0.03	-0.05 / 0.0
MUON SAGITTA RESBIAS	-0.05 / -0.06	0.01 / 0.1	-0.04 / 0.09	0.16 / 0.06	-0.03 / -0.12
pileup	-0.21 / 0.24	-0.27 / 0.2	-0.16 / 0.12	-0.23 / 0.12	0.43 / -0.33
Modelling uncertainties					
$tq \mu_R$	0.28 / -0.18	0.41 / -0.15	0.37 / -0.19	0.05 / -0.14	-0.46 / 0.26
$tq \mu_F$	0.19 / -0.18	0.29 / -0.14	0.17 / -0.13	-0.11 / -0.08	-0.37 / 0.29
tq FSR	0.02 / -0.68	0.2 / -0.43	0.12 / 0.34	-0.05 / -0.24	-0.17 / 0.4
tq ISR α_S	-0.05 / 0.06	0.09 / 0.06	0.05 / 0.0	-0.02 / -0.13	-0.05 / -0.01
tq PDF	-0.08 / 0.08	0.01 / 0.12	-0.03 / 0.09	-0.18 / 0.05	-0.06 / 0.01
tq Parton shower	-0.44 / (0.44)	0.45 / (-0.45)	0.32 / (-0.32)	0.83 / (-0.83)	-0.64 / (0.64)
tq NLO matching	0.34 / (-0.34)	-0.47 / (0.47)	-0.19 / (0.19)	0.29 / (-0.29)	0.0 / (0.0)
JES Flavor Composition $t\bar{t}$	0.1 / -0.1	0.04 / -0.03	0.03 / 0.05	0.06 / -0.03	-0.1 / (0.04)
mj e shape	0.21 / -0.08	0.17 / 0.07	0.25 / -0.1	-0.13 / 0.24	-0.28 / -0.05
mj fe shape	-0.15 / -0.13	-0.17 / -0.14	-0.18 / -0.14	0.02 / -0.06	0.26 / 0.24
mj μ shape	-0.2 / 0.2	-0.08 / 0.08	-0.22 / 0.22	0.01 / -0.01	0.25 / -0.25
$t\bar{t}$ FSR	-0.07 / 0.47	0.06 / -0.25	0.04 / -0.12	-0.06 / 0.17	0.0 / -0.06
$tW + t\bar{W}$ DS	0.08 / (-0.08)	-0.03 / (0.03)	-0.09 / (0.09)	-0.06 / (0.06)	0.06 / (-0.06)
$tW + t\bar{W}, tb/t\bar{b}$ FSR	0.03 / -0.03	-0.01 / 0.0	0.0 / 0.05	0.05 / -0.07	-0.03 / 0.01
$W + b\bar{b} \mu_F$	0.18 / -0.18	0.18 / -0.18	-0.09 / 0.09	0.41 / -0.41	-0.29 / 0.29
$W + b\bar{b} \mu_R$	0.07 / -0.07	0.02 / -0.09	0.2 / -0.16	0.1 / -0.57	-0.21 / 0.42
$W + c(\bar{c}) \mu_F$	0.35 / -0.13	0.33 / -0.13	0.47 / 0.44	1.0 / -0.31	-1.05 / -0.02
$W + c(\bar{c}) \mu_R$	0.27 / 0.16	0.23 / 0.48	0.09 / -0.33	0.31 / 0.35	-0.42 / -0.27
$tW + t\bar{W}, tb/t\bar{b}$ Parton shower	0.11 / (-0.11)	0.04 / (-0.04)	-0.12 / (0.12)	0.06 / (-0.06)	-0.02 / (0.02)
$t\bar{t}$ Parton shower	0.03 / (-0.03)	0.04 / (-0.04)	0.16 / (-0.16)	0.23 / (-0.23)	-0.23 / (0.23)
$t\bar{t}$ NLO matching	0.03 / (-0.03)	0.04 / (-0.04)	0.11 / (-0.11)	0.02 / (-0.02)	-0.11 / (0.11)
$tW + t\bar{W}$ NLO matching	0.17 / (-0.17)	-0.03 / (0.03)	-0.02 / (0.02)	0.04 / (-0.04)	-0.05 / (0.05)
$t\bar{t} h_{damp}$	0.04 / (-0.04)	0.07 / (-0.07)	0.08 / (-0.08)	-0.01 / (0.01)	-0.1 / (0.1)
Background rate uncertainties					
$t\bar{t}$ rate	-0.04 / 0.04	-0.03 / 0.03	-0.02 / 0.02	0.0 / 0.0	0.04 / -0.04
$W + b\bar{b}$ rate	0.16 / -0.16	0.09 / -0.1	0.05 / -0.06	0.02 / -0.02	-0.16 / 0.16
$W + c(\bar{c})$ rate	-0.01 / 0.01	-0.02 / 0.03	0.04 / -0.04	0.27 / -0.27	-0.13 / 0.13
$VV, +jets$ rate	0.13 / -0.13	0.12 / -0.12	0.08 / -0.08	-0.02 / 0.02	-0.15 / 0.16
mj e rate	-0.05 / 0.05	-0.05 / 0.06	-0.08 / 0.08	0.04 / -0.04	0.08 / -0.08
mj fe rate	0.06 / -0.06	0.06 / -0.06	0.05 / -0.05	0.14 / -0.14	-0.14 / 0.15
mj μ rate	0.04 / -0.04	0.07 / -0.07	0.09 / -0.09	-0.02 / 0.02	-0.1 / 0.1
Statistical uncertainties					
Data stat.	1.72 / -1.72	1.44 / -1.44	1.64 / -1.64	1.92 / -1.92	1.89 / -1.89
MC stat.	0.76 / -0.76	0.73 / -0.73	0.74 / -0.74	0.81 / -0.81	0.84 / -0.84
Total uncertainty	2.8 / -4.1	3.7 / -2.6	2.7 / -3.2	3.3 / -4.4	5.0 / -4.1



Table F.9.: Contribution of each individual uncertainty on the normalised differential $\bar{t}q$ cross section binned in $|\mathbf{y}(\bar{t})|$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]									
	Bin 1		Bin 2		Bin 3		Bin 4		Bin 5	
Experimental uncertainties										
JER DataVsMC MC16	-1.74 /	0.19	0.79 /	-0.53	1.73 /	0.21	-0.51 /	-0.62	-0.69 /	0.47
JER Effective NP 1	1.74 /	-3.07	-0.99 /	0.39	-0.15 /	1.01	1.83 /	-1.0	-1.15 /	1.16
JER Effective NP 2	1.24 /	-2.22	-0.75 /	1.67	-0.44 /	1.24	-0.38 /	0.17	0.43 /	-1.06
JER Effective NP 3	-1.6 /	1.41	1.26 /	-0.71	0.36 /	0.01	-0.25 /	0.34	-0.17 /	-0.45
JER Effective NP 4	-1.83 /	0.34	0.41 /	-0.22	-0.77 /	1.67	0.09 /	0.02	1.23 /	-1.34
JER Effective NP 5	-1.09 /	0.02	-0.31 /	-0.21	0.64 /	-0.36	-0.45 /	-0.98	0.56 /	0.99
JER Effective NP 6	-1.52 /	0.48	-0.32 /	-0.29	0.86 /	0.75	-0.2 /	0.34	0.48 /	-0.83
JER Effective NP 7	-0.37 /	-0.4	-0.34 /	-0.11	0.99 /	-0.2	-0.2 /	0.06	-0.22 /	0.41
JER Effective NP 8	-0.41 /	-1.26	0.8 /	0.61	0.58 /	-0.55	-0.39 /	0.47	-0.58 /	0.4
JER Effective NP 9	-0.39 /	-0.6	0.47 /	-0.69	-0.25 /	0.25	-0.2 /	-0.13	0.19 /	0.68
JER Effective NP 10	0.07 /	-0.68	-0.17 /	0.17	0.04 /	-0.65	0.76 /	-0.23	-0.39 /	0.89
JER Effective NP 11	-0.9 /	-0.55	-0.14 /	0.35	0.28 /	-0.62	0.1 /	0.58	0.3 /	0.2
JER Effective NP 12restTerm	-0.22 /	-0.23	-0.18 /	0.03	0.01 /	-1.1	0.46 /	-0.52	-0.03 /	1.26
JES Effective NP Detector1	0.2 /	0.15	-0.29 /	0.07	-0.04 /	0.19	0.14 /	-0.02	0.04 /	-0.27
JES Effective NP Detector2	0.01 /	0.07	0.0 /	-0.01	0.01 /	-0.03	0.0 /	-0.02	-0.01 /	0.0
JES Effective NP Modelling1	0.37 /	0.67	0.15 /	-0.11	0.5 /	-0.28	0.21 /	0.0	-0.82 /	-0.06
JES Effective NP Modelling2	0.19 /	0.07	-0.08 /	-0.02	0.1 /	0.0	0.1 /	0.06	-0.18 /	-0.05
JES Effective NP Modelling3	0.03 /	0.26	-0.05 /	-0.15	0.09 /	0.02	0.03 /	0.15	-0.07 /	-0.14
JES Effective NP Modelling4	-0.04 /	0.05	0.02 /	0.02	-0.02 /	-0.04	-0.02 /	-0.05	0.03 /	0.02
JES Effective NP Mixed1	0.17 /	0.05	-0.28 /	0.06	0.05 /	0.14	0.12 /	-0.18	0.0 /	-0.08
JES Effective NP Mixed2	0.07 /	0.07	0.17 /	-0.25	0.13 /	0.11	-0.06 /	0.17	-0.22 /	-0.05
JES Effective NP Mixed3	0.18 /	0.05	-0.29 /	0.0	-0.01 /	0.16	0.11 /	-0.12	0.06 /	-0.08
JES Effective NP Statistical1	0.01 /	0.07	0.0 /	0.01	0.01 /	-0.02	-0.01 /	-0.04	-0.01 /	-0.01
JES Effective NP Statistical2	0.05 /	0.09	0.14 /	-0.26	0.2 /	0.1	-0.04 /	0.15	-0.26 /	-0.03
JES Effective NP Statistical4	0.14 /	0.1	-0.23 /	-0.03	0.03 /	0.0	0.11 /	-0.01	0.0 /	-0.03
JES Effective NP Statistical6	0.0 /	0.11	-0.02 /	-0.01	0.04 /	-0.02	0.03 /	-0.05	-0.04 /	0.0
JES Effective NP Statistical5	0.05 /	0.18	-0.08 /	-0.24	0.12 /	0.0	0.02 /	0.11	-0.07 /	0.01
JES Flavor Response	0.14 /	0.27	-0.6 /	0.09	0.38 /	0.55	-0.17 /	1.11	0.15 /	-1.28
BJES Response	-0.06 /	0.08	-0.15 /	-0.24	0.18 /	0.06	0.38 /	0.29	-0.22 /	-0.09
JES Flavor Composition $tq, \bar{t}q$	0.56 /	-0.26	0.38 /	-0.36	0.4 /	0.25	0.25 /	-0.06	-1.02 /	0.25
JES pileup OffsetMu	0.1 /	0.4	-0.65 /	-0.04	0.82 /	-0.48	0.91 /	0.06	-0.76 /	0.15
JES pileup OffsetNPV	0.47 /	-0.42	0.15 /	0.07	0.18 /	0.34	0.11 /	0.18	-0.56 /	-0.19
JES pileup RhoTopology	0.73 /	0.65	0.61 /	-0.1	0.56 /	0.42	0.5 /	-0.24	-1.54 /	-0.47
JES pileup PtTerm	0.49 /	0.26	-0.37 /	-0.01	0.4 /	0.08	0.29 /	0.04	-0.48 /	-0.22
JES EtaIntercalibration Modelling	0.65 /	0.34	0.33 /	-0.94	1.12 /	-0.43	0.51 /	0.88	-1.75 /	0.31
JES EtaIntercalibration TotalStat	0.1 /	0.26	-0.14 /	-0.02	0.25 /	0.04	-0.02 /	0.02	-0.14 /	-0.16
JES EtaIntercalibration NonClosure negEta	0.15 /	0.04	0.14 /	-0.07	-0.3 /	0.04	0.09 /	0.06	0.0 /	-0.04
JES EtaIntercalibration NonClosure 2018data	0.2 /	0.04	-0.04 /	-0.23	0.0 /	-0.03	-0.15 /	-0.1	0.01 /	0.22
MET SoftTrk Scale	-0.01 /	0.49	-0.41 /	-0.14	0.36 /	0.09	-0.26 /	0.66	0.16 /	-0.61
MET SoftTrk ResoPara	0.46 /	-	-0.65 /	-	0.04 /	-	0.69 /	-	-0.21 /	-
MET SoftTrk ResoPerp	-0.12 /	-	-0.77 /	-	-0.07 /	-	0.33 /	-	0.47 /	-
JVT	-0.02 /	0.01	-0.01 /	0.01	0.05 /	-0.04	-0.04 /	0.03	0.0 /	0.0
fJVT	0.01 /	-0.02	-0.14 /	0.14	-0.02 /	0.01	-0.04 /	0.04	0.13 /	-0.12
b-tag B4	-0.01 /	0.01	-0.01 /	0.01	-0.02 /	0.02	-0.03 /	0.03	0.05 /	-0.05
b-tag B5	-0.03 /	0.03	-0.03 /	0.03	-0.03 /	0.03	-0.02 /	0.02	0.07 /	-0.07
b-tag B6	0.03 /	-0.03	0.03 /	-0.03	0.02 /	-0.02	0.01 /	-0.01	-0.07 /	0.07
b-tag C0	-0.01 /	0.01	0.0 /	0.0	-0.04 /	0.04	-0.02 /	0.02	0.05 /	-0.05
b-tag C3	0.01 /	-0.01	0.0 /	0.0	0.03 /	-0.03	0.02 /	-0.02	-0.04 /	0.04



F. Systematic uncertainties

b-tag C5	0.09 / -0.09	0.02 / -0.02	0.02 / -0.02	-0.01 / 0.01	-0.08 / 0.08
b-tag C6	-0.01 / 0.01	0.0 / 0.0	-0.03 / 0.03	-0.05 / 0.05	0.05 / -0.05
b-tag Light0	0.0 / 0.0	0.01 / -0.01	-0.01 / 0.01	0.04 / -0.04	-0.02 / 0.02
EG RESOLUTION ALL	0.49 / 0.06	-0.04 / -0.13	0.3 / -0.02	-0.48 / -0.09	-0.19 / 0.13
EG SCALE ALL	0.13 / 0.03	0.17 / -0.1	0.44 / 0.06	-0.55 / -0.04	-0.21 / 0.03
EL Isol	-0.11 / 0.11	-0.06 / 0.06	-0.02 / 0.02	0.09 / -0.09	0.06 / -0.06
MU Isol syst.	0.05 / -0.05	0.04 / -0.04	0.01 / -0.01	-0.05 / 0.05	-0.04 / 0.04
MU CB	-0.29 / 0.1	-0.07 / -0.13	0.18 / -0.22	-0.01 / 0.3	0.07 / 0.03
MU Momentum Scale	0.04 / 0.0	-0.32 / 0.05	-0.04 / 0.02	0.06 / 0.05	0.19 / -0.08
MUON SAGITTA DATASTAT	-0.03 / -0.02	-0.04 / 0.03	0.0 / 0.0	-0.03 / 0.03	0.06 / -0.03
MUON SAGITTA RESBIAS	0.09 / 0.04	-0.08 / -0.37	-0.12 / 0.03	0.14 / 0.09	0.02 / 0.16
pileup	0.04 / -0.09	0.07 / 0.05	-0.15 / 0.09	-0.17 / 0.15	0.15 / -0.15
Modelling uncertainties					
$\bar{t}q \mu_R$	-0.19 / -0.32	0.11 / 0.0	-0.04 / -0.07	-0.13 / -0.26	0.06 / 0.42
$\bar{t}q \mu_F$	0.05 / -0.56	0.29 / -0.18	0.07 / -0.19	-0.2 / -0.24	-0.3 / 0.81
$\bar{t}q$ FSR	-0.17 / 0.08	0.22 / -0.23	-0.36 / -0.27	-0.79 / -0.33	0.66 / 0.52
$\bar{t}q$ ISR α_S	-0.28 / -0.28	0.01 / 0.06	-0.1 / -0.08	-0.33 / -0.08	0.4 / 0.21
$\bar{t}q$ PDF	-0.46 / -0.08	-0.16 / 0.25	-0.34 / 0.22	-0.48 / 0.07	0.39 / 0.17
$\bar{t}q$ Parton shower	-1.09 / (1.09)	-0.03 / (0.03)	1.32 / (-1.32)	0.91 / (-0.91)	-1.06 / (1.06)
$\bar{t}q$ NLO matching	-1.17 / (1.17)	0.19 / (-0.19)	1.9 / (-1.9)	1.9 / (-1.9)	-2.08 / (2.08)
JES Flavor Composition $t\bar{t}$	-0.03 / -0.1	0.08 / -0.11	0.23 / 0.0	0.08 / 0.04	-0.26 / 0.11
mj e shape	-0.61 / -0.18	0.92 / -0.25	0.51 / -0.14	-0.55 / 0.72	-0.4 / -0.03
mj fe shape	0.87 / 0.06	0.91 / 0.07	1.12 / 0.12	0.8 / 0.06	-2.43 / -0.21
mj μ shape	0.08 / -0.08	0.04 / -0.04	0.42 / -0.42	0.11 / -0.11	-0.46 / 0.46
$t\bar{t} \mu_F$	0.0 / 0.01	-0.03 / 0.02	-0.07 / 0.06	-0.03 / 0.02	0.09 / -0.08
$t\bar{t}$ FSR	-0.12 / -0.47	0.0 / -0.03	0.29 / -0.35	0.04 / -0.25	-0.18 / 0.69
$t\bar{t}$ ISR α_S	0.01 / -0.01	0.02 / -0.01	0.03 / -0.03	0.04 / -0.02	-0.07 / 0.05
$tW + t\bar{W}$ DS	0.03 / (-0.03)	-0.03 / (0.03)	0.12 / (-0.12)	-0.29 / (0.29)	0.08 / (-0.08)
$tW + t\bar{W}, tb/\bar{t}b$ FSR	-0.03 / -0.22	-0.01 / -0.03	0.08 / -0.05	0.04 / -0.09	-0.06 / 0.23
$tW + t\bar{W}, tb/\bar{t}b$ ISR α_S	0.01 / 0.0	0.04 / -0.03	-0.01 / -0.02	0.0 / 0.02	-0.02 / 0.02
$W + b\bar{b} \mu_F$	-1.84 / 1.84	0.06 / -0.06	0.17 / -0.17	0.73 / -0.73	0.39 / -0.39
$W + b\bar{b} \mu_R$	0.0 / 0.04	0.04 / -0.05	0.6 / 0.66	0.5 / 0.88	-0.78 / -1.0
$W + c(\bar{c}) \mu_F$	-0.46 / -0.46	0.12 / 0.04	-0.05 / -0.02	-0.36 / 0.92	0.4 / -0.3
$W + c(\bar{c}) \mu_R$	0.22 / 0.49	-0.33 / -0.34	-0.63 / -1.05	-0.14 / -0.51	0.68 / 1.09
$t\bar{t}, tW + t\bar{W}, tb/\bar{t}b$ PDF	0.05 / -0.05	0.03 / -0.03	-0.01 / 0.01	-0.05 / 0.05	-0.01 / 0.01
$tW + t\bar{W}, tb/\bar{t}b$ Parton shower	-0.1 / (0.1)	-0.01 / (0.01)	0.0 / (0.0)	-0.09 / (0.09)	0.11 / (-0.11)
$t\bar{t}$ Parton shower	-0.09 / (0.09)	-0.23 / (0.23)	0.43 / (-0.43)	0.32 / (-0.32)	-0.3 / (0.3)
$t\bar{t}$ NLO matching	0.09 / (-0.09)	0.03 / (-0.03)	0.42 / (-0.42)	0.54 / (-0.54)	-0.71 / (0.71)
$tW + t\bar{W}$ NLO matching	-0.08 / (0.08)	-0.08 / (0.08)	0.06 / (-0.06)	-0.04 / (0.04)	0.08 / (-0.08)
$t\bar{t} h_{damp}$	0.2 / (-0.2)	0.11 / (-0.11)	0.07 / (-0.07)	0.23 / (-0.23)	-0.36 / (0.36)
Background rate uncertainties					
$t\bar{t}$ rate	-0.06 / 0.06	-0.04 / 0.04	-0.03 / 0.03	0.0 / 0.0	0.08 / -0.08
$W + b\bar{b}$ rate	0.03 / -0.04	0.01 / -0.01	-0.05 / 0.05	0.0 / 0.0	0.01 / -0.01
$W + c(\bar{c})$ rate	0.05 / -0.05	0.0 / 0.0	0.08 / -0.09	-0.02 / 0.02	-0.08 / 0.09
$VV, +jets$ rate	0.24 / -0.24	0.22 / -0.22	0.07 / -0.07	-0.11 / 0.12	-0.27 / 0.27
mj e rate	-0.09 / 0.09	-0.15 / 0.15	-0.1 / 0.1	0.06 / -0.06	0.2 / -0.2
mj fe rate	0.02 / -0.02	-0.04 / 0.04	0.02 / -0.02	0.2 / -0.2	-0.11 / 0.11
mj μ rate	0.24 / -0.25	0.05 / -0.05	0.1 / -0.1	0.23 / -0.23	-0.38 / 0.38
Statistical uncertainties					
Data stat.	2.31 / -2.31	1.92 / -1.92	2.22 / -2.22	2.57 / -2.57	2.77 / -2.77
MC stat.	0.68 / -0.68	0.64 / -0.64	0.65 / -0.65	0.76 / -0.76	0.81 / -0.81
Total uncertainty	4.9 / -6.6	3.7 / -3.5	5.3 / -4.1	5.0 / -4.3	5.2 / -6.3



Table F.10.: Contribution of each individual uncertainty on the differential $tq/\bar{t}q$ cross-section ratio binned in $p_T(t \text{ or } \bar{t})$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]															
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8								
	Experimental uncertainties															
JER DataVsMC MC16	-2.29 / -0.12	-1.66 / 0.84	0.97 / -0.37	0.24 / -0.12	0.59 / 0.77	-0.67 / -1.37	0.05 / 0.56	-0.75 / -1.22								
JER Effective NP 1	1.86 / -4.62	1.19 / -1.85	0.01 / 0.82	0.35 / 0.13	0.94 / 1.02	-0.01 / -1.51	-0.64 / -0.39	0.5 / 2.31								
JER Effective NP 2	-0.22 / -4.19	1.43 / -1.39	-0.02 / 1.88	-0.21 / -0.13	1.59 / -1.16	0.8 / -2.25	-1.0 / 0.48	0.91 / 0.71								
JER Effective NP 3	-3.43 / 0.54	-1.74 / 0.37	1.49 / -1.33	0.41 / -0.27	0.63 / 1.26	-1.43 / 0.12	3.02 / -0.41	0.53 / 0.66								
JER Effective NP 4	-1.95 / -2.74	-0.2 / -0.14	0.21 / 0.86	0.35 / 0.26	0.56 / 0.66	0.19 / -1.37	-2.03 / 0.81	2.46 / -1.06								
JER Effective NP 5	-2.47 / 0.07	-0.31 / -0.84	0.66 / -0.77	-0.03 / 0.14	1.01 / 0.82	-2.05 / 0.8	0.76 / 0.48	0.2 / 1.1								
JER Effective NP 6	-0.03 / -3.59	-1.1 / 0.67	-1.0 / 0.04	0.31 / -0.23	1.28 / 0.31	-2.47 / 1.39	0.97 / -0.21	0.35 / 0.92								
JER Effective NP 7	-2.41 / -1.72	0.22 / -0.85	0.83 / 0.74	-0.73 / 0.77	0.27 / -0.18	0.03 / -0.01	-0.04 / 0.12	0.83 / 0.25								
JER Effective NP 8	0.31 / -0.81	0.1 / -0.8	-0.09 / 0.3	0.53 / -0.15	1.02 / 0.07	-0.88 / -0.87	0.68 / 0.22	-0.07 / -0.71								
JER Effective NP 9	-1.67 / -1.0	0.23 / 0.13	0.21 / -0.03	-0.15 / 0.36	-0.12 / 0.7	0.19 / -2.17	-0.17 / 1.67	0.21 / 0.57								
JER Effective NP 10	-0.74 / -0.15	0.32 / -0.55	0.64 / 0.43	-0.06 / 0.21	-0.54 / 0.75	0.13 / 0.22	0.81 / -0.03	-0.77 / 1.8								
JER Effective NP 11	-0.16 / -0.45	0.0 / 0.06	-0.42 / 0.61	0.58 / -0.38	0.71 / -0.04	-1.02 / -0.8	0.89 / 0.66	-0.73 / 2.15								
JER Effective NP 12restTerm	-1.85 / -0.76	-0.32 / -0.41	0.34 / 0.52	-0.07 / 0.57	0.0 / 0.34	1.24 / -1.87	-0.55 / 2.25	0.88 / 0.6								
JES Effective NP Detector1	-0.01 / 0.08	0.01 / 0.01	0.4 / -0.03	0.04 / -0.03	-0.12 / -0.06	0.15 / 0.17	0.14 / -0.28	-0.24 / 0.21								
JES Effective NP Detector2	-0.01 / -0.12	-0.01 / -0.01	0.05 / 0.0	0.02 / 0.04	-0.08 / -0.07	0.13 / 0.03	-0.04 / -0.06	0.04 / 0.1								
JES Effective NP Modelling1	0.79 / -0.01	0.42 / 0.14	-0.32 / 0.48	-0.39 / -0.82	0.39 / -0.45	0.24 / 1.11	-0.43 / -0.85	-0.26 / 0.28								
JES Effective NP Modelling2	0.05 / 0.24	0.04 / 0.01	0.39 / -0.08	0.0 / 0.06	0.0 / -0.13	0.2 / 0.23	-0.29 / -0.15	0.32 / -0.14								
JES Effective NP Modelling3	-0.07 / -0.06	-0.03 / 0.01	-0.09 / 0.43	0.01 / -0.02	-0.1 / -0.01	0.08 / 0.11	-0.1 / -0.09	0.0 / 0.27								
JES Effective NP Modelling4	-0.05 / 0.02	-0.04 / -0.03	0.02 / -0.04	0.08 / 0.08	-0.08 / -0.12	0.06 / 0.12	0.27 / 0.04	0.25 / 0.51								
JES Effective NP Mixed1	-0.19 / -0.09	-0.09 / -0.1	0.46 / 0.01	0.07 / 0.02	-0.23 / -0.29	0.13 / 0.62	0.02 / -0.52	0.45 / 0.32								
JES Effective NP Mixed2	0.19 / 0.53	-0.1 / -0.15	-0.04 / 0.3	0.0 / 0.02	-0.26 / -0.16	0.53 / 0.16	-0.43 / 0.21	0.56 / -0.31								
JES Effective NP Mixed3	0.03 / 0.0	0.01 / -0.06	0.39 / -0.04	0.04 / 0.02	-0.11 / -0.02	0.1 / -0.05	0.0 / -0.07	-0.12 / 0.08								
JES Effective NP Statistical1	0.04 / -0.14	0.01 / 0.01	-0.01 / 0.01	0.0 / 0.02	-0.03 / -0.11	0.06 / 0.01	0.02 / -0.06	-0.22 / 0.1								
JES Effective NP Statistical2	0.32 / 0.45	0.04 / -0.09	-0.23 / 0.31	-0.04 / 0.08	0.05 / -0.09	0.05 / 0.24	0.09 / -0.02	-0.05 / -0.55								
JES Effective NP Statistical3	-0.02 / -0.01	0.03 / 0.01	-0.01 / -0.01	0.03 / 0.02	-0.13 / -0.06	0.2 / 0.14	-0.14 / -0.22	-0.05 / 0.15								
JES Effective NP Statistical4	-0.12 / -0.01	-0.01 / 0.0	0.43 / -0.01	-0.01 / 0.05	-0.02 / -0.23	0.12 / 0.18	-0.23 / -0.17	0.16 / 0.23								
JES Effective NP Statistical6	0.01 / 0.02	0.0 / 0.01	0.07 / 0.02	0.03 / 0.04	-0.04 / -0.1	-0.04 / -0.03	0.26 / 0.03	-0.2 / 0.07								
JES Effective NP Statistical5	-0.03 / -0.2	-0.03 / -0.01	-0.05 / 0.44	0.03 / 0.03	-0.03 / -0.11	0.06 / 0.0	0.05 / -0.15	-0.18 / 0.0								
JES Flavor Response	0.27 / 2.01	-0.17 / -0.01	-0.74 / -0.37	-0.05 / 0.18	-1.0 / 0.84	-0.17 / 0.18	-1.46 / -0.43	-0.6 / -0.56								
BJES Response	-0.22 / 0.17	0.33 / 0.02	0.41 / -0.24	-0.16 / -0.22	-0.49 / -0.18	0.38 / 0.53	0.16 / -0.14	-0.09 / 0.16								
JES Flavor Composition $tq, \bar{t}q$	0.95 / -1.2	0.82 / -0.97	0.65 / -0.87	0.16 / 0.05	0.46 / 0.02	0.43 / -0.16	-0.67 / -1.42	0.34 / -0.01								
JES pileup OffsetMu	5.23 / -1.03	-0.64 / -0.43	0.0 / 0.5	0.05 / -0.86	0.16 / 0.52	-0.18 / 0.71	0.26 / -0.58	0.03 / -0.71								
JES pileup OffsetNPV	1.02 / -0.09	0.05 / 0.03	-0.17 / 0.36	0.0 / -0.66	0.33 / 0.09	0.22 / 0.47	-0.34 / -0.34	-1.26 / 0.02								
JES pileup RhoTopology	1.33 / 0.51	0.75 / 0.29	-0.41 / -0.13	-0.11 / -0.06	0.5 / -0.21	-0.04 / 0.37	-1.11 / 0.42	-0.7 / 0.86								
JES pileup PtTerm	-0.12 / 0.5	0.11 / -0.21	0.47 / -0.24	-0.42 / 0.21	0.26 / -0.29	1.12 / 0.79	0.37 / -0.61	0.3 / 0.92								
JES SingleParticle HighPt	-0.07 / -0.07	-0.01 / -0.01	-0.03 / -0.03	0.06 / 0.06	0.12 / 0.12	-0.06 / -0.06	0.25 / 0.25	0.32 / 0.32								
JES PunchThrough MC16	-0.07 / -0.07	0.03 / 0.02	0.0 / 0.0	0.02 / 0.04	0.04 / 0.05	-0.05 / -0.05	0.29 / 0.28	-0.1 / -0.03								
JES EtaIntercalibration Modelling	2.6 / -0.29	1.02 / -0.35	-0.61 / -0.27	-0.76 / 0.26	0.63 / -0.51	0.57 / 1.37	-1.29 / -1.89	-0.19 / -0.35								
JES EtaIntercalibration TotalStat	0.89 / -0.18	0.01 / -0.04	-0.19 / 0.51	0.11 / -0.66	0.05 / -0.11	0.11 / 0.19	-0.49 / 0.13	-0.75 / 0.17								
JES EtaIntercalibration NonClosure highE	-0.02 / -0.02	0.03 / 0.02	-0.02 / -0.01	0.01 / 0.01	0.02 / 0.08	0.01 / -0.11	0.15 / 0.1	-0.5 / -0.04								
JES EtaIntercalibration NonClosure negEta	-0.19 / -0.02	-0.01 / 0.06	0.43 / -0.1	-0.03 / -0.05	-0.11 / 0.12	-0.16 / -0.15	0.5 / -0.1	-0.45 / 0.27								
JES EtaIntercalibration NonClosure posEta	-0.04 / -0.12	0.04 / 0.11	-0.06 / 0.02	-0.02 / 0.02	0.07 / 0.11	0.12 / -0.15	-0.22 / 0.28	-0.03 / -0.25								
JES EtaIntercalibration NonClosure 2018data	0.01 / 0.49	-0.1 / -0.09	-0.05 / -0.06	-0.01 / 0.06	-0.19 / -0.04	0.17 / 0.14	-0.11 / -0.14	-0.73 / 0.06								
MET SoftTrk Scale	0.37 / 0.0	-0.14 / -0.19	-0.13 / 0.4	-0.26 / 0.08	-0.38 / 0.47	0.55 / -0.09	1.17 / -0.63	0.08 / 1.86								
MET SoftTrk ResoPara	0.22 / -	-1.06 / -	-0.1 / -	0.33 / -	-2.23 / -	0.17 / -	1.37 / -	1.46 / -								
MET SoftTrk ResoPerp	0.14 / -	-0.51 / -	-0.28 / -	0.02 / -	-0.44 / -	0.37 / -	0.25 / -	0.06 / -								
JVT	-0.1 / 0.06	-0.04 / 0.02	-0.06 / 0.04	-0.02 / 0.01	-0.05 / 0.03	-0.08 / 0.07	-0.06 / 0.04	-0.08 / 0.06								
IJVT	-0.19 / 0.17	-0.02 / 0.02	-0.16 / 0.17	-0.04 / 0.04	-0.11 / 0.13	-0.13 / 0.14	-0.04 / 0.04	-0.18 / 0.18								
b-tag B0	-0.04 / 0.04	-0.04 / 0.04	-0.03 / 0.03	-0.04 / 0.04	-0.03 / 0.03	-0.03 / 0.03	-0.04 / 0.04	0.1 / -0.1								
b-tag B3	0.01 / -0.01	0.0 / 0.0	0.0 / 0.0	0.01 / -0.01	0.0 / 0.0	-0.01 / 0.01	0.02 / -0.02	0.06 / -0.06								
b-tag B4	-0.05 / 0.06	-0.04 / 0.04	-0.01 / 0.01	-0.06 / 0.06	0.0 / 0.0	0.03 / -0.04	-0.12 / 0.12	0.0 / 0.0								
b-tag B5	0.04 / -0.04	0.06 / -0.06	0.05 / -0.05	0.04 / -0.04	0.05 / -0.05	0.04 / -0.04	0.02 / -0.02	0.11 / -0.11								
b-tag B6	0.02 / -0.02	0.0 / 0.0	0.02 / -0.02	0.01 / -0.01	0.01 / -0.01	0.02 / -0.02	0.05 / -0.05	0.05 / -0.05								
b-tag C0	-0.14 / 0.14	-0.15 / 0.15	-0.14 / 0.14	-0.08 / 0.08	-0.09 / 0.09	-0.15 / 0.15	-0.26 / 0.27	-0.14 / 0.14								



F. Systematic uncertainties

b-tag C1	0.09	-0.09	0.09	-0.09	0.09	-0.09	0.05	-0.05	0.05	-0.05	0.04	-0.04	0.0	0.0	0.04	-0.04
b-tag C2	0.03	-0.03	0.06	-0.06	0.06	-0.06	0.03	-0.03	0.03	-0.03	0.02	-0.02	0.0	0.0	0.01	-0.01
b-tag C3	0.09	-0.08	0.1	-0.1	0.11	-0.11	0.06	-0.06	0.07	-0.07	0.06	-0.06	0.03	-0.03	0.04	-0.04
b-tag C4	0.05	-0.05	0.05	-0.05	0.06	-0.06	0.03	-0.03	0.03	-0.03	0.04	-0.04	0.03	-0.03	0.02	-0.02
b-tag C5	0.24	-0.24	0.09	-0.09	0.03	-0.03	0.04	-0.04	0.08	-0.08	0.04	-0.04	0.05	-0.05	0.0	0.0
b-tag C6	0.02	-0.02	0.07	-0.07	0.01	-0.01	-0.04	0.04	-0.03	0.03	-0.03	0.03	-0.02	0.02	0.01	-0.01
b-tag C7	-0.04	0.04	-0.1	0.1	-0.06	0.06	0.02	-0.02	0.01	-0.01	0.0	0.0	0.0	0.0	0.03	-0.03
b-tag Light0	0.0	0.0	-0.05	0.05	0.0	0.0	-0.12	0.12	-0.03	0.03	0.01	-0.01	-0.04	0.04	-0.24	0.24
b-tag Light2	0.0	0.0	0.02	-0.02	0.0	0.0	0.03	-0.03	0.01	-0.01	-0.01	0.01	-0.01	0.01	-0.05	-0.05
EG RESOLUTION ALL	0.88	-0.22	-0.01	-0.04	-0.32	0.04	-0.01	0.2	-0.34	-0.04	0.08	-0.22	0.5	0.17	-0.18	0.55
EG SCALE ALL	0.82	0.1	-0.06	-0.04	-0.24	-0.02	0.17	-0.02	-0.06	-0.22	-0.06	0.22	0.06	0.31	0.13	0.17
EL Isol	0.05	-0.05	0.08	-0.08	0.05	-0.05	0.05	-0.05	0.06	-0.06	0.04	-0.04	0.09	-0.08	0.12	-0.12
MU Trigger syst.	-0.01	0.01	-0.03	0.03	-0.04	0.04	-0.02	0.02	-0.02	0.02	-0.03	0.03	-0.03	0.03	-0.03	0.03
MU CB	-0.2	-0.07	-0.36	-0.16	-0.23	0.32	0.11	0.17	0.26	-0.1	0.13	-0.15	0.45	0.13	0.29	0.62
MU Momentum Scale	0.02	0.1	-0.02	-0.11	0.27	-0.05	0.08	0.1	0.11	0.05	0.0	-0.02	0.16	0.31	0.25	0.3
MUON SAGITTA DATASTAT	0.04	-0.03	-0.02	-0.05	-0.05	-0.05	0.08	0.09	0.11	0.14	-0.01	-0.09	0.28	0.25	0.19	0.36
MUON SAGITTA RESBIAS	0.17	-0.11	-0.15	-0.04	-0.03	0.22	0.09	0.05	-0.01	0.05	0.06	0.05	0.27	0.14	0.57	0.43
pileup	0.54	-0.23	0.04	0.0	-0.16	0.21	-0.09	0.06	-0.14	-0.01	-0.57	0.43	0.26	-0.38	-0.18	0.04
Modelling uncertainties																
$lq/lq \mu_R$	0.12	-0.13	0.22	-0.16	0.31	0.22	-0.19	0.03	-0.19	0.02	-1.17	-0.89	-0.28	-0.51	-1.97	0.19
$lq/lq \mu_F$	0.37	-0.31	0.35	-0.27	0.54	0.05	0.14	-0.15	0.47	-0.37	-0.89	-1.04	-0.31	-0.52	-1.51	0.0
lq/lq FSR	-0.02	-0.94	-0.03	-0.59	0.35	0.7	-0.21	2.18	-1.01	2.06	-1.25	-3.57	-1.02	-0.98	0.29	-7.81
lq/lq ISR α_S	-0.16	0.06	-0.06	0.07	0.17	0.34	0.1	-0.14	0.18	-0.27	-0.68	-1.25	-0.38	-0.46	-0.85	-0.82
lq/lq PDF	0.5	-0.54	0.63	-0.63	0.93	-0.39	0.74	-0.81	0.86	-0.94	-0.19	-1.77	0.59	-1.42	0.67	-2.03
lq/lq Parton shower	-1.31	(1.24)	-1.22	(1.14)	0.2	(-0.19)	1.04	(-1.01)	0.3	(-0.29)	-1.27	(1.22)	3.91	(-3.34)	-2.86	(2.74)
JES Flavor Composition tt	-0.2	(0.2)	0.25	(-0.24)	-0.42	(0.39)	-0.7	(0.65)	7.72	(-6.1)	3.15	(-2.66)	-1.21	(0.99)	7.17	(-4.72)
JES Flavor Composition $tW + tW, tb/tb$	-0.18	0.04	0.06	0.03	-0.19	0.12	-0.3	0.3	-0.25	-0.12	-0.07	0.42	0.34	0.8	0.05	-0.81
JES Flavor Composition $tW + tW, tb/tb$	0.04	-0.1	-0.01	0.05	0.01	0.04	-0.06	-0.07	0.13	-0.08	-0.22	-0.11	0.04	-0.01	-0.38	-0.12
m_j e shape	-0.45	-1.29	0.47	-0.08	-0.17	1.1	-0.38	-0.56	0.38	-0.04	-0.04	0.05	-0.05	-0.01	0.01	0.0
m_j e shape	0.72	-0.21	0.37	0.11	-0.12	0.23	0.88	0.02	0.0	-0.03	-0.14	0.0	0.03	0.0	0.0	0.0
m_j μ shape	-0.15	0.15	-0.07	0.07	-0.02	0.02	-0.18	0.18	0.7	-0.7	-0.31	0.31	-0.19	0.19	0.11	-0.11
$tt \mu_R$	0.04	-0.03	0.08	-0.06	0.05	-0.04	0.09	-0.07	0.13	-0.09	0.05	-0.03	-0.06	0.05	0.3	-0.19
$tt \mu_F$	0.03	-0.03	0.03	-0.03	0.09	-0.08	0.09	-0.08	0.07	-0.07	0.09	-0.08	0.15	-0.15	-0.11	-0.01
tt FSR	-0.23	0.4	0.16	0.11	-0.01	0.04	-0.02	0.15	0.01	-0.01	0.47	-0.41	-0.43	-0.01	0.9	-2.1
tt ISR α_S	-0.04	0.04	0.0	0.0	-0.06	0.04	0.0	0.0	-0.02	0.08	-0.3	0.29	-0.06	0.12	0.17	-0.26
$tW + tW, tb/tb \mu_R$	-0.01	0.01	-0.01	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.02	-0.02	-0.04	0.03	0.14	-0.1
$tW + tW$ DS	-0.21	(0.21)	0.05	(-0.05)	0.07	(-0.07)	0.06	(-0.06)	0.02	(-0.02)	-0.44	(0.45)	0.94	(-0.93)	0.28	(-0.28)
$tW + tW, tb/tb \mu_F$	-0.01	0.01	0.0	0.0	0.01	-0.01	0.02	-0.02	-0.01	0.0	0.04	-0.03	0.02	-0.01	0.14	-0.12
$tW + tW, tb/tb$ FSR	0.06	-0.03	0.0	-0.06	-0.01	0.05	0.14	-0.29	-0.06	0.08	-0.25	0.48	0.09	-0.54	-0.15	0.46
$tW + tW, tb/tb$ ISR α_S	-0.02	0.03	-0.02	0.06	-0.04	0.03	-0.03	0.01	0.0	-0.03	-0.08	0.04	0.03	-0.08	0.03	0.04
$W + b \mu_F$	0.48	-0.48	0.35	-0.34	0.01	-0.01	0.04	-0.04	0.34	-0.34	-0.19	0.19	-0.51	0.51	-0.06	0.06
$W + b \mu_R$	-0.14	-0.95	0.06	0.59	-0.05	0.16	-0.12	0.14	0.06	0.09	-0.09	-0.34	0.24	0.43	-0.12	0.2
$W + c(c) \mu_F$	-0.83	2.77	0.21	0.41	0.23	-0.14	0.2	-0.19	0.1	-0.26	0.28	-0.1	-0.05	0.33	0.07	0.18
$W + c(c) \mu_R$	0.24	0.17	0.25	0.48	-0.37	0.07	0.0	0.06	0.12	0.82	0.1	0.4	0.08	0.4	-0.05	-0.28
$tt, tW + tW, tb/tb$ PDF	0.03	-0.03	0.05	-0.05	0.09	-0.09	0.15	-0.15	0.23	-0.23	0.39	-0.38	0.18	-0.18	0.35	-0.35
$tW + tW, tb/tb$ Parton shower	-0.24	(0.24)	0.01	(-0.01)	0.08	(-0.08)	0.1	(-0.1)	-0.15	(0.15)	-1.07	(1.09)	1.34	(-1.3)	-0.13	(0.13)
tt Parton shower	-0.07	(0.07)	0.21	(-0.21)	0.29	(-0.29)	-0.26	(0.26)	-0.91	(0.94)	0.01	(-0.01)	-5.58	(6.05)	0.41	(-0.41)
tt NLO matching	-0.1	(0.1)	-0.24	(0.24)	0.08	(-0.08)	0.49	(-0.49)	0.58	(-0.57)	2.2	(-2.1)	-3.01	(3.1)	-0.06	(0.06)
$tW + tW$ NLO matching	-0.07	(0.07)	0.06	(-0.06)	0.02	(-0.02)	-0.06	(0.06)	0.04	(-0.04)	-0.18	(0.18)	1.22	(-1.2)	-0.06	(0.06)
$tt h_{\text{damp}}$	0.03	(-0.03)	-0.4	(0.4)	0.12	(-0.12)	0.11	(-0.11)	-0.11	(0.11)	0.4	(-0.39)	0.4	(-0.4)	-2.78	(2.84)
$tW + tW h_{\text{damp}}$	-0.09	/	0.09	-0.09	/	0.09	-0.09	/	0.09	-0.09	/	0.09	-0.09	/	0.09	-0.09
Background rate uncertainties																
tt	0.1	-0.1	0.11	-0.11	0.13	-0.13	0.16	-0.16	0.18	-0.18	0.16	-0.16	0.28	-0.28	0.4	-0.39
$tW + tW, tb/tb$	0.09	-0.09	0.06	-0.06	0.05	-0.05	0.06	-0.06	0.1	-0.1	0.12	-0.12	0.05	-0.05	0.19	-0.19
$W + b \ell^+ \ell^-$ SR rate	-1.15	1.15	-0.61	0.61	-0.33	0.33	-0.17	0.17	-0.18	0.18	-0.22	0.22	-0.16	0.16	-0.15	0.15
$W + b \ell^+ \ell^-$ SR rate	-1.0	1.0	-0.79	0.79	-0.43	0.43	-0.25	0.25	-0.32	0.32	-0.19	0.19	-0.21	0.21	-0.25	0.25
$W + c \ell^+ \ell^-$ SR rate	-2.54	2.53	-1.08	1.08	-0.32	0.32	-0.34	0.34	-0.29	0.29	-0.26	0.26	-0.29	0.29	-0.2	0.2
$W + c \ell^+ \ell^-$ SR rate	-2.43	2.43	-1.29	1.3	-0.59	0.59	-0.4	0.4	-0.42	0.42	-0.45	0.45	-0.5	0.5	-0.24	0.24
VV, z jets rate	0.4	-0.39	0.19	-0.19	0.08	-0.08	0.05	-0.05	0.07	-0.07	0.15	-0.15	0.03	-0.03	-0.02	0.02
m_j e rate	0.3	-0.29	0.13	-0.13	0.12	-0.12	0.06	-0.06	-0.11	0.11	0.02	-0.02	0.01	-0.01	0.0	0.0
m_j e rate	0.3	-0.29	0.15	-0.14	0.14	-0.13	0.05	-0.05	-0.12	0.12	0.02	-0.02	0.01	-0.01	0.0	0.0
m_j μ rate	0.29	-0.29	0.12	-0.12	0.19	-0.19	0.18	-0.18	0.39	-0.38	-0.29	0.29	-0.13	0.13	0.04	-0.03
Statistical uncertainties																
Data stat.	3.12	-3.12	2.17	-2.17	2.34	-2.34	3.43	-3.43	6.14	-6.14	9.04	-9.04	12.37	-12.37	15.93	-15.93
MC stat.	-0.02	0.02	-0.05	0.05	-0.06	0.06	-0.1	0.1	-0.19	0.19	-0.31	0.31	-0.47	0.47	-0.64	0.64
Total uncertainty	9.3	-11.4	4.5	-5.4	4.9	-3.7	4.8	-4.4	11.0	-9.5	10.7	-12.3	15.8	-15.3	18.9	-19.5



Table F.11.: Contribution of each individual uncertainty on the differential $tq/\bar{t}q$ cross-section ratio binned in $|y(t \text{ or } \bar{t})|$. Brackets around down systematics indicate that this systematic is symmetrised. Uncertainties whose impact is below 0.05 % for all bins are not listed for the sake of brevity.

Systematic	Systematic uncertainty in [%]				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
Experimental uncertainties					
JER DataVsMC MC16	1.42 / -0.46	-0.2 / 0.67	-2.42 / -0.55	0.16 / 0.41	-2.0 / 0.66
JER Effective NP 1	-1.24 / 1.24	3.07 / -1.21	1.55 / -2.59	-2.08 / -0.52	2.78 / -3.73
JER Effective NP 2	-1.54 / 1.75	1.43 / -2.05	1.06 / -1.35	-0.56 / -0.02	1.41 / -1.73
JER Effective NP 3	1.25 / -2.04	-1.53 / 1.35	-1.15 / -0.24	-0.15 / -1.45	-1.49 / 2.32
JER Effective NP 4	1.31 / -0.78	-0.95 / 1.43	-0.48 / -1.79	0.35 / -0.4	-2.71 / 0.62
JER Effective NP 5	0.23 / -0.69	0.54 / 0.06	-1.34 / -0.19	-0.65 / 0.23	-1.2 / -2.08
JER Effective NP 6	1.04 / -1.66	-0.02 / 1.01	-1.86 / -1.14	-1.09 / -0.88	-0.71 / 0.1
JER Effective NP 7	-0.66 / 0.55	0.7 / 0.12	-1.33 / -0.44	0.08 / -0.73	0.18 / -1.43
JER Effective NP 8	0.71 / 1.27	-0.3 / -0.78	0.04 / -0.41	0.36 / -1.46	0.73 / -0.31
JER Effective NP 9	-0.01 / 0.18	-0.31 / 0.86	-0.06 / -0.54	-0.74 / -0.58	0.18 / -1.36
JER Effective NP 10	0.09 / 0.44	0.44 / -0.27	-0.2 / 0.83	-0.89 / -0.24	1.62 / -1.67
JER Effective NP 11	0.24 / 0.61	0.41 / -0.33	0.17 / 0.24	-0.74 / -0.96	-1.11 / 0.98
JER Effective NP 12restTerm	-0.21 / 0.05	0.21 / -0.3	-0.76 / 0.99	-1.21 / 0.21	0.59 / -2.3
JES Effective NP Detector1	-0.04 / -0.12	0.33 / -0.03	0.09 / -0.17	0.0 / 0.21	0.09 / 0.44
JES Effective NP Detector2	0.06 / -0.1	0.0 / -0.02	-0.01 / 0.02	0.01 / 0.0	0.0 / -0.03
JES Effective NP Modelling1	0.01 / -0.71	0.11 / 0.1	-0.1 / 0.11	0.13 / -0.01	0.92 / 1.39
JES Effective NP Modelling2	0.02 / -0.04	0.23 / -0.01	0.02 / 0.09	0.06 / 0.1	0.48 / 0.03
JES Effective NP Modelling3	-0.1 / -0.05	-0.01 / 0.25	-0.12 / 0.08	0.08 / -0.02	-0.01 / 0.3
JES Effective NP Modelling4	0.06 / -0.11	-0.05 / -0.07	-0.01 / 0.01	0.03 / 0.15	-0.03 / 0.04
JES Effective NP Mixed1	-0.03 / -0.19	0.31 / -0.1	-0.04 / -0.14	-0.12 / 0.31	0.09 / 0.16
JES Effective NP Mixed2	-0.18 / 0.15	-0.14 / 0.32	-0.15 / -0.02	0.12 / 0.01	0.9 / 0.19
JES Effective NP Mixed3	-0.02 / -0.09	0.38 / -0.05	0.1 / -0.21	-0.01 / 0.21	0.04 / 0.18
JES Effective NP Statistical2	-0.11 / 0.13	-0.08 / 0.32	-0.22 / 0.11	0.03 / 0.03	0.91 / 0.16
JES Effective NP Statistical4	-0.01 / -0.13	0.29 / -0.02	0.03 / 0.01	-0.01 / 0.15	0.1 / -0.01
JES Effective NP Statistical6	0.08 / -0.14	0.02 / -0.03	-0.02 / 0.02	-0.01 / 0.18	0.1 / 0.09
JES Effective NP Statistical5	-0.11 / -0.06	0.03 / 0.27	-0.15 / 0.05	0.07 / -0.01	0.13 / 0.09
JES Flavor Response	-0.64 / 0.29	0.11 / 0.53	-0.9 / 0.02	-0.01 / -0.87	0.97 / 1.95
BJES Response	0.39 / -0.16	0.28 / 0.22	-0.08 / -0.25	-0.16 / -0.25	0.41 / -0.02
JES Flavor Composition $tq, \bar{t}q$	0.6 / -0.53	0.67 / -0.45	0.21 / -1.24	0.37 / -0.4	0.8 / 0.02
JES pileup OffsetMu	0.85 / -0.63	1.66 / -0.52	0.62 / -0.2	-0.67 / -0.22	1.95 / 0.28
JES pileup OffsetNPV	-0.16 / 0.67	0.35 / -0.35	0.13 / -0.59	0.11 / -0.1	0.75 / 0.96
JES pileup RhoTopology	-0.1 / -0.77	0.3 / 0.13	0.56 / -0.08	-0.21 / 0.05	2.44 / 2.16
JES pileup PtTerm	-0.44 / -0.1	0.69 / -0.05	-0.24 / -0.23	0.1 / -0.12	0.78 / 1.04
JES EtaIntercalibration Modelling	1.04 / -0.93	0.53 / 0.13	0.26 / -0.34	-0.26 / -1.04	1.72 / 1.65
JES EtaIntercalibration TotalStat	0.14 / -0.21	0.26 / 0.07	0.16 / -0.2	-0.11 / -0.14	0.17 / 0.97
JES EtaIntercalibration NonClosure negEta	-0.07 / -0.03	-0.07 / 0.04	0.39 / -0.05	0.0 / -0.04	0.1 / -0.03
JES EtaIntercalibration NonClosure posEta	0.02 / -0.05	-0.05 / 0.03	-0.01 / 0.05	-0.06 / -0.01	0.07 / 0.17
JES EtaIntercalibration NonClosure 2018data	-0.21 / -0.12	0.0 / 0.19	-0.1 / 0.09	0.11 / 0.05	-0.06 / -0.08
MET SoftTrk Scale	-0.34 / -0.28	0.21 / 0.41	-0.49 / 0.16	0.52 / -0.29	0.08 / 0.48
MET SoftTrk ResoPara	-1.6 / -	0.37 / -	-0.39 / -	-0.84 / -	1.42 / -
MET SoftTrk ResoPerp	-1.3 / -	0.45 / -	-0.33 / -	-0.51 / -	1.02 / -
JVT	-0.03 / 0.01	-0.05 / 0.03	-0.12 / 0.08	0.0 / -0.01	-0.02 / 0.01
fJVT	-0.1 / 0.1	0.03 / -0.02	-0.04 / 0.04	0.01 / -0.01	-0.15 / 0.15
b-tag B0	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04	-0.04 / 0.04
b-tag B4	-0.04 / 0.04	-0.03 / 0.03	-0.05 / 0.05	-0.02 / 0.02	-0.11 / 0.12
b-tag B5	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06	0.06 / -0.06	0.0 / 0.0
b-tag C0	-0.14 / 0.14	-0.16 / 0.16	-0.12 / 0.12	-0.23 / 0.23	-0.15 / 0.15
b-tag C1	0.08 / -0.08	0.1 / -0.1	0.07 / -0.07	0.14 / -0.14	0.09 / -0.09
b-tag C2	0.06 / -0.06	0.06 / -0.06	0.03 / -0.03	0.08 / -0.08	0.05 / -0.05
b-tag C3	0.1 / -0.1	0.12 / -0.12	0.08 / -0.08	0.16 / -0.16	0.11 / -0.11
b-tag C4	0.05 / -0.05	0.06 / -0.06	0.05 / -0.05	0.08 / -0.08	0.06 / -0.06



F. Systematic uncertainties

b-tag C5	0.02 / -0.02	0.08 / -0.08	0.13 / -0.13	0.18 / -0.17	0.14 / -0.14
b-tag C6	0.03 / -0.03	-0.01 / 0.01	0.04 / -0.04	0.06 / -0.06	-0.01 / 0.01
b-tag C7	-0.05 / 0.05	-0.03 / 0.03	-0.08 / 0.08	-0.11 / 0.11	-0.03 / 0.03
b-tag Light0	-0.04 / 0.04	-0.04 / 0.04	-0.02 / 0.02	-0.07 / 0.07	0.01 / 0.0
b-tag Light3	-0.02 / 0.02	0.01 / -0.01	0.0 / 0.0	-0.05 / 0.05	0.02 / -0.02
EG RESOLUTION ALL	-0.54 / 0.01	0.18 / 0.11	-0.25 / -0.05	0.57 / -0.1	0.82 / -0.13
EG SCALE ALL	0.0 / -0.11	0.0 / 0.08	-0.36 / -0.09	0.57 / 0.1	0.81 / -0.01
EL Isol	0.07 / -0.07	0.05 / -0.05	0.08 / -0.08	0.07 / -0.06	0.04 / -0.04
EL Reco	0.02 / -0.02	0.01 / -0.01	0.02 / -0.02	0.01 / -0.01	0.05 / -0.05
MU Isol syst.	0.03 / -0.03	0.04 / -0.04	0.03 / -0.03	0.04 / -0.04	0.0 / 0.0
MU CB	0.01 / -0.13	-0.19 / 0.29	-0.33 / 0.17	-0.02 / -0.14	-0.38 / -0.14
MU Momentum Scale	-0.1 / -0.03	0.35 / -0.05	0.07 / 0.07	0.08 / 0.0	-0.16 / -0.01
MUON SAGITTA DATASTAT	-0.03 / -0.01	0.0 / -0.03	0.06 / -0.01	0.05 / 0.0	-0.13 / 0.02
MUON SAGITTA RESBIAS	-0.16 / -0.15	0.08 / 0.42	0.07 / 0.01	0.0 / -0.08	-0.07 / -0.32
pileup	-0.08 / 0.27	-0.16 / 0.09	0.15 / -0.03	0.1 / -0.09	0.43 / -0.24
Modelling uncertainties					
$tq/\bar{t}q \mu_R$	0.6 / -0.04	0.42 / -0.32	0.54 / -0.3	0.3 / -0.06	-0.42 / -0.34
$tq/\bar{t}q \mu_F$	0.48 / 0.01	0.33 / -0.32	0.43 / -0.3	0.44 / -0.21	0.25 / -0.85
$tq/\bar{t}q$ FSR	-0.07 / -0.49	-0.29 / 0.03	0.22 / 0.8	0.5 / 0.31	-1.13 / 0.11
$tq/\bar{t}q$ ISR α_S	0.12 / 0.32	-0.03 / -0.03	0.04 / 0.06	0.2 / -0.08	-0.55 / -0.24
$tq/\bar{t}q$ PDF	0.74 / -0.31	0.53 / -0.6	0.67 / -0.6	0.66 / -0.49	-0.1 / -0.63
$tq/\bar{t}q$ Parton shower	0.46 / (-0.43)	0.28 / (-0.26)	-1.25 / (1.22)	-0.31 / (0.3)	0.22 / (-0.2)
$tq/\bar{t}q$ NLO matching	2.21 / (-1.98)	-0.18 / (0.16)	-1.7 / (1.62)	-1.19 / (1.14)	2.87 / (-2.52)
JES Flavor Composition $t\bar{t}$	0.03 / 0.08	-0.14 / 0.16	-0.3 / 0.14	-0.12 / 0.01	0.06 / 0.02
JES Flavor Composition $tW + t\bar{t}W, tb/t\bar{b}$	0.0 / -0.03	0.03 / -0.01	-0.05 / -0.04	0.01 / 0.0	-0.01 / 0.09
mj e shape	0.77 / 0.04	-0.78 / 0.26	-0.31 / -0.02	0.36 / -0.54	0.07 / -0.08
mj fe shape	0.04 / 0.01	-0.02 / 0.0	-0.25 / -0.07	0.27 / 0.08	3.9 / 0.65
mj μ shape	-0.14 / 0.14	0.01 / -0.01	-0.49 / 0.5	0.04 / -0.04	0.85 / -0.85
$t\bar{t} \mu_R$	0.04 / -0.03	0.06 / -0.04	0.09 / -0.07	0.07 / -0.05	0.08 / -0.06
$t\bar{t} \mu_F$	0.02 / -0.03	0.06 / -0.06	0.11 / -0.1	0.07 / -0.06	-0.03 / 0.03
$t\bar{t}$ FSR	0.1 / 0.88	0.1 / -0.29	-0.2 / 0.17	-0.05 / 0.36	0.23 / -0.8
$t\bar{t}$ ISR α_S	-0.01 / 0.02	-0.02 / 0.01	-0.05 / 0.05	-0.1 / 0.08	0.06 / -0.03
$tW + t\bar{t}W$ DS	0.07 / (-0.07)	0.02 / (-0.02)	-0.19 / (0.19)	0.25 / (-0.25)	-0.01 / (0.01)
$tW + t\bar{t}W, tb/t\bar{b}$ FSR	0.08 / 0.08	0.03 / -0.07	-0.05 / 0.0	0.04 / -0.08	0.05 / -0.33
$tW + t\bar{t}W, tb/t\bar{b}$ ISR α_S	-0.01 / 0.0	-0.07 / 0.05	0.0 / 0.04	-0.03 / 0.02	-0.02 / 0.02
$W + b\bar{b} \mu_F$	1.95 / -1.88	0.02 / -0.02	-0.36 / 0.36	-0.42 / 0.43	-0.78 / 0.78
$W + b\bar{b} \mu_R$	0.14 / 0.32	0.06 / 0.39	-0.32 / -0.39	-0.33 / -1.02	0.65 / 1.89
$W + c(\bar{c}) \mu_F$	0.36 / 0.95	-0.24 / 0.44	0.07 / 1.07	0.91 / -0.62	-1.9 / 0.9
$W + c(\bar{c}) \mu_R$	-0.26 / -0.41	0.26 / 0.74	0.41 / 0.65	0.15 / 0.79	-1.39 / -1.43
$t\bar{t}, tW + t\bar{t}W, tb/t\bar{b}$ PDF	0.06 / -0.06	0.08 / -0.08	0.1 / -0.1	0.13 / -0.13	0.09 / -0.09
$tW + t\bar{t}W, tb/t\bar{b}$ Parton shower	0.15 / (-0.15)	-0.02 / (0.02)	-0.19 / (0.19)	0.08 / (-0.08)	-0.19 / (0.19)
$t\bar{t}$ Parton shower	0.08 / (-0.08)	0.24 / (-0.23)	-0.3 / (0.31)	-0.12 / (0.12)	0.04 / (-0.04)
$t\bar{t}$ NLO matching	0.1 / (-0.1)	0.16 / (-0.16)	-0.16 / (0.16)	-0.36 / (0.36)	0.77 / (-0.75)
$tW + t\bar{t}W$ NLO matching	0.2 / (-0.2)	0.02 / (-0.02)	-0.12 / (0.12)	0.05 / (-0.05)	-0.17 / (0.17)
$t\bar{t} h_{damp}$	-0.17 / (0.17)	-0.05 / (0.05)	-0.01 / (0.01)	-0.26 / (0.26)	0.24 / (-0.24)
$tW + t\bar{t}W h_{damp}$	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09	-0.09 / 0.09
Background rate uncertainties					
$t\bar{t}$	0.14 / -0.14	0.14 / -0.14	0.14 / -0.13	0.13 / -0.13	0.09 / -0.08
$tW + t\bar{t}W, tb/t\bar{b}$ rate	0.06 / -0.06	0.06 / -0.06	0.08 / -0.08	0.06 / -0.06	0.07 / -0.07
$W + b\bar{b} (\ell^\pm)$ SR rate	-0.4 / 0.4	-0.47 / 0.47	-0.51 / 0.51	-0.55 / 0.55	-0.72 / 0.72
$W + b\bar{b} (\ell^\pm)$ SR rate	-0.57 / 0.57	-0.59 / 0.59	-0.65 / 0.65	-0.61 / 0.61	-0.59 / 0.59
$W + c(\bar{c}) (\ell^\pm)$ SR rate	-0.95 / 0.95	-0.96 / 0.96	-0.9 / 0.9	-0.67 / 0.67	-1.07 / 1.07
$W + c(\bar{c}) (\ell^\pm)$ SR rate	-1.08 / 1.08	-1.13 / 1.13	-1.05 / 1.05	-1.15 / 1.15	-1.22 / 1.22
$VV, +jets$ rate	0.1 / -0.1	0.11 / -0.11	0.22 / -0.22	0.3 / -0.3	0.33 / -0.32
mj e rate	0.15 / -0.15	0.21 / -0.21	0.13 / -0.13	0.09 / -0.09	0.0 / 0.0
mj fe rate	0.16 / -0.16	0.23 / -0.22	0.15 / -0.15	0.06 / -0.06	0.09 / -0.09
mj μ rate	0.05 / -0.05	0.28 / -0.28	0.25 / -0.24	0.01 / -0.01	0.54 / -0.53
Statistical uncertainties					
Data stat.	2.79 / -2.79	2.28 / -2.28	2.59 / -2.59	3.07 / -3.07	4.47 / -4.47
MC stat.	-0.05 / 0.05	-0.06 / 0.06	-0.05 / 0.05	-0.08 / 0.08	-0.12 / 0.12
Total uncertainty	6.3 / -6.3	5.9 / -4.5	4.9 / -6.8	4.3 / -5.9	10.2 / -9.5



F.3. Signal modelling breakdown plots

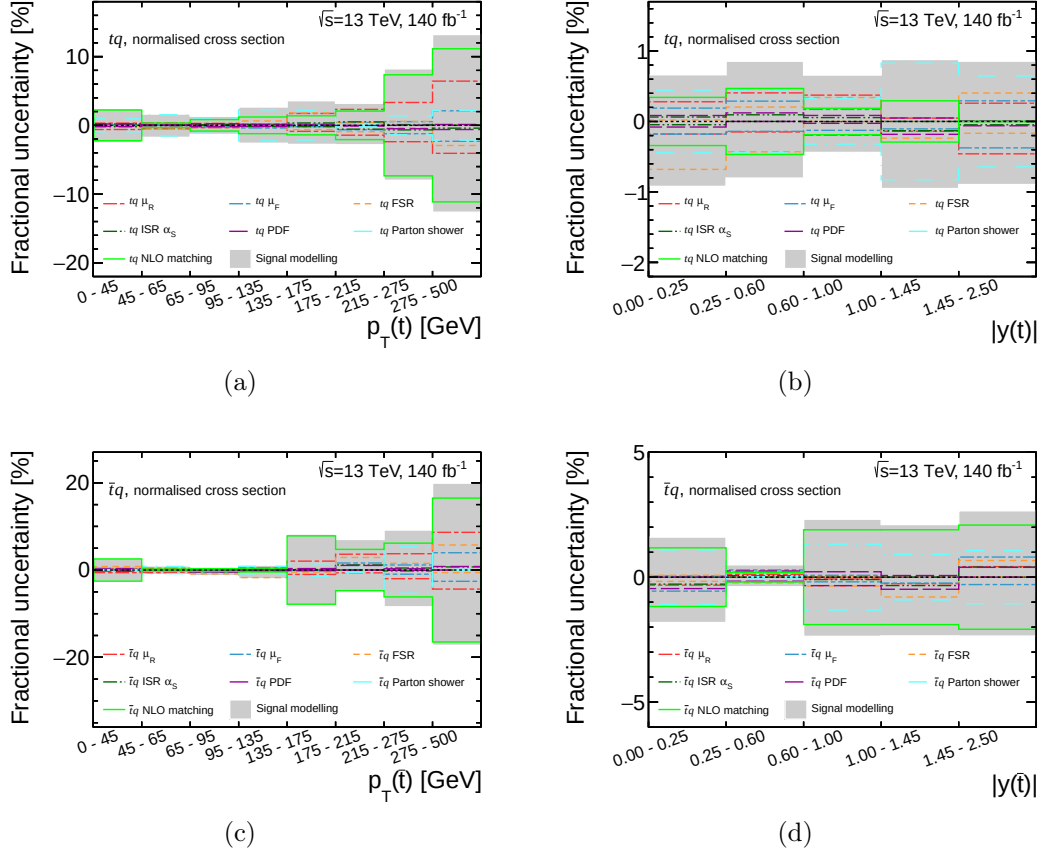


Figure F.1: Signal modelling uncertainties in the normalised differential tq and $\bar{t}q$ production cross sections measured as a function of (a) $p_T(t)$, (b) $|y(t)|$, (c) $p_T(\bar{t})$ and (d) $|y(\bar{t})|$. The shaded band indicates the combined uncertainty, defined as the quadratic sum of all individual uncertainties.

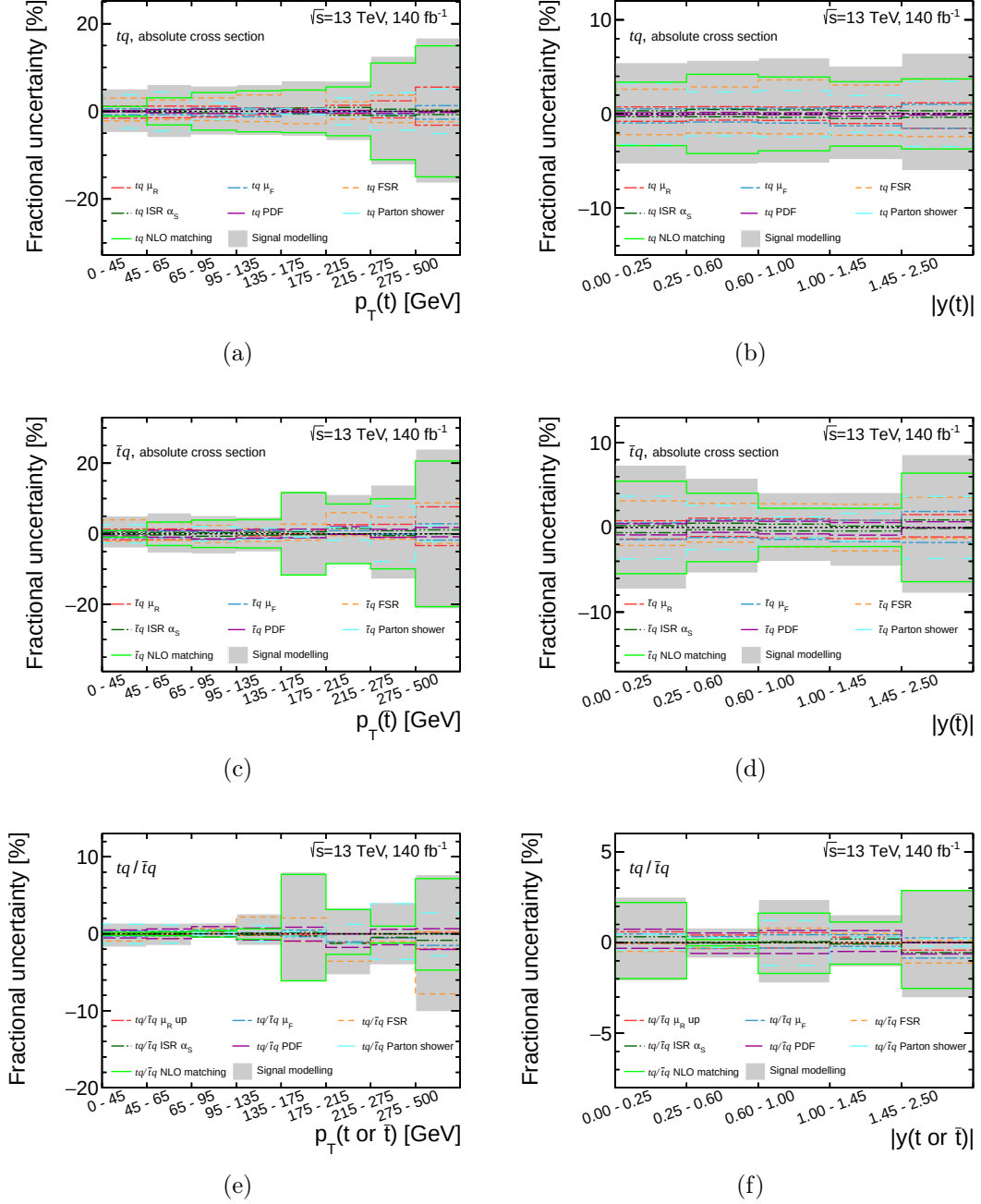


Figure F.2: Signal modelling uncertainties in the absolute differential tq and $\bar{t}q$ production cross sections measured as a function of (a) $p_T(t)$, (b) $|y(t)|$, (c) $p_T(\bar{t})$ and (d) $|y(\bar{t})|$ and in the ratio of the cross sections measured as a function of (e) $p_T(t \text{ or } \bar{t})$ and (f) $|y(t \text{ or } \bar{t})|$. The shaded band indicates the combined uncertainty, defined as the quadratic sum of all individual uncertainties.



F.4. Experimental uncertainties breakdown plots

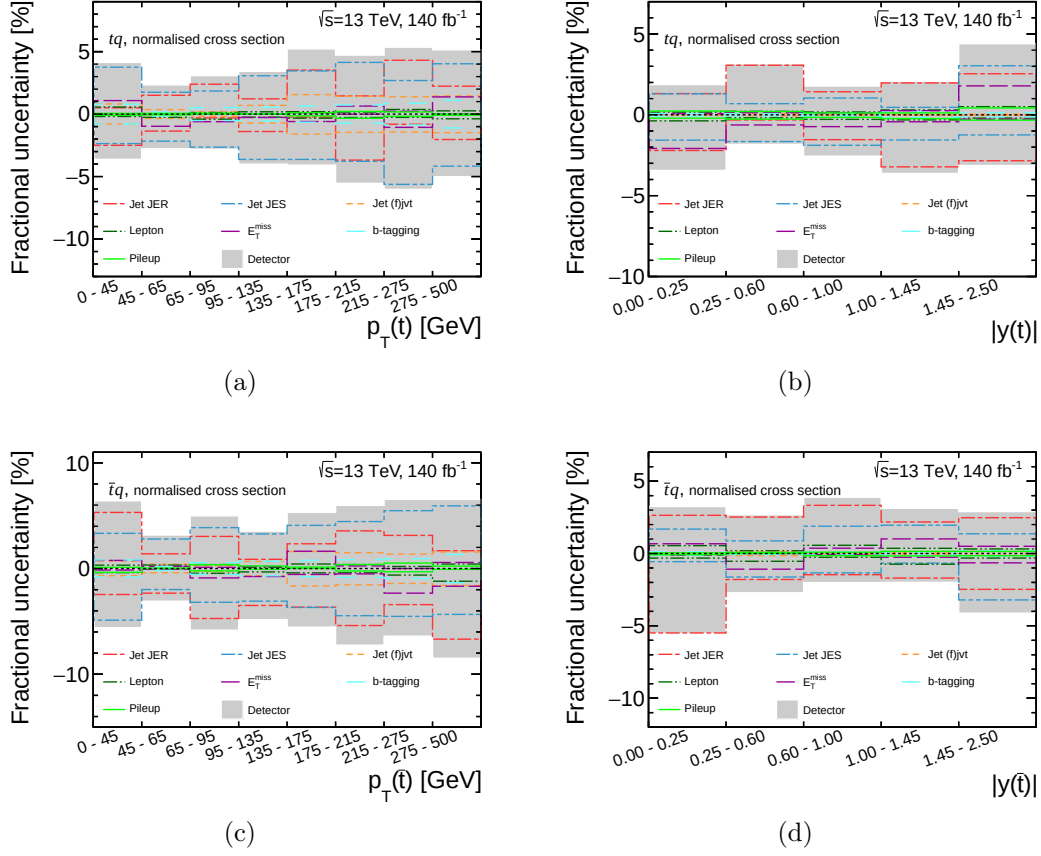


Figure F.3: Experimental uncertainties in the normalised differential tq and $\bar{t}q$ production cross sections measured as a function of (a) $p_T(t)$, (b) $|y(t)|$, (c) $p_T(\bar{t})$ and (d) $|y(\bar{t})|$. The shaded band indicates the combined uncertainty, defined as the quadratic sum of all individual uncertainties.

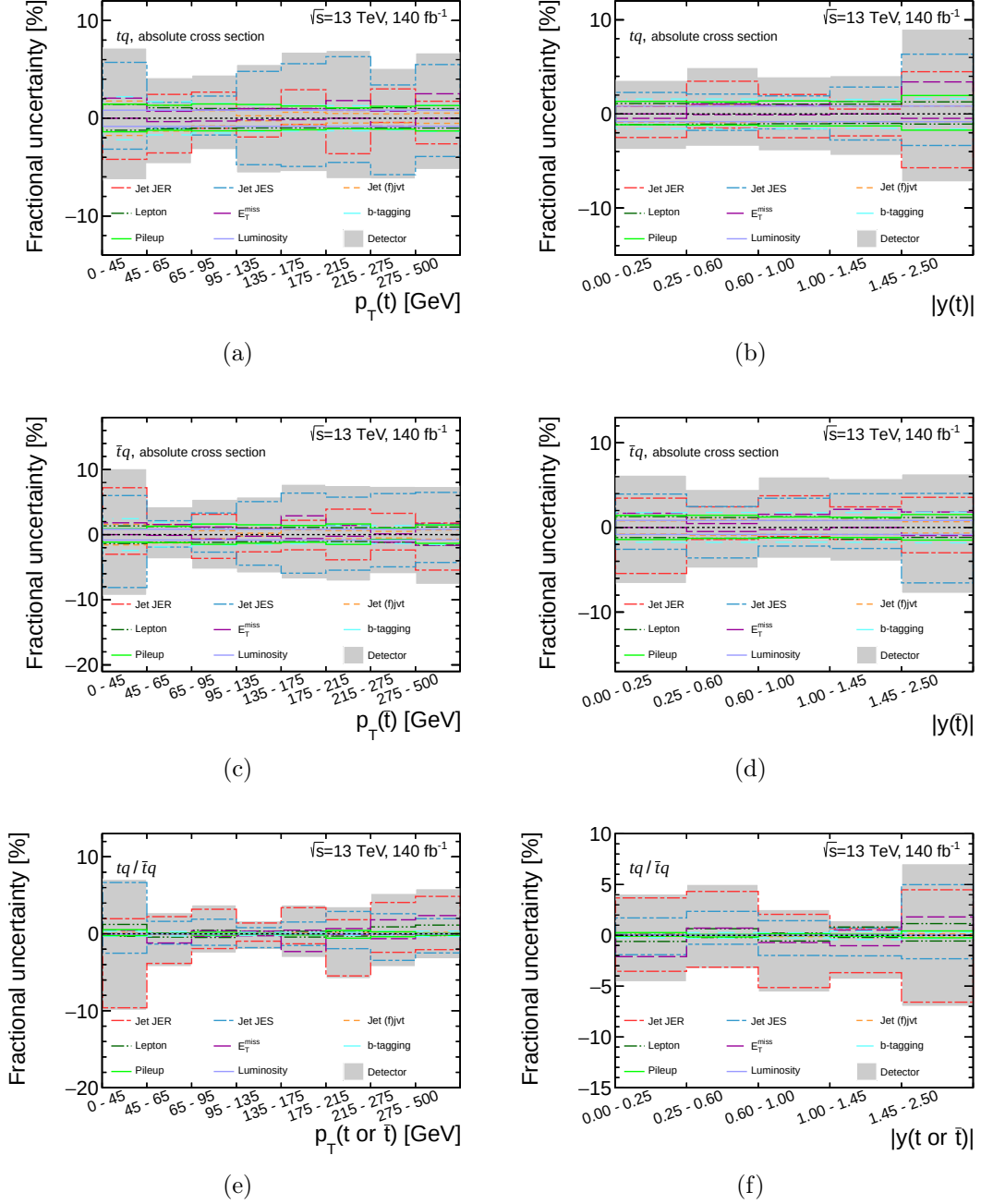


Figure F.4: Experimental uncertainties in the absolute differential tq and $\bar{t}q$ production cross sections measured as a function of (a) $p_T(t)$, (b) $|y(t)|$, (c) $p_T(\bar{t})$ and (d) $|y(\bar{t})|$ and in the ratio of the cross sections measured as a function of (e) $p_T(t \text{ or } \bar{t})$ and (f) $|y(t \text{ or } \bar{t})|$. The shaded band indicates the combined uncertainty, defined as the quadratic sum of all individual uncertainties.



F.5. Impact of signal modelling on the number of jets

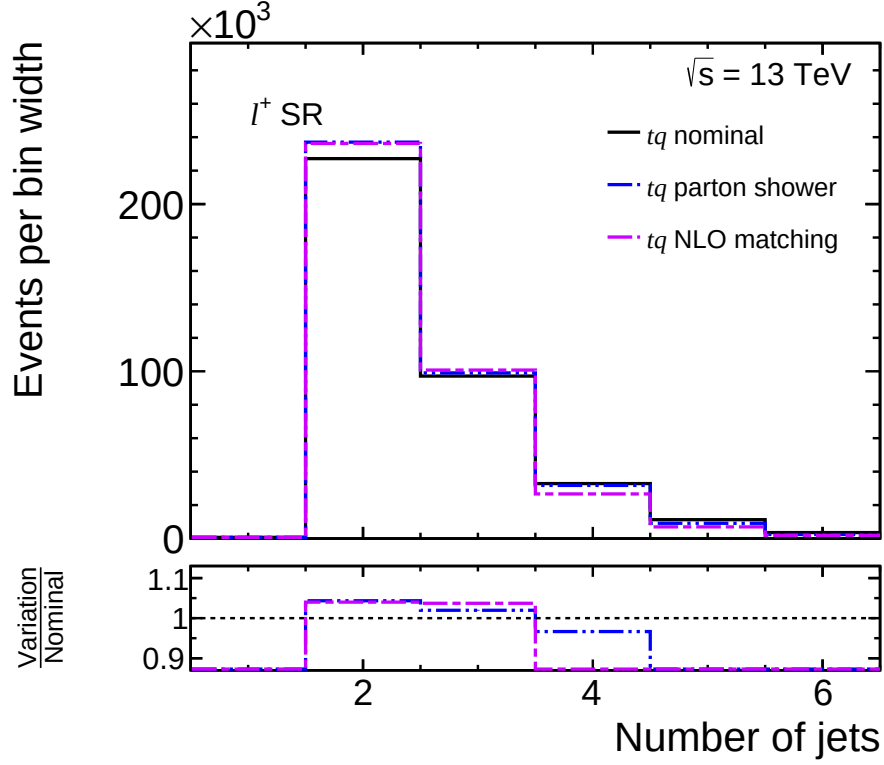


Figure F.5: Impact of the parton shower and NLO modelling variations on the number of jets in simulated tq events. Selected events are required to contain one charged lepton with $p_T(\ell) > 28$ GeV, $E_T^{miss} > 30$ GeV, two or more jets with $p_T(j) > 30$ GeV and $|\eta(j)| < 4.5$ and one jet b -tagged at the 60% working point.

F.6. Statistical uncertainty in systematic variations

As discussed in Section 10.2, the statistical uncertainty in the modelling and jet-related experimental uncertainties is evaluated. The results are presented in the following tables.

central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

Systematic	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8
JER Data/MC MC16	-1.354(±0.52)/-0.114(±0.56)	-1.140(±0.25)/0.79(±0.26)	0.054(±0.23)/0.35(±0.16)	0.114(±0.12)/-0.28(±0.13)	0.484(±0.06)/0.34(±0.18)	-0.57(±0.23)/-0.17(±0.31)	0.944(±0.29)/0.49(±0.3)	-0.95(±0.30)/0.06(±0.36)
JER Effective NP 1	-0.294(±0.72)/-0.80(±0.73)	1.784(±0.37)/-2.48(±0.39)	1.84(±0.26)/-0.59(±0.25)	0.734(±0.17)/-0.03(±0.16)	7.74(±0.27)/-0.66(±0.24)	-0.94(±0.67)/-1.88(±0.36)	0.95(±0.43)/-0.09(±0.45)	1.15(±0.40)/-1.04(±0.41)
JER Effective NP 2	1.24(±0.40)/-0.74(±0.41)	0.04(±0.27)/-0.48(±0.29)	1.52(±0.19)/-0.71(±0.25)	0.324(±0.17)/-0.02(±0.16)	0.96(±0.28)/-0.26(±0.24)	1.39(±0.61)/0.63(±0.39)	0.34(±0.48)/-0.46(±0.47)	0.144(±0.37)/0.124(±0.35)
JER Effective NP 3	-1.28(±0.49)/-0.74(±0.51)	-1.08(±0.22)/-0.73(±0.21)	0.134(±0.22)/0.75(±0.22)	-0.234(±0.13)/-0.36(±0.12)	0.06(±0.22)/0.97(±0.22)	-0.48(±0.29)/0.35(±0.3)	1.06(±0.38)/0.84(±0.34)	-1.07(±0.41)/0.33(±0.41)
JER Effective NP 4	-1.14(±0.51)/-0.54(±0.56)	-1.38(±0.22)/-0.85(±0.24)	0.11(±0.20)/-0.61(±0.21)	-0.434(±0.12)/0.07(±0.11)	0.754(±0.18)/0.67(±0.18)	-0.44(±0.26)/0.35(±0.28)	0.35(±0.33)/-0.14(±0.31)	-0.09(±0.37)/-0.29(±0.38)
JER Effective NP 5	-1.19(±0.51)/-0.54(±0.56)	-1.38(±0.22)/-0.85(±0.24)	0.11(±0.20)/-0.61(±0.21)	-0.434(±0.12)/0.07(±0.11)	0.754(±0.18)/0.67(±0.18)	-0.44(±0.26)/0.35(±0.28)	0.35(±0.33)/-0.14(±0.31)	-0.09(±0.37)/-0.29(±0.38)
JER Effective NP 6	-0.68(±0.46)/-0.39(±0.45)	-0.79(±0.26)/0.61(±0.23)	-0.334(±0.25)/0.68(±0.22)	-0.374(±0.13)/-0.05(±0.13)	0.714(±0.2)/0.33(±0.25)	-1.01(±0.29)/-0.36(±0.28)	0.98(±0.38)/-0.09(±0.34)	-0.11(±0.38)/0.34(±0.38)
JER Effective NP 7	-0.99(±0.41)/-0.49(±0.47)	0.324(±0.17)/-0.63(±0.24)	0.134(±0.15)/0.74(±0.18)	-0.13(±0.11)/-0.27(±0.11)	0.334(±0.16)/0.09(±0.15)	-0.14(±0.2)/0.2(±0.22)	0.534(±0.26)/-0.45(±0.26)	-0.7(±0.31)/-0.45(±0.31)
JER Effective NP 8	-0.75(±0.29)/-0.86(±0.35)	0.343(±0.15)/-0.19(±0.16)	0.154(±0.14)/-0.27(±0.19)	-0.04(±0.11)/-0.06(±0.11)	0.334(±0.14)/-0.37(±0.16)	0.68(±0.21)/-0.68(±0.49)	0.69(±0.25)/0.85(±0.26)	-1.18(±0.29)/-0.52(±0.29)
JER Effective NP 9	-0.56(±0.38)/-0.74(±0.35)	0.224(±0.16)/0.214(±0.19)	0.514(±0.14)/0.23(±0.17)	-0.01(±0.11)/-0.19(±0.11)	0.21(±0.22)/0.65(±0.16)	-0.46(±0.15)/-0.79(±0.23)	0.194(±0.27)/0.83(±0.27)	0.35(±0.33)/0.03(±0.33)
JER Effective NP 10	0.124(±0.32)/0.004(±0.27)	0.054(±0.15)/0.124(±0.14)	0.164(±0.12)/-0.02(±0.09)	-0.27(±0.08)/-0.07(±0.08)	-0.08(±0.13)/0.33(±0.13)	0.22(±0.18)/-0.17(±0.18)	0.28(±0.21)/0.45(±0.21)	-0.24(±0.24)/0.174(±0.24)
JER Effective NP 11	0.40(±0.33)/0.35(±0.37)	0.034(±0.14)/0.174(±0.15)	0.224(±0.14)/0.40(±0.11)	0.04(±0.17)/0.33(±0.19)	0.174(±0.15)/0.83(±0.19)	-0.37(±0.23)/-1.17(±0.34)	0.92(±0.28)/0.40(±0.28)	-1.28(±0.34)/0.38(±0.29)
JER Effective NP 12	0.40(±0.33)/0.35(±0.37)	0.034(±0.14)/0.174(±0.15)	0.224(±0.14)/0.40(±0.11)	0.04(±0.17)/0.33(±0.19)	0.174(±0.15)/0.83(±0.19)	-0.37(±0.23)/-1.17(±0.34)	0.92(±0.28)/0.40(±0.28)	-1.28(±0.34)/0.38(±0.29)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.06(±0.29)/0.13(±0.29)	-0.15(±0.41)/0.08(±0.41)	-0.16(±0.61)/-0.46(±0.61)	0.68(±0.47)/0.06(±0.68)	0.02(±0.16)/0.14(±0.16)
JES Effective NP Diagonal	-0.04(±0.80)/-0.06(±0.89)	-0.08(±0.39)/-0.05(±0.39)	0.04(±0.32)/0.02(±0.32)	0.				

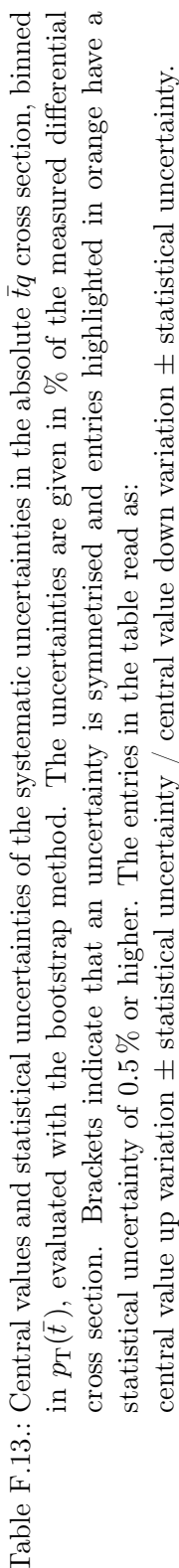


Table F.13.: Central values and statistical uncertainties of the systematic uncertainties in the absolute $\bar{t}\bar{q}$ cross section, binned in $p_T(\bar{t})$, evaluated with the bootstrap method. The uncertainties are given in % of the measured differential cross section. Brackets indicate that an uncertainty is symmetrised and entries highlighted in orange have a statistical uncertainty of 0.5 % or higher. The entries in the table read as: central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

Systematic	Bu 1	Bu 2	Bu 3	Bu 4	Systematic uncertainty in [%]	Bu 5	Bu 6	Bu 7	Bu 8
JER Down/MC16	0.9457/0.014672	0.5745/0.02	-0.14536	-0.9248/0.48	0.7450.4	-0.1542/0.2	-0.1750.18	0.1242/0.37	0.8943/0.39
JER Effective NP 1	-2.5341/0.07	3.8574/0.08	1.5543/0.39	-1.3945/0.47	0.1243/0.21	-1.1445/0.25	-0.7653/0.41	1.5444/0.65	-0.1750.58
JER Effective NP 2	1.8548/0.27	0.1143/0.89	0.2948/0.49	-1.0940.45	1.5543/0.39	-2.5445/0.22	0.6345/0.41	1.7745/0.34	0.7244/0.87
JER Effective NP 3	2.2141/0.07	-0.0740.52	0.0345/0.2	0.3453/0.34	-1.3543/0.36	1.5243/0.2	-0.0940.18	0.9540.17	1.5345/0.7
JER Effective NP 4	2.9940/0.13	-0.1074/0.52	-0.7445/0.36	0.3543/0.34	-1.3543/0.36	1.5243/0.2	-0.0940.18	0.9540.17	1.5345/0.7
JER Effective NP 5	2.9940/0.13	0.0854/0.1	-0.1143/0.32	0.0854/0.1	-0.1143/0.32	0.0854/0.1	-0.1143/0.32	0.0854/0.1	-0.1143/0.32
JER Effective NP 6	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 7	1.1545/0.07	0.8340.22	0.0745/0.35	0.2243/0.3	-0.6145/0.19	0.1944/0.2	-0.6145/0.19	0.1944/0.2	-0.6145/0.19
JER Effective NP 8	-1.0445/0.47	0.3440.43	0.3342/0.41	0.7340.29	-0.3545/0.24	0.2340.36	-0.3545/0.24	0.2340.36	-0.3545/0.24
JER Effective NP 9	1.1645/0.45	0.3440.43	-0.0945/0.2	0.3240.28	-0.2745/0.13	-0.0834/0.1	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 10	1.1445/0.45	0.0840.45	-0.2745/0.13	0.0440.26	-0.1545/0.35	-0.8340.17	-0.2143/0.3	-0.5340.27	-0.8340.17
JER Effective NP 11	-0.5145/0.13	0.1045/0.1	0.0145/0.2	0.0940.27	-0.3545/0.24	0.2340.36	-0.3545/0.24	0.2340.36	-0.3545/0.24
JER Effective NP 12	1.2645/0.46	0.2243/0.35	0.4341/0.37	0.3740.29	-0.1143/0.17	-0.0534/0.1	0.2243/0.41	-0.1443/0.19	0.2243/0.41
JER Effective NP 13	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 14	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 15	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 16	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 17	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 18	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 19	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 20	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 21	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 22	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 23	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 24	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 25	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 26	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 27	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 28	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 29	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 30	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 31	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 32	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 33	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 34	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 35	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 36	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 37	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 38	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 39	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 40	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 41	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 42	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 43	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 44	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 45	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 46	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 47	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 48	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 49	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 50	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 51	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 52	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 53	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 54	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 55	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 56	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 57	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 58	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 59	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 60	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 61	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 62	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 63	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 64	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 65	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 66	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 67	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 68	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 69	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 70	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 71	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 72	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 73	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 74	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 75	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 76	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 77	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 78	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 79	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.0440.33	-0.6745/0.19	0.1944/0.2	-0.6647/0.22	0.0240.27	1.4243/0.7
JER Effective NP 80	0.9456/0.06	3.8457/0.07	0.6645/0.46	0.04					

F. Systematic uncertainties



Table F.14.: Central values and statistical uncertainties of the systematic uncertainties in the normalised tq cross section, binned in $p_T(t)$, evaluated with the bootstrap method. The uncertainties are given in % of the measured differential cross section. Brackets indicate that an uncertainty is symmetrised and entries highlighted in orange have a statistical uncertainty of 0.5 % or higher. The entries in the table read as: central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

Systematic	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8
BR DataMC MC16	-0.73 $\pm$ 0.36 / -0.27 $\pm$ 0.4	-0.19 $\pm$ 0.28 / 0.63 $\pm$ 0.32	0.66 $\pm$ 0.53 / 0.19 $\pm$ 0.26	0.71 $\pm$ 0.2 / -0.14 $\pm$ 0.24	1.05 $\pm$ 0.22 / 0.14 $\pm$ 0.24	0.83 $\pm$ 0.26 / -0.63 $\pm$ 0.35	1.54 $\pm$ 0.32 / 0.33 $\pm$ 0.34	-0.34 $\pm$ 0.41 / -0.14 $\pm$ 0.4
BR Effective NP 1	0.09 $\pm$ 0.36 / -1.14 $\pm$ 0.37	0.67 $\pm$ 0.37 / 0.82 $\pm$ 0.33	0.82 $\pm$ 0.27 / 0.92 $\pm$ 0.23	0.84 $\pm$ 0.22 / 0.71 $\pm$ 0.23	0.84 $\pm$ 0.31 / 0.73 $\pm$ 0.26	2.74 $\pm$ 0.17 / 0.64 $\pm$ 0.15	0.72 $\pm$ 0.53 / 2.07 $\pm$ 0.48	0.98 $\pm$ 0.53 / 1.74 $\pm$ 0.51
BR Effective NP 2	-0.02 $\pm$ 0.31 / 0.09 $\pm$ 0.37	-0.13 $\pm$ 0.25 / 0.34 $\pm$ 0.29	0.44 $\pm$ 0.27 / -0.24 $\pm$ 0.28	0.14 $\pm$ 0.2 / -0.74 $\pm$ 0.23	0.74 $\pm$ 0.25 / 0.82 $\pm$ 0.26	0.16 $\pm$ 0.37 / 0.24 $\pm$ 0.35	1.74 $\pm$ 0.35 / 0.54 $\pm$ 0.38	-0.42 $\pm$ 0.43 / -0.02 $\pm$ 0.42
BR Effective NP 3	-0.04 $\pm$ 0.36 / -0.03 $\pm$ 0.38	0.14 $\pm$ 0.33 / -0.32 $\pm$ 0.26	0.75 $\pm$ 0.25 / 0.81 $\pm$ 0.21	-0.11 $\pm$ 0.19 / 0.26 $\pm$ 0.22	0.76 $\pm$ 0.26 / 0.83 $\pm$ 0.25	-0.73 $\pm$ 0.57 / -0.32 $\pm$ 0.45	0.37 $\pm$ 0.47 / 1.02 $\pm$ 0.44	0.55 $\pm$ 0.45 / -0.37 $\pm$ 0.46
BR Effective NP 4	-0.01 $\pm$ 0.38 / -0.74 $\pm$ 0.34	-0.29 $\pm$ 0.25 / 0.09 $\pm$ 0.26	0.08 $\pm$ 0.34 / 0.09 $\pm$ 0.32	-0.21 $\pm$ 0.2 / 0.34 $\pm$ 0.17	0.88 $\pm$ 0.24 / 0.41 $\pm$ 0.23	-0.22 $\pm$ 0.37 / -0.16 $\pm$ 0.35	0.83 $\pm$ 0.37 / 1.37 $\pm$ 0.36	0.14 $\pm$ 0.17 / -0.02 $\pm$ 0.42
BR Effective NP 5	-0.22 $\pm$ 0.34 / -0.52 $\pm$ 0.35	-0.33 $\pm$ 0.29 / 0.47 $\pm$ 0.26	0.15 $\pm$ 0.28 / 0.55 $\pm$ 0.28	0.09 $\pm$ 0.18 / -0.18 $\pm$ 0.21	1.19 $\pm$ 0.24 / 0.18 $\pm$ 0.28	-0.55 $\pm$ 0.32 / -0.47 $\pm$ 0.35	1.43 $\pm$ 0.38 / -0.22 $\pm$ 0.39	0.32 $\pm$ 0.39 / 0.22 $\pm$ 0.4
BR Effective NP 6	-0.74 $\pm$ 0.28 / -0.67 $\pm$ 0.34	0.56 $\pm$ 0.2 / -0.38 $\pm$ 0.28	0.84 $\pm$ 0.22 / 1.04 $\pm$ 0.24	0.12 $\pm$ 0.16 / 0.04 $\pm$ 0.17	0.55 $\pm$ 0.19 / 0.39 $\pm$ 0.21	0.15 $\pm$ 0.26 / 0.86 $\pm$ 0.27	0.75 $\pm$ 0.28 / 0.81 $\pm$ 0.29	-0.45 $\pm$ 0.33 / -0.14 $\pm$ 0.34
BR Effective NP 7	-0.63 $\pm$ 0.21 / 0.05 $\pm$ 0.36	0.54 $\pm$ 0.16 / -0.07 $\pm$ 0.21	0.36 $\pm$ 0.17 / -0.15 $\pm$ 0.21	0.08 $\pm$ 0.14 / 0.06 $\pm$ 0.13	0.46 $\pm$ 0.17 / 0.49 $\pm$ 0.18	0.19 $\pm$ 0.27 / 0.35 $\pm$ 0.26	0.81 $\pm$ 0.36 / 0.75 $\pm$ 0.28	-1.07 $\pm$ 0.33 / 0.38 $\pm$ 0.34
BR Effective NP 8	-0.32 $\pm$ 0.27 / -0.33 $\pm$ 0.26	0.26 $\pm$ 0.19 / 0.24 $\pm$ 0.22	0.35 $\pm$ 0.2 / 0.14 $\pm$ 0.2	0.03 $\pm$ 0.16 / -0.03 $\pm$ 0.15	0.25 $\pm$ 0.23 / 0.83 $\pm$ 0.19	0.49 $\pm$ 0.31 / 0.61 $\pm$ 0.25	0.23 $\pm$ 0.29 / 0.84 $\pm$ 0.28	0.14 $\pm$ 0.31 / 0.21 $\pm$ 0.33
BR Effective NP 9	-0.04 $\pm$ 0.37 / 0.04 $\pm$ 0.38	0.18 $\pm$ 0.19 / 0.15 $\pm$ 0.19	0.07 $\pm$ 0.15 / -0.07 $\pm$ 0.15	0.03 $\pm$ 0.16 / -0.03 $\pm$ 0.15	0.25 $\pm$ 0.23 / 0.83 $\pm$ 0.19	0.49 $\pm$ 0.31 / 0.61 $\pm$ 0.25	0.23 $\pm$ 0.29 / 0.84 $\pm$ 0.28	0.14 $\pm$ 0.31 / 0.21 $\pm$ 0.33
BR Effective NP 10	-0.15 $\pm$ 0.27 / -0.26 $\pm$ 0.2	0.17 $\pm$ 0.2 / 0.18 $\pm$ 0.15	0.28 $\pm$ 0.19 / 0.07 $\pm$ 0.17	0.22 $\pm$ 0.13 / -0.23 $\pm$ 0.12	0.37 $\pm$ 0.18 / 0.24 $\pm$ 0.12	0.61 $\pm$ 0.27 / -0.34 $\pm$ 0.22	0.03 $\pm$ 0.26 / 1.14 $\pm$ 0.26	0.14 $\pm$ 0.31 / 0.21 $\pm$ 0.33
BR Effective NP 11	-0.51 $\pm$ 0.27 / 0.84 $\pm$ 0.2	0.17 $\pm$ 0.2 / 0.18 $\pm$ 0.15	0.28 $\pm$ 0.19 / 0.07 $\pm$ 0.17	0.22 $\pm$ 0.13 / -0.23 $\pm$ 0.12	0.37 $\pm$ 0.18 / 0.24 $\pm$ 0.12	0.61 $\pm$ 0.27 / -0.34 $\pm$ 0.22	0.03 $\pm$ 0.26 / 1.14 $\pm$ 0.26	0.14 $\pm$ 0.31 / 0.21 $\pm$ 0.33
BR Effective NP 12	-0.03 $\pm$ 0.58 / 0.02 $\pm$ 0.58	-0.03 $\pm$ 0.42 / -0.05 $\pm$ 0.42	0.05 $\pm$ 0.45 / -0.03 $\pm$ 0.46	0.04 $\pm$ 0.4 / 0.06 $\pm$ 0.4	-0.12 $\pm$ 0.48 / 0.04 $\pm$ 0.48	-0.18 $\pm$ 0.67 / -0.07 $\pm$ 0.64	0.92 $\pm$ 0.67 / -0.14 $\pm$ 0.67	-0.11 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Detector1	-0.04 $\pm$ 0.58 / -0.04 $\pm$ 0.58	-0.03 $\pm$ 0.42 / -0.05 $\pm$ 0.42	0.05 $\pm$ 0.45 / -0.03 $\pm$ 0.46	0.04 $\pm$ 0.4 / 0.06 $\pm$ 0.4	-0.12 $\pm$ 0.48 / 0.04 $\pm$ 0.48	-0.18 $\pm$ 0.67 / -0.07 $\pm$ 0.64	0.92 $\pm$ 0.67 / -0.14 $\pm$ 0.67	-0.11 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Detector2	0.34 $\pm$ 0.57 / 0.54 $\pm$ 0.57	0.21 $\pm$ 0.43 / -0.45 $\pm$ 0.41	-0.03 $\pm$ 0.46 / -0.49 $\pm$ 0.45	-0.49 $\pm$ 0.4 / -0.14 $\pm$ 0.4	-0.49 $\pm$ 0.49 / 0.03 $\pm$ 0.49	-0.69 $\pm$ 0.67 / -0.24 $\pm$ 0.64	-0.07 $\pm$ 0.68 / 0.66 $\pm$ 0.66	0.03 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Modelling1	0.07 $\pm$ 0.57 / 0.04 $\pm$ 0.57	-0.01 $\pm$ 0.42 / -0.14 $\pm$ 0.42	0.05 $\pm$ 0.46 / -0.14 $\pm$ 0.46	-0.49 $\pm$ 0.4 / -0.14 $\pm$ 0.4	-0.49 $\pm$ 0.49 / 0.03 $\pm$ 0.49	-0.69 $\pm$ 0.67 / -0.24 $\pm$ 0.64	-0.07 $\pm$ 0.68 / 0.66 $\pm$ 0.66	0.03 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Modelling2	0.04 $\pm$ 0.57 / 0.04 $\pm$ 0.58	-0.12 $\pm$ 0.42 / 0.01 $\pm$ 0.42	0.06 $\pm$ 0.46 / 0.09 $\pm$ 0.46	0.19 $\pm$ 0.47 / -0.14 $\pm$ 0.4	0.25 $\pm$ 0.48 / -0.24 $\pm$ 0.48	0.13 $\pm$ 0.67 / -0.32 $\pm$ 0.63	0.14 $\pm$ 0.67 / -0.14 $\pm$ 0.68	-0.03 $\pm$ 0.67 / -0.13 $\pm$ 0.68
BR Effective NP Modelling3	-0.02 $\pm$ 0.57 / 0.04 $\pm$ 0.58	-0.12 $\pm$ 0.42 / 0.01 $\pm$ 0.42	0.06 $\pm$ 0.46 / 0.09 $\pm$ 0.46	0.19 $\pm$ 0.47 / -0.14 $\pm$ 0.4	0.25 $\pm$ 0.48 / -0.24 $\pm$ 0.48	0.13 $\pm$ 0.67 / -0.32 $\pm$ 0.63	0.14 $\pm$ 0.67 / -0.14 $\pm$ 0.68	-0.03 $\pm$ 0.67 / -0.13 $\pm$ 0.68
BR Effective NP Modelling4	0.07 $\pm$ 0.57 / 0.04 $\pm$ 0.58	-0.12 $\pm$ 0.42 / 0.01 $\pm$ 0.42	0.06 $\pm$ 0.46 / 0.09 $\pm$ 0.46	0.19 $\pm$ 0.47 / -0.14 $\pm$ 0.4	0.25 $\pm$ 0.48 / -0.24 $\pm$ 0.48	0.13 $\pm$ 0.67 / -0.32 $\pm$ 0.63	0.14 $\pm$ 0.67 / -0.14 $\pm$ 0.68	-0.03 $\pm$ 0.67 / -0.13 $\pm$ 0.68
BR Effective NP Modelling5	0.07 $\pm$ 0.57 / 0.04 $\pm$ 0.58	-0.12 $\pm$ 0.42 / 0.01 $\pm$ 0.42	0.06 $\pm$ 0.46 / 0.09 $\pm$ 0.46	0.19 $\pm$ 0.47 / -0.14 $\pm$ 0.4	0.25 $\pm$ 0.48 / -0.24 $\pm$ 0.48	0.13 $\pm$ 0.67 / -0.32 $\pm$ 0.63	0.14 $\pm$ 0.67 / -0.14 $\pm$ 0.68	-0.03 $\pm$ 0.67 / -0.13 $\pm$ 0.68
BR Effective NP Modelling6	0.07 $\pm$ 0.57 / 0.04 $\pm$ 0.58	-0.12 $\pm$ 0.42 / 0.01 $\pm$ 0.42	0.06 $\pm$ 0.46 / 0.09 $\pm$ 0.46	0.19 $\pm$ 0.47 / -0.14 $\pm$ 0.4	0.25 $\pm$ 0.48 / -0.24 $\pm$ 0.48	0.13 $\pm$ 0.67 / -0.32 $\pm$ 0.63	0.14 $\pm$ 0.67 / -0.14 $\pm$ 0.68	-0.03 $\pm$ 0.67 / -0.13 $\pm$ 0.68
BR Effective NP Modelling7	-0.02 $\pm$ 0.58 / 0.07 $\pm$ 0.58	-0.02 $\pm$ 0.42 / -0.03 $\pm$ 0.42	0.03 $\pm$ 0.46 / -0.03 $\pm$ 0.46	0.03 $\pm$ 0.4 / 0.02 $\pm$ 0.4	0.01 $\pm$ 0.49 / -0.14 $\pm$ 0.4	-0.18 $\pm$ 0.67 / -0.24 $\pm$ 0.64	0.06 $\pm$ 0.67 / 0.14 $\pm$ 0.68	-0.01 $\pm$ 0.67 / 0.14 $\pm$ 0.68
BR Effective NP Modelling8	-0.02 $\pm$ 0.58 / 0.07 $\pm$ 0.58	-0.02 $\pm$ 0.42 / -0.03 $\pm$ 0.42	0.03 $\pm$ 0.46 / -0.03 $\pm$ 0.46	0.03 $\pm$ 0.4 / 0.02 $\pm$ 0.4	0.01 $\pm$ 0.49 / -0.14 $\pm$ 0.4	-0.18 $\pm$ 0.67 / -0.24 $\pm$ 0.64	0.06 $\pm$ 0.67 / 0.14 $\pm$ 0.68	-0.01 $\pm$ 0.67 / 0.14 $\pm$ 0.68
BR Effective NP Statistical1	0.39 $\pm$ 0.57 / 0.60 $\pm$ 0.58	-0.13 $\pm$ 0.42 / -0.11 $\pm$ 0.42	-0.27 $\pm$ 0.46 / -0.02 $\pm$ 0.46	0.62 $\pm$ 0.4 / 0.01 $\pm$ 0.4	-0.22 $\pm$ 0.48 / -0.02 $\pm$ 0.49	-0.32 $\pm$ 0.67 / -0.02 $\pm$ 0.65	-0.24 $\pm$ 0.68 / 0.18 $\pm$ 0.68	-0.14 $\pm$ 0.67 / -0.01 $\pm$ 0.65
BR Effective NP Statistical2	-0.04 $\pm$ 0.57 / -0.01 $\pm$ 0.58	-0.02 $\pm$ 0.42 / -0.01 $\pm$ 0.42	0.01 $\pm$ 0.46 / -0.02 $\pm$ 0.46	0.06 $\pm$ 0.4 / 0.08 $\pm$ 0.4	-0.01 $\pm$ 0.48 / 0.02 $\pm$ 0.49	-0.04 $\pm$ 0.67 / -0.02 $\pm$ 0.65	0.02 $\pm$ 0.68 / 0.19 $\pm$ 0.68	0.09 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Statistical3	0.01 $\pm$ 0.57 / 0.02 $\pm$ 0.58	-0.01 $\pm$ 0.42 / -0.01 $\pm$ 0.42	0.08 $\pm$ 0.46 / -0.02 $\pm$ 0.46	-0.04 $\pm$ 0.4 / 0.06 $\pm$ 0.4	-0.11 $\pm$ 0.49 / 0.03 $\pm$ 0.49	0.15 $\pm$ 0.67 / 0.07 $\pm$ 0.64	0.28 $\pm$ 0.68 / 0.19 $\pm$ 0.68	-0.11 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Statistical4	0.06 $\pm$ 0.57 / 0.01 $\pm$ 0.58	-0.08 $\pm$ 0.42 / -0.03 $\pm$ 0.42	0.01 $\pm$ 0.46 / -0.02 $\pm$ 0.46	0.15 $\pm$ 0.47 / 0.02 $\pm$ 0.4	0.01 $\pm$ 0.49 / 0.03 $\pm$ 0.49	-0.13 $\pm$ 0.67 / -0.04 $\pm$ 0.68	0.05 $\pm$ 0.68 / 0.07 $\pm$ 0.68	-0.02 $\pm$ 0.67 / 0.02 $\pm$ 0.68
BR Effective NP Statistical5	-0.04 $\pm$ 0.57 / 0.01 $\pm$ 0.58	-0.02 $\pm$ 0.42 / -0.03 $\pm$ 0.42	0.01 $\pm$ 0.46 / -0.02 $\pm$ 0.46	0.06 $\pm$ 0.4 / 0.08 $\pm$ 0.4	-0.01 $\pm$ 0.48 / 0.02 $\pm$ 0.49	-0.04 $\pm$ 0.67 / -0.02 $\pm$ 0.65	0.02 $\pm$ 0.68 / 0.19 $\pm$ 0.68	0.09 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Statistical6	-0.25 $\pm$ 0.57 / 1.11 $\pm$ 0.57	-0.84 $\pm$ 0.41 / 0.22 $\pm$ 0.42	0.03 $\pm$ 0.46 / -0.03 $\pm$ 0.46	0.03 $\pm$ 0.4 / 0.02 $\pm$ 0.4	0.01 $\pm$ 0.49 / 0.03 $\pm$ 0.49	0.15 $\pm$ 0.67 / 0.07 $\pm$ 0.64	0.28 $\pm$ 0.68 / 0.19 $\pm$ 0.68	-0.11 $\pm$ 0.67 / 0.13 $\pm$ 0.67
BR Effective NP Statistical7	1.76 $\pm$ 0.16 / -1.89 $\pm$ 0.16	1.34 $\pm$ 0.11 / -1.45 $\pm$ 0.11	-0.32 $\pm$ 0.18 / 0.75 $\pm$ 0.17	-0.29 $\pm$ 0.23 / 0.19 $\pm$ 0.23	-0.24 $\pm$ 0.23 / 0.19 $\pm$ 0.23	2.74 $\pm$ 0.17 / 0.64 $\pm$ 0.15	0.72 $\pm$ 0.53 / 2.07 $\pm$ 0.48	0.98 $\pm$ 0.53 / 1.74 $\pm$ 0.51
BR Flavor Composition q_u	0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition q_d	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition q_s	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition q_b	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition q_t	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition $q_{\bar{t}}$	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition $q_{\bar{b}}$	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition $q_{\bar{s}}$	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.04 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.14 $\pm$ 0.03 / 0.20 $\pm$ 0.03	0.27 $\pm$ 0.26 / -0.35 $\pm$ 0.26
BR Flavor Composition $q_{\bar{d}}$	-0.03 $\pm$ 0.05 / 0.02 $\pm$ 0.05	-0.03 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.07 $\pm$ 0.05 / -0.04 $\pm$ 0.05	0.04 $\pm$ 0.03 / 0.01 $\pm$				

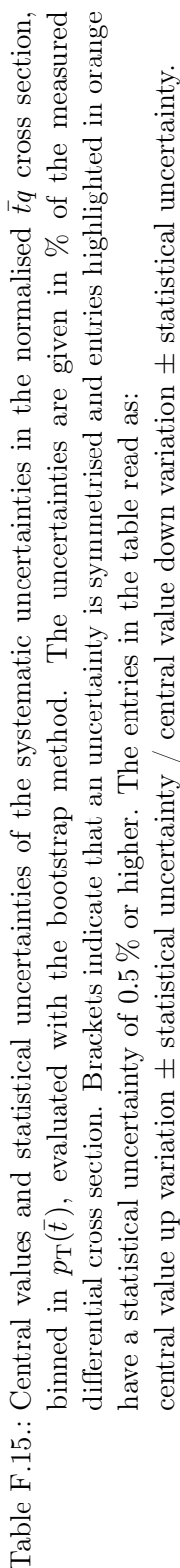


Table F.15.: Central values and statistical uncertainties of the systematic uncertainties in the normalised $\bar{t}q$ cross section, binned in $p_T(\bar{t})$, evaluated with the bootstrap method. The uncertainties are given in % of the measured differential cross section. Brackets indicate that an uncertainty is symmetrised and entries highlighted in orange have a statistical uncertainty of 0.5 % or higher. The entries in the table read as: central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

[illegible]



F. Systematic uncertainties

Table F.16.: Central values and statistical uncertainties of the systematic uncertainties in the absolute tq cross section, binned in $|y(t)|$, evaluated with the bootstrap method. The uncertainties are given in % of the measured differential cross section. Brackets indicate that an uncertainty is symmetrised and entries highlighted in orange have a statistical uncertainty of 0.5 % or higher. The entries in the table read as: central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

Systematic	Systematic uncertainty in [%]				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
JER DataVsMC MC16	-0.37±0.3 / 0.03±0.22	0.53±0.21/ 0.43±0.17	-0.79±0.26/ -0.05±0.23	-0.41±0.29/ 0.05±0.31	-2.7±0.55/ 1.51±0.6
JER Effective NP 1	0.24±0.35/ -1.29±0.39	1.77±0.26/ -0.33±0.3	1.13±0.35/ -1.16±0.31	-0.54±0.38/ -0.99±0.36	1.39±0.62/ -2.11±0.58
JER Effective NP 2	0.58±0.27/ -1.5±0.4	1.61±0.24/ -1.35±0.24	1.53±0.26/ -1.13±0.27	-0.05±0.33/ -0.87±0.32	2.85±0.47/ -3.71±0.57
JER Effective NP 3	-0.28±0.32/ -0.29±0.27	-0.21±0.19/ 1.01±0.2	-0.75±0.23/ 0.14±0.3	-0.35±0.3/ -0.74±0.28	-1.55±0.53/ 2.27±0.48
JER Effective NP 4	-0.47±0.17/ -0.11±0.34	-0.48±0.19/ 1.51±0.23	-1.19±0.22/ 0.14±0.23	0.47±0.33/ -0.14±0.26	-1.43±0.44/ -0.34±0.64
JER Effective NP 5	-0.49±0.38/ -0.2±0.15	0.56±0.2/ 0.33±0.16	-0.41±0.28/ -0.07±0.22	-0.79±0.26/ -0.28±0.27	-0.29±0.58/ -0.61±0.48
JER Effective NP 6	-0.23±0.28/ -0.56±0.36	-0.07±0.2/ 1.34±0.22	-0.79±0.31/ 0.19±0.22	-1.06±0.3/ 0.06±0.27	0.05±0.32/ -0.04±0.57
JER Effective NP 7	-0.85±0.21/ 0.36±0.27	0.53±0.18/ 0.22±0.17	-0.18±0.13/ -0.44±0.17	0.05±0.2/ -0.47±0.27	0.24±0.47/ -0.78±0.39
JER Effective NP 8	-0.02±0.17/ 0.31±0.12	0.19±0.15/ 0.13±0.12	0.31±0.12/ -0.66±0.24	-0.37±0.18/ -0.68±0.19	-0.14±0.46/ 0.44±0.22
JER Effective NP 9	-0.03±0.23/ -0.15±0.24	0.51±0.14/ 0.45±0.18	0.05±0.12/ -0.04±0.15	-0.57±0.21/ -0.46±0.2	0.79±0.53/ -0.44±0.38
JER Effective NP 10	0.08±0.21/ -0.01±0.17	0.24±0.15/ 0.13±0.11	-0.26±0.13/ 0.42±0.11	-0.22±0.13/ -0.24±0.16	1.24±0.41/ -0.57±0.34
JER Effective NP 11	-0.55±0.18/ 0.18±0.17	0.37±0.17/ 0.14±0.1	0.55±0.12/ -0.26±0.12	-0.54±0.15/ -0.29±0.16	-0.71±0.35/ 1.35±0.42
JER Effective NP 12restTerm	-0.03±0.22/ 0.04±0.16	0.44±0.12/ -0.14±0.14	-0.36±0.12/ 0.05±0.12	-0.36±0.14/ -0.14±0.15	0.99±0.37/ -0.89±0.35
JES Effective NP Detector1	0.06±0.5/ -0.01±0.5	-0.05±0.39/ 0.01±0.39	-0.04±0.42/ -0.0±0.42	0.05±0.48/ 0.17±0.48	-0.03±0.89/ 0.07±0.89
JES Effective NP Detector2	0.05±0.5/ -0.03±0.5	-0.04±0.39/ -0.0±0.39	-0.0±0.42/ 0.0±0.42	0.0±0.48/ -0.01±0.48	-0.08±0.89/ -0.09±0.89
JES Effective NP Modelling1	-0.16±0.51/ 0.37±0.49	-0.26±0.39/ 0.45±0.38	-0.14±0.43/ 0.31±0.41	-0.18±0.48/ 0.44±0.46	-0.52±0.89/ 1.76±0.7
JES Effective NP Modelling2	0.02±0.5/ 0.04±0.5	-0.03±0.39/ -0.01±0.39	-0.07±0.42/ 0.11±0.43	-0.02±0.48/ 0.18±0.48	0.04±0.89/ -0.07±0.89
JES Effective NP Modelling3	0.01±0.5/ 0.01±0.5	0.03±0.39/ -0.08±0.39	0.07±0.42/ -0.08±0.42	0.24±0.48/ -0.05±0.48	-0.05±0.89/ -0.09±0.89
JES Effective NP Modelling4	0.02±0.49/ -0.04±0.5	-0.02±0.39/ -0.01±0.39	-0.02±0.42/ 0.0±0.42	0.02±0.48/ 0.14±0.48	-0.05±0.89/ 0.03±0.89
JES Effective NP Mixed1	0.06±0.5/ -0.1±0.5	-0.04±0.39/ 0.01±0.39	-0.06±0.42/ 0.05±0.42	-0.08±0.48/ 0.18±0.48	-0.05±0.89/ 0.06±0.89
JES Effective NP Mixed2	-0.08±0.5/ 0.04±0.5	0.08±0.39/ -0.09±0.39	0.02±0.42/ -0.07±0.42	0.11±0.47/ 0.01±0.48	0.75±0.71/ -0.09±0.89
JES Effective NP Mixed3	0.04±0.5/ -0.01±0.5	-0.02±0.39/ -0.04±0.39	-0.02±0.42/ -0.01±0.42	-0.01±0.48/ 0.13±0.48	-0.07±0.89/ 0.06±0.89
JES Effective NP Statistical1	-0.03±0.5/ -0.03±0.5	0.0±0.39/ -0.0±0.39	0.01±0.42/ 0.03±0.42	-0.04±0.48/ 0.04±0.48	-0.07±0.89/ -0.09±0.89
JES Effective NP Statistical2	-0.07±0.5/ 0.08±0.5	0.07±0.39/ -0.06±0.39	-0.02±0.42/ 0.09±0.43	-0.01±0.47/ 0.06±0.48	0.65±0.71/ -0.05±0.89
JES Effective NP Statistical3	-0.02±0.5/ -0.03±0.5	-0.04±0.39/ -0.0±0.39	0.02±0.42/ -0.0±0.42	-0.04±0.48/ -0.04±0.48	-0.07±0.89/ -0.08±0.89
JES Effective NP Statistical4	0.04±0.49/ -0.02±0.5	-0.02±0.39/ -0.02±0.39	-0.02±0.42/ 0.03±0.42	0.03±0.48/ 0.17±0.48	-0.04±0.89/ -0.08±0.89
JES Effective NP Statistical5	-0.01±0.5/ 0.02±0.5	0.02±0.39/ -0.05±0.39	0.04±0.42/ -0.03±0.42	0.15±0.48/ 0.01±0.48	0.06±0.89/ -0.06±0.89
JES Effective NP Statistical6	0.05±0.5/ -0.02±0.5	-0.02±0.39/ -0.01±0.39	0.04±0.42/ 0.02±0.42	-0.01±0.48/ 0.15±0.48	-0.03±0.89/ 0.04±0.89
JES Flavor Response	0.54±0.48/ -0.31±0.51	0.59±0.38/ -0.22±0.39	0.55±0.41/ -0.28±0.43	0.94±0.46/ -0.64±0.48	2.21±0.7/ -0.22±0.7
BJES Response	0.03±0.5/ 0.09±0.5	-0.15±0.39/ 0.17±0.39	-0.19±0.43/ -0.0±0.42	-0.08±0.49/ 0.22±0.48	-0.14±0.72/ 0.01±0.89
JES Flavor Composition tq,tq	-0.68±0.2/ 1.28±0.2	-0.79±0.15/ 1.28±0.14	-1.22±0.17/ 1.06±0.17	-1.24±0.21/ 1.62±0.21	-2.12±0.3/ 2.33±0.3
JES Flavor Composition tt	0.21±0.05/ -0.26±0.05	0.15±0.04/ -0.24±0.04	0.14±0.04/ -0.1±0.05	0.17±0.05/ -0.19±0.05	0.01±0.06/ -0.12±0.06
JES Flavor Composition tW + tW, tb/tb	0.04±0.02/ -0.01±0.02	0.02±0.02/ -0.01±0.02	-0.02±0.02/ -0.03±0.02	-0.04±0.02/ 0.04±0.02	0.03±0.03/ 0.02±0.03
JES pileup OffsetMu	-0.51±0.51/ 0.94±0.48	-0.47±0.39/ 0.62±0.39	0.04±0.41/ 0.51±0.39	-1.18±0.5/ 1.03±0.46	-0.36±0.85/ 1.61±0.7
JES pileup OffsetNPV	0.1±0.51/ 0.26±0.48	0.31±0.39/ -0.23±0.39	0.12±0.42/ -0.19±0.41	0.02±0.49/ 0.16±0.48	-0.08±0.9/ 0.82±0.71
JES pileup RhoTopology	-0.07±0.51/ 0.11±0.48	0.23±0.39/ 0.31±0.38	0.44±0.43/ 0.64±0.39	-0.44±0.48/ 0.11±0.48	0.13±0.7/ 1.98±0.7
JES pileup PtTerm	-0.27±0.51/ 0.28±0.48	0.01±0.39/ 0.14±0.39	-0.15±0.43/ 0.01±0.42	0.09±0.48/ 0.08±0.47	-0.08±0.89/ 0.96±0.7
JES SingleParticle HighPt	-0.04±0.5/ -0.04±0.5	0.01±0.39/ 0.01±0.39	0.01±0.42/ 0.01±0.42	0.03±0.48/ 0.03±0.48	-0.09±0.89/ -0.09±0.89
JES PunchThrough MC16	-0.03±0.5/ -0.02±0.5	0.0±0.39/ 0.0±0.39	0.01±0.42/ 0.01±0.42	0.04±0.48/ -0.01±0.48	-0.08±0.89/ -0.07±0.89
JES EtaIntercalibration Modelling	-0.56±0.49/ 1.34±0.48	-1.36±0.42/ 1.18±0.38	-0.85±0.43/ 1.24±0.4	-1.96±0.5/ 1.74±0.45	-2.45±0.89/ 3.95±0.69
JES EtaIntercalibration TotalStat	-0.03±0.5/ 0.19±0.49	-0.13±0.39/ 0.22±0.39	0.16±0.42/ 0.01±0.42	-0.38±0.49/ 0.05±0.47	-0.31±0.9/ 0.99±0.71
JES EtaIntercalibration NonClosure highE	-0.04±0.5/ -0.01±0.5	0.01±0.39/ 0.01±0.39	0.01±0.42/ 0.02±0.42	-0.01±0.48/ -0.04±0.48	-0.09±0.89/ -0.08±0.89
JES EtaIntercalibration NonClosure negEta	-0.04±0.5/ -0.02±0.5	-0.04±0.39/ -0.03±0.39	0.02±0.42/ -0.02±0.42	0.03±0.48/ 0.04±0.48	-0.03±0.89/ -0.14±0.89
JES EtaIntercalibration NonClosure posEta	-0.02±0.5/ -0.08±0.5	0.01±0.39/ 0.04±0.39	0.02±0.42/ 0.01±0.42	-0.03±0.48/ -0.07±0.48	0.01±0.89/ 0.02±0.89
JES EtaIntercalibration NonClosure 2018data	0.15±0.5/ -0.13±0.5	0.14±0.39/ -0.07±0.39	0.07±0.42/ 0.03±0.43	0.13±0.48/ -0.09±0.48	0.04±0.89/ 0.05±0.89
JVT	0.04±0.5/ 0.01±0.5	-0.04±0.39/ 0.05±0.39	-0.01±0.42/ 0.04±0.42	0.01±0.48/ 0.02±0.48	-0.03±0.89/ -0.07±0.89
IJVT	-0.89±0.5/ 0.85±0.49	-0.91±0.4/ 0.91±0.38	-0.85±0.43/ 0.84±0.42	-0.83±0.49/ 0.82±0.48	-0.89±0.9/ 0.83±0.72
tq μR	-0.79±0.21/ 0.74±0.2	-0.65±0.15/ 0.78±0.14	-0.69±0.18/ 0.73±0.17	-1.04±0.21/ 0.77±0.21	-1.56±0.31/ 1.16±0.29
tq μF	-0.96±0.2/ 0.54±0.2	-0.85±0.15/ 0.59±0.14	-0.98±0.18/ 0.64±0.17	-1.27±0.21/ 0.63±0.21	-1.55±0.31/ 1.04±0.29
tq FSR	-2.22±0.23/ 2.62±0.31	-2.01±0.16/ 2.88±0.24	-2.11±0.2/ 3.62±0.26	-2.31±0.24/ 3.04±0.23	-2.44±0.34/ 3.68±0.44
tq ISR αS	0.33±0.21/ -0.3±0.2	0.48±0.14/ -0.34±0.15	0.43±0.18/ -0.36±0.18	0.34±0.21/ -0.51±0.21	0.31±0.3/ -0.39±0.3
tq Parton shower	-3.23±0.2/ (3.23±0.2)	-2.36±0.16/ (2.36±0.16)	-2.48±0.18/ (2.48±0.18)	-1.94±0.23/ (1.94±0.23)	-3.46±0.32/ (3.46±0.32)
tq NLO matching	-3.37±0.44/ (3.37±0.44)	-4.25±0.35/ (4.25±0.35)	-3.93±0.39/ (3.93±0.39)	-3.45±0.45/ (3.45±0.45)	-3.71±0.64/ (3.71±0.64)
tt μR	-0.07±0.05/ 0.05±0.05	-0.06±0.04/ 0.04±0.04	-0.02±0.05/ 0.02±0.04	-0.02±0.05/ 0.02±0.05	0.02±0.06/ 0.04±0.06
tt μF	-0.06±0.05/ 0.05±0.05	-0.04±0.04/ 0.03±0.04	-0.03±0.05/ 0.03±0.05	-0.04±0.05/ 0.04±0.05	-0.01±0.06/ 0.03±0.06
tt FSR	-0.09±0.06/ 0.34±0.12	0.04±0.05/ -0.39±0.12	0.03±0.05/ -0.25±0.11	-0.07±0.06/ 0.06±0.11	-0.01±0.07/ -0.19±0.15
tt ISR αS	0.07±0.05/ -0.07±0.05	0.07±0.04/ -0.08±0.04	0.06±0.05/ -0.05±0.05	0.02±0.05/ -0.01±0.05	0.07±0.06/ -0.04±0.06
tW + tW, tb/tb μR	0.04±0.02/ 0.04±0.02	0.04±0.02/ -0.04±0.02	-0.04±0.02/ -0.04±0.02	0.04±0.02/ -0.04±0.02	-0.04±0.03/ 0.01±0.03
tW + tW, tb/tb μF	0.04±0.02/ 0.04±0.02	0.04±0.02/ -0.04±0.02	-0.04±0.02/ 0.04±0.02	0.04±0.02/ -0.04±0.02	0.04±0.03/ 0.01±0.03
tW + tW DS	0.07±0.02/ (-0.07±0.02)	-0.04±0.02/ (0.04±0.02)	-0.11±0.02/ (0.11±0.02)	-0.07±0.02/ (0.07±0.02)	0.05±0.03/ (-0.05±0.03)
tW + tW, tb/tb FSR	0.01±0.03/ -0.04±0.04	-0.02±0.02/ 0.03±0.03	-0.02±0.02/ 0.08±0.02	0.03±0.03/ -0.03±0.04	-0.04±0.04/ 0.04±0.05
tW + tW, tb/tb ISR αS	0.03±0.02/ -0.03±0.03	0.01±0.02/ -0.01±0.02	0.02±0.02/ -0.02±0.02	0.04±0.02/ -0.04±0.02	-0.01±0.03/ 0.01±0.03
tW + bbbμF	0.09±0.29/ -0.09±0.29	0.11±0.24/ -0.11±0.24	-0.15±0.26/ 0.15±0.26	0.35±0.29/ -0.35±0.29	-0.25±0.66/ 0.25±0.66
W + bbbμR	0.01±0.36/ -0.22±0.36	0.0±0.26/ -0.21±0.26	0.2±0.27/ -0.25±0.29	0.08±0.34/ -0.67±0.38	-0.22±0.53/ 0.33±0.53
W + c(c)μF	-0.05±0.36/ -0.09±0.37	-0.08±0.27/ -0.11±0.32	0.04±0.29/ 0.45±0.34	0.6±0.31/ -0.28±0.31	-1.57±1.41/ 0.02±0.58
W + c(c)μR	0.35±0.33/ -0.33±0.38	0.31±0.24/ -0.03±0.28	0.14±0.24/ -0.87±0.32	0.38±0.25/ -0.16±0.31	-0.23±0.68/ -0.82±0.85
tW + tW, tb/tb Parton shower	0.12±0.02/ (-0.12±0.02)	0.05±0.02/ (-0.05±0.02)	-0.11±0.02/ (0.11±0.02)	0.07±0.02/ (-0.07±0.02)	-0.04±0.03/ (0.04±0.03)
tt Parton shower	0.08±0.09/ (-0.08±0.09)	0.09±0.06/ (-0.09±0.06)	0.22±0.07/ (-0.22±0.07)	0.28±0.07/ (-0.28±0.07)	-0.17±0.09/ (0.17±0.09)
tt NLO matching	0.08±0.05/ (-0.08±0.05)	0.1±0.04/ (-0.1±0.04)	0.17±0.04/ (-0.17±0.04)	0.07±0.05/ (-0.07±0.05)	-0.05±0.06/ (0.05±0.06)
tW + tW NLO matching	0.17±0.02/ (-0.17±0.02)	-0.02±0.02/ (0.02±0.02)	-0.02±0.02/ (0.02±0.02)	0.05±0.02/ (-0.05±0.02)	-0.05±0.03/ (0.05±0.03)
tt h _{damp}	0.12±0.04/ (-0.12±0.04)	0.16±0.03/ (-0.16±0.03)	0.16±0.03/ (-0.16±0.03)	0.07±0.04/ (-0.07±0.04)	-0.01±0.05/ (0.01±0.05)



Table F.17.: Central values and statistical uncertainties of the systematic uncertainties in the absolute $\bar{t}q$ cross section, binned in $|y(\bar{t})|$, evaluated with the bootstrap method. The uncertainties are given in % of the measured differential cross section. Brackets indicate that an uncertainty is symmetrised and entries highlighted in orange have a statistical uncertainty of 0.5 % or higher. The entries in the table read as: central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

Systematic	Systematic uncertainty in [%]				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
JER DataVsMC MC16	-1.8 $\pm$ 0.57 / 0.5 $\pm$ 0.46	0.72 $\pm$ 0.35 / -0.24 $\pm$ 0.31	1.66 $\pm$ 0.52 / 0.48 $\pm$ 0.4	-0.59 $\pm$ 0.51 / -0.35 $\pm$ 0.61	-0.7 $\pm$ 0.55 / 0.81 $\pm$ 0.63
JER Effective NP 1	1.52 $\pm$ 0.61 / -2.51 $\pm$ 0.6	-1.21 $\pm$ 0.51 / 0.89 $\pm$ 0.42	-0.43 $\pm$ 0.48 / 1.51 $\pm$ 0.55	1.55 $\pm$ 0.62 / -0.48 $\pm$ 0.55	-1.35 $\pm$ 0.66 / 1.61 $\pm$ 0.61
JER Effective NP 2	2.11 $\pm$ 0.54 / -3.2 $\pm$ 0.53	0.2 $\pm$ 0.42 / 0.66 $\pm$ 0.42	0.5 $\pm$ 0.51 / 0.23 $\pm$ 0.47	0.54 $\pm$ 0.56 / -0.83 $\pm$ 0.6	1.4 $\pm$ 0.65 / -2.03 $\pm$ 0.53
JER Effective NP 3	-1.52 $\pm$ 0.57 / 1.78 $\pm$ 0.5	1.31 $\pm$ 0.37 / -0.32 $\pm$ 0.37	0.41 $\pm$ 0.43 / 0.39 $\pm$ 0.39	-0.21 $\pm$ 0.47 / 0.71 $\pm$ 0.48	-0.11 $\pm$ 0.46 / -0.03 $\pm$ 0.58
JER Effective NP 4	-1.75 $\pm$ 0.55 / 0.68 $\pm$ 0.48	0.44 $\pm$ 0.39 / 0.05 $\pm$ 0.31	-0.72 $\pm$ 0.35 / 1.95 $\pm$ 0.47	0.13 $\pm$ 0.58 / 0.31 $\pm$ 0.45	1.27 $\pm$ 0.47 / -0.98 $\pm$ 0.6
JER Effective NP 5	-0.74 $\pm$ 0.46 / 0.51 $\pm$ 0.45	0.0 $\pm$ 0.33 / 0.29 $\pm$ 0.41	0.98 $\pm$ 0.41 / 0.12 $\pm$ 0.51	-0.11 $\pm$ 0.36 / -0.54 $\pm$ 0.54	0.9 $\pm$ 0.5 / 1.43 $\pm$ 0.51
JER Effective NP 6	-1.23 $\pm$ 0.46 / 1.08 $\pm$ 0.5	-0.08 $\pm$ 0.3 / 0.32 $\pm$ 0.32	1.1 $\pm$ 0.48 / 1.33 $\pm$ 0.49	0.09 $\pm$ 0.48 / 0.91 $\pm$ 0.34	0.73 $\pm$ 0.48 / -0.16 $\pm$ 0.54
JER Effective NP 7	-0.22 $\pm$ 0.49 / -0.17 $\pm$ 0.34	-0.17 $\pm$ 0.25 / 0.07 $\pm$ 0.28	1.16 $\pm$ 0.38 / -0.0 $\pm$ 0.2	-0.0 $\pm$ 0.45 / 0.31 $\pm$ 0.46	-0.01 $\pm$ 0.49 / 0.64 $\pm$ 0.41
JER Effective NP 8	-0.71 $\pm$ 0.36 / -0.93 $\pm$ 0.33	0.5 $\pm$ 0.24 / 0.9 $\pm$ 0.29	0.27 $\pm$ 0.26 / -0.24 $\pm$ 0.2	-0.71 $\pm$ 0.41 / 0.77 $\pm$ 0.21	-0.84 $\pm$ 0.45 / 0.7 $\pm$ 0.36
JER Effective NP 9	-0.0 $\pm$ 0.33 / -0.33 $\pm$ 0.35	0.84 $\pm$ 0.22 / -0.42 $\pm$ 0.27	0.11 $\pm$ 0.2 / 0.52 $\pm$ 0.35	0.15 $\pm$ 0.21 / 0.15 $\pm$ 0.4	0.57 $\pm$ 0.28 / 0.99 $\pm$ 0.47
JER Effective NP 10	0.0 $\pm$ 0.27 / -0.46 $\pm$ 0.47	-0.24 $\pm$ 0.2 / 0.41 $\pm$ 0.19	-0.06 $\pm$ 0.15 / -0.41 $\pm$ 0.19	0.68 $\pm$ 0.21 / -0.02 $\pm$ 0.38	-0.42 $\pm$ 0.4 / 1.11 $\pm$ 0.29
JER Effective NP 11	-0.78 $\pm$ 0.27 / -0.44 $\pm$ 0.39	-0.03 $\pm$ 0.17 / 0.48 $\pm$ 0.22	0.37 $\pm$ 0.3 / -0.49 $\pm$ 0.17	0.21 $\pm$ 0.37 / 0.67 $\pm$ 0.24	0.42 $\pm$ 0.31 / 0.35 $\pm$ 0.39
JER Effective NP 12restTerm	0.22 $\pm$ 0.3 / -0.07 $\pm$ 0.46	0.21 $\pm$ 0.19 / 0.23 $\pm$ 0.18	0.39 $\pm$ 0.18 / -0.92 $\pm$ 0.18	0.86 $\pm$ 0.17 / -0.33 $\pm$ 0.38	0.37 $\pm$ 0.18 / 1.44 $\pm$ 0.33
JES Effective NP Detector1	0.13 $\pm$ 0.66 / 0.15 $\pm$ 0.66	-0.34 $\pm$ 0.58 / 0.06 $\pm$ 0.58	-0.06 $\pm$ 0.63 / 0.24 $\pm$ 0.62	-0.02 $\pm$ 0.85 / 0.01 $\pm$ 0.7	-0.07 $\pm$ 1.05 / -0.32 $\pm$ 1.05
JES Effective NP Detector2	0.03 $\pm$ 0.67 / 0.11 $\pm$ 0.66	0.02 $\pm$ 0.58 / 0.03 $\pm$ 0.58	0.06 $\pm$ 0.63 / 0.05 $\pm$ 0.63	-0.06 $\pm$ 0.85 / -0.06 $\pm$ 0.85	-0.02 $\pm$ 1.05 / -0.0 $\pm$ 1.05
JES Effective NP Modelling1	-0.12 $\pm$ 0.66 / 1.16 $\pm$ 0.65	-0.36 $\pm$ 0.57 / 0.36 $\pm$ 0.57	0.05 $\pm$ 0.62 / 0.25 $\pm$ 0.62	-0.37 $\pm$ 0.86 / 0.49 $\pm$ 0.69	-1.36 $\pm$ 1.06 / 0.39 $\pm$ 1.04
JES Effective NP Modelling2	0.04 $\pm$ 0.67 / 0.12 $\pm$ 0.66	-0.23 $\pm$ 0.58 / 0.02 $\pm$ 0.58	-0.03 $\pm$ 0.63 / 0.08 $\pm$ 0.63	-0.14 $\pm$ 0.85 / 0.02 $\pm$ 0.85	-0.38 $\pm$ 1.05 / -0.05 $\pm$ 1.05
JES Effective NP Modelling3	0.15 $\pm$ 0.66 / 0.1 $\pm$ 0.66	0.06 $\pm$ 0.58 / -0.29 $\pm$ 0.58	0.26 $\pm$ 0.62 / -0.09 $\pm$ 0.63	0.07 $\pm$ 0.85 / -0.09 $\pm$ 0.85	0.01 $\pm$ 1.05 / -0.34 $\pm$ 1.05
JES Effective NP Modelling4	0.0 $\pm$ 0.67 / 0.11 $\pm$ 0.66	0.05 $\pm$ 0.57 / 0.08 $\pm$ 0.58	0.05 $\pm$ 0.63 / 0.06 $\pm$ 0.63	-0.07 $\pm$ 0.85 / -0.07 $\pm$ 0.85	0.03 $\pm$ 1.05 / 0.04 $\pm$ 1.05
JES Effective NP Mixed1	0.12 $\pm$ 0.66 / 0.12 $\pm$ 0.66	-0.31 $\pm$ 0.58 / 0.13 $\pm$ 0.58	0.06 $\pm$ 0.63 / 0.25 $\pm$ 0.62	-0.02 $\pm$ 0.85 / -0.19 $\pm$ 0.85	-0.09 $\pm$ 1.05 / -0.05 $\pm$ 1.05
JES Effective NP Mixed2	0.14 $\pm$ 0.66 / -0.06 $\pm$ 0.67	0.23 $\pm$ 0.58 / -0.37 $\pm$ 0.58	0.23 $\pm$ 0.61 / 0.02 $\pm$ 0.63	0.03 $\pm$ 0.69 / -0.06 $\pm$ 0.85	-0.19 $\pm$ 1.05 / -0.23 $\pm$ 1.05
JES Effective NP Mixed3	0.1 $\pm$ 0.66 / 0.12 $\pm$ 0.66	-0.35 $\pm$ 0.59 / 0.07 $\pm$ 0.58	-0.05 $\pm$ 0.63 / 0.27 $\pm$ 0.62	-0.06 $\pm$ 0.85 / -0.14 $\pm$ 0.85	-0.06 $\pm$ 1.05 / -0.06 $\pm$ 1.05
JES Effective NP Statistical1	0.03 $\pm$ 0.67 / 0.11 $\pm$ 0.66	0.01 $\pm$ 0.58 / 0.05 $\pm$ 0.58	0.06 $\pm$ 0.63 / 0.06 $\pm$ 0.63	-0.08 $\pm$ 0.85 / -0.08 $\pm$ 0.85	-0.03 $\pm$ 1.05 / -0.01 $\pm$ 1.05
JES Effective NP Statistical2	0.08 $\pm$ 0.66 / -0.01 $\pm$ 0.67	0.17 $\pm$ 0.58 / -0.34 $\pm$ 0.59	0.27 $\pm$ 0.62 / 0.05 $\pm$ 0.64	0.01 $\pm$ 0.7 / -0.03 $\pm$ 0.85	-0.28 $\pm$ 1.05 / -0.16 $\pm$ 1.05
JES Effective NP Statistical3	0.03 $\pm$ 0.67 / 0.02 $\pm$ 0.67	0.02 $\pm$ 0.58 / 0.01 $\pm$ 0.58	0.06 $\pm$ 0.63 / 0.07 $\pm$ 0.63	-0.07 $\pm$ 0.85 / -0.07 $\pm$ 0.85	-0.02 $\pm$ 1.05 / -0.03 $\pm$ 1.05
JES Effective NP Statistical4	0.09 $\pm$ 0.67 / 0.15 $\pm$ 0.66	-0.27 $\pm$ 0.58 / 0.02 $\pm$ 0.58	0.02 $\pm$ 0.63 / 0.09 $\pm$ 0.63	-0.03 $\pm$ 0.85 / -0.04 $\pm$ 0.85	-0.09 $\pm$ 1.05 / -0.02 $\pm$ 1.05
JES Effective NP Statistical5	0.14 $\pm$ 0.66 / 0.12 $\pm$ 0.66	0.01 $\pm$ 0.58 / -0.28 $\pm$ 0.58	0.24 $\pm$ 0.62 / -0.01 $\pm$ 0.63	0.02 $\pm$ 0.85 / -0.04 $\pm$ 0.85	-0.02 $\pm$ 1.05 / -0.09 $\pm$ 1.05
JES Effective NP Statistical6	0.01 $\pm$ 0.67 / 0.15 $\pm$ 0.66	-0.02 $\pm$ 0.58 / 0.04 $\pm$ 0.58	0.08 $\pm$ 0.63 / 0.06 $\pm$ 0.63	-0.05 $\pm$ 0.85 / -0.09 $\pm$ 0.85	-0.07 $\pm$ 1.05 / 0.04 $\pm$ 1.05
JES Flavor Response	1.29 $\pm$ 0.65 / -0.57 $\pm$ 0.67	0.51 $\pm$ 0.57 / -0.75 $\pm$ 0.57	1.5 $\pm$ 0.59 / -0.21 $\pm$ 0.63	0.99 $\pm$ 0.69 / 0.34 $\pm$ 0.69	1.23 $\pm$ 1.04 / -2.13 $\pm$ 1.07
BJES Response	-0.32 $\pm$ 0.67 / 0.29 $\pm$ 0.67	-0.44 $\pm$ 0.59 / -0.03 $\pm$ 0.58	-0.05 $\pm$ 0.63 / 0.32 $\pm$ 0.63	0.02 $\pm$ 0.85 / 0.39 $\pm$ 0.85	-0.49 $\pm$ 1.09 / 0.09 $\pm$ 1.05
JES Flavor Composition tq, tq	-1.27 $\pm$ 0.2 / 1.84 $\pm$ 0.2	-1.45 $\pm$ 0.17 / 1.74 $\pm$ 0.17	-1.44 $\pm$ 0.19 / 2.35 $\pm$ 0.19	-1.6 $\pm$ 0.23 / 2.03 $\pm$ 0.23	-2.88 $\pm$ 0.34 / 2.32 $\pm$ 0.34
JES Flavor Composition tt	0.17 $\pm$ 0.1 / -0.35 $\pm$ 0.1	0.3 $\pm$ 0.08 / -0.35 $\pm$ 0.08	0.45 $\pm$ 0.08 / -0.24 $\pm$ 0.09	0.29 $\pm$ 0.09 / -0.21 $\pm$ 0.1	-0.05 $\pm$ 0.13 / -0.14 $\pm$ 0.13
JES Flavor Composition $tW + tW, tb/tb$	0.03 $\pm$ 0.04 / 0.01 $\pm$ 0.04	-0.01 $\pm$ 0.03 / -0.04 $\pm$ 0.03	0.03 $\pm$ 0.04 / 0.01 $\pm$ 0.04	-0.02 $\pm$ 0.04 / 0.01 $\pm$ 0.04	0.04 $\pm$ 0.06 / -0.07 $\pm$ 0.07
JES pileup OffsetMu	-1.32 $\pm$ 0.67 / 1.63 $\pm$ 0.65	-2.06 $\pm$ 0.62 / 1.16 $\pm$ 0.55	-0.55 $\pm$ 0.65 / 0.76 $\pm$ 0.63	-0.61 $\pm$ 0.87 / 1.19 $\pm$ 0.84	-2.24 $\pm$ 1.1 / 1.35 $\pm$ 1.02
JES pileup OffsetNPV	0.33 $\pm$ 0.65 / -0.33 $\pm$ 0.67	-0.03 $\pm$ 0.57 / 0.13 $\pm$ 0.56	0.06 $\pm$ 0.64 / 0.45 $\pm$ 0.63	-0.14 $\pm$ 0.86 / 0.31 $\pm$ 0.69	-0.77 $\pm$ 1.06 / -0.14 $\pm$ 1.04
JES pileup RhoTopology	0.06 $\pm$ 0.66 / 0.98 $\pm$ 0.66	-0.08 $\pm$ 0.58 / 0.19 $\pm$ 0.56	-0.06 $\pm$ 0.63 / 0.77 $\pm$ 0.62	-0.25 $\pm$ 0.86 / -0.01 $\pm$ 0.88	-2.22 $\pm$ 1.1 / -0.17 $\pm$ 1.04
JES pileup PtTerm	0.21 $\pm$ 0.67 / 0.45 $\pm$ 0.66	-0.65 $\pm$ 0.58 / 0.17 $\pm$ 0.57	0.16 $\pm$ 0.63 / 0.3 $\pm$ 0.61	-0.06 $\pm$ 0.85 / 0.14 $\pm$ 0.85	-0.79 $\pm$ 1.06 / 0.08 $\pm$ 1.04
JES SingleParticle HighPt	0.03 $\pm$ 0.67 / 0.03 $\pm$ 0.67	0.03 $\pm$ 0.58 / 0.03 $\pm$ 0.58	0.07 $\pm$ 0.63 / 0.07 $\pm$ 0.63	-0.05 $\pm$ 0.85 / -0.05 $\pm$ 0.85	-0.04 $\pm$ 1.05 / -0.04 $\pm$ 1.05
JES PunchThrough MC16	0.04 $\pm$ 0.67 / 0.04 $\pm$ 0.67	0.0 $\pm$ 0.58 / -0.0 $\pm$ 0.58	0.07 $\pm$ 0.63 / 0.07 $\pm$ 0.63	-0.06 $\pm$ 0.85 / -0.06 $\pm$ 0.85	-0.04 $\pm$ 1.05 / -0.03 $\pm$ 1.05
JES EtaIntercalibration Modelling	-1.53 $\pm$ 0.67 / 2.34 $\pm$ 0.66	-1.88 $\pm$ 0.59 / 1.06 $\pm$ 0.57	-1.06 $\pm$ 0.63 / 1.61 $\pm$ 0.63	-1.79 $\pm$ 0.87 / 2.85 $\pm$ 0.67	-3.97 $\pm$ 1.11 / 2.26 $\pm$ 1.03
JES EtaIntercalibration TotalStat	-0.11 $\pm$ 0.67 / 0.47 $\pm$ 0.65	-0.37 $\pm$ 0.58 / 0.17 $\pm$ 0.58	0.06 $\pm$ 0.63 / 0.27 $\pm$ 0.62	-0.32 $\pm$ 0.86 / 0.24 $\pm$ 0.7	-0.44 $\pm$ 1.06 / -0.01 $\pm$ 1.04
JES EtaIntercalibration NonClosure highE	0.03 $\pm$ 0.67 / 0.04 $\pm$ 0.67	0.02 $\pm$ 0.58 / 0.01 $\pm$ 0.58	0.06 $\pm$ 0.63 / 0.06 $\pm$ 0.63	-0.05 $\pm$ 0.85 / 0.06 $\pm$ 0.85	-0.01 $\pm$ 1.05 / -0.01 $\pm$ 1.05
JES EtaIntercalibration NonClosure negEta	0.12 $\pm$ 0.67 / 0.06 $\pm$ 0.67	0.09 $\pm$ 0.58 / -0.06 $\pm$ 0.58	-0.29 $\pm$ 0.65 / 0.09 $\pm$ 0.63	-0.03 $\pm$ 0.85 / -0.01 $\pm$ 0.85	-0.08 $\pm$ 1.05 / -0.06 $\pm$ 1.05
JES EtaIntercalibration NonClosure posEta	0.01 $\pm$ 0.67 / 0.01 $\pm$ 0.67	0.06 $\pm$ 0.58 / -0.01 $\pm$ 0.58	0.1 $\pm$ 0.63 / 0.02 $\pm$ 0.63	-0.02 $\pm$ 0.85 / -0.12 $\pm$ 0.85	-0.04 $\pm$ 1.05 / -0.09 $\pm$ 1.05
JES EtaIntercalibration NonClosure 2018data	0.41 $\pm$ 0.66 / 0.04 $\pm$ 0.67	0.15 $\pm$ 0.58 / -0.24 $\pm$ 0.58	0.23 $\pm$ 0.63 / 0.01 $\pm$ 0.64	-0.03 $\pm$ 0.86 / -0.19 $\pm$ 0.85	0.17 $\pm$ 1.04 / 0.18 $\pm$ 1.05
JVT	0.07 $\pm$ 0.67 / 0.04 $\pm$ 0.67	0.07 $\pm$ 0.58 / 0.03 $\pm$ 0.58	0.17 $\pm$ 0.63 / 0.03 $\pm$ 0.63	-0.04 $\pm$ 0.85 / -0.03 $\pm$ 0.85	0.04 $\pm$ 1.05 / -0.02 $\pm$ 1.04
IJVT	-0.77 $\pm$ 0.67 / 0.81 $\pm$ 0.67	-0.92 $\pm$ 0.59 / 0.95 $\pm$ 0.57	-0.75 $\pm$ 0.64 / 0.88 $\pm$ 0.63	-0.89 $\pm$ 0.86 / 0.77 $\pm$ 0.84	-0.69 $\pm$ 1.06 / 0.66 $\pm$ 1.04
$tq \mu_R$	-1.37 $\pm$ 0.21 / 0.79 $\pm$ 0.2	-1.06 $\pm$ 0.18 / 1.11 $\pm$ 0.16	-1.21 $\pm$ 0.19 / 1.05 $\pm$ 0.18	-1.32 $\pm$ 0.25 / 0.85 $\pm$ 0.24	-1.13 $\pm$ 0.35 / 1.51 $\pm$ 0.33
$tq \mu_F$	-1.43 $\pm$ 0.2 / 0.54 $\pm$ 0.2	-1.18 $\pm$ 0.17 / 0.91 $\pm$ 0.16	-1.38 $\pm$ 0.19 / 0.92 $\pm$ 0.18	-1.69 $\pm$ 0.24 / 0.85 $\pm$ 0.23	-1.79 $\pm$ 0.35 / 1.88 $\pm$ 0.33
$tq \text{ FSR}$	-2.14 $\pm$ 0.23 / 3.15 $\pm$ 0.32	-1.74 $\pm$ 0.19 / 2.84 $\pm$ 0.27	-2.3 $\pm$ 0.22 / 2.82 $\pm$ 0.3	-2.78 $\pm$ 0.27 / 2.77 $\pm$ 0.37	-1.3 $\pm$ 0.38 / 3.55 $\pm$ 0.5
$tq \text{ ISR } \alpha_S$	0.21 $\pm$ 0.2 / -0.62 $\pm$ 0.21	0.51 $\pm$ 0.17 / 0.27 $\pm$ 0.17	0.41 $\pm$ 0.19 / -0.44 $\pm$ 0.19	0.15 $\pm$ 0.24 / -0.42 $\pm$ 0.24	0.88 $\pm$ 0.34 / -0.13 $\pm$ 0.35
$tq \text{ Parton shower}$	-3.7 $\pm$ 0.23 / (3.7 $\pm$ 0.23)	-2.61 $\pm$ 0.17 / (2.61 $\pm$ 0.17)	-1.21 $\pm$ 0.19 / (1.21 $\pm$ 0.19)	-1.67 $\pm$ 0.23 / (1.67 $\pm$ 0.23)	-3.7 $\pm$ 0.36 / (3.7 $\pm$ 0.36)
$tq \text{ NLO matching}$	-5.49 $\pm$ 0.65 / (5.49 $\pm$ 0.65)	-3.99 $\pm$ 0.51 / (3.99 $\pm$ 0.51)	-2.25 $\pm$ 0.58 / (2.25 $\pm$ 0.58)	-2.26 $\pm$ 0.64 / (2.26 $\pm$ 0.64)	-6.49 $\pm$ 1.15 / (6.49 $\pm$ 1.15)
$tt \mu_R$	-0.12 $\pm$ 0.11 / 0.07 $\pm$ 0.1	-0.11 $\pm$ 0.08 / 0.09 $\pm$ 0.08	-0.11 $\pm$ 0.09 / 0.1 $\pm$ 0.09	-0.1 $\pm$ 0.1 / 0.06 $\pm$ 0.09	-0.07 $\pm$ 0.13 / 0.06 $\pm$ 0.12
$tt \mu_F$	-0.08 $\pm$ 0.1 / 0.07 $\pm$ 0.1	-0.1 $\pm$ 0.08 / 0.09 $\pm$ 0.08	-0.14 $\pm$ 0.09 / 0.14 $\pm$ 0.09	-0.11 $\pm$ 0.1 / 0.09 $\pm$ 0.09	0.02 $\pm$ 0.13 / -0.04 $\pm$ 0.13
$tt \text{ FSR}$	-0.2 $\pm$ 0.13 / -0.52 $\pm$ 0.27	-0.06 $\pm$ 0.1 / -0.11 $\pm$ 0.16	0.24 $\pm$ 0.1 / -0.39 $\pm$ 0.21	-0.03 $\pm$ 0.11 / -0.31 $\pm$ 0.23	-0.24 $\pm$ 0.16 / 0.62 $\pm$ 0.2
$tt \text{ ISR } \alpha_S$	0.08 $\pm$ 0.1 / -0.09 $\pm$ 0.11	0.1 $\pm$ 0.08 / -0.08 $\pm$ 0.08	0.12 $\pm$ 0.09 / -0.09 $\pm$ 0.09	0.11 $\pm$ 0.09 / -0.1 $\pm$ 0.1	0.01 $\pm$ 0.13 / -0.02 $\pm$ 0.13
$tW + tW, tb/tb \mu_R$	-0.0 $\pm$ 0.04 / -0.04 $\pm$ 0.04	0.0 $\pm$ 0.03 / -0.01 $\pm$ 0.03	0.01 $\pm$ 0.04 / -0.01 $\pm$ 0.04	0.01 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.04 $\pm$ 0.06 / 0.01 $\pm$ 0.06
$tW + tW, tb/tb \mu_F$	-0.0 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.01 $\pm$ 0.03 / -0.04 $\pm$ 0.03	0.0 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.02 $\pm$ 0.04 / 0.01 $\pm$ 0.04	-0.04 $\pm$ 0.06 / 0.01 $\pm$ 0.06
$tW + tW \text{ DS}$	0.0 $\pm$ 0.04 / (-0.04 $\pm$ 0.04)	-0.06 $\pm$ 0.03 / (0.06 $\pm$ 0.03)	0.08 $\pm$ 0.04 / (-0.08 $\pm$ 0.04)	-0.32 $\pm$ 0.05 / (0.32 $\pm$ 0.05)	0.05 $\pm$ 0.06 / (-0.05 $\pm$ 0.06)
$tW + tW, tb/tb \text{ FSR}$	-0.07 $\pm$ 0.0				



F. Systematic uncertainties

Table F.18.: Central values and statistical uncertainties of the systematic uncertainties in the normalised tq cross section, binned in $|y(t)|$, evaluated with the bootstrap method. The uncertainties are given in % of the measured differential cross section. Brackets indicate that an uncertainty is symmetrised and entries highlighted in orange have a statistical uncertainty of 0.5 % or higher. The entries in the table read as: central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

Systematic	Systematic uncertainty in [%]				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
JER DataVsMC MC16	0.71±0.33 / -0.56±0.29	1.6±0.24 / -0.16±0.26	0.3±0.3 / -0.64±0.33	0.67±0.37 / -0.54±0.4	-1.61±0.4 / 0.95±0.48
JER Effective NP 1	-0.74±0.4 / 0.04±0.41	0.8±0.32 / 0.99±0.31	0.14±0.41 / 0.17±0.34	-1.54±0.45 / 0.33±0.41	0.45±0.5 / -0.78±0.42
JER Effective NP 2	-1.06±0.3 / 0.54±0.4	-0.02±0.27 / 0.69±0.27	-0.1±0.29 / 0.91±0.32	-1.7±0.36 / 1.15±0.38	1.25±0.35 / -1.65±0.41
JER Effective NP 3	0.52±0.33 / -1.13±0.31	0.59±0.23 / 0.19±0.25	0.06±0.28 / -0.69±0.32	0.46±0.38 / -1.59±0.33	-0.76±0.39 / 1.48±0.36
JER Effective NP 4	0.33±0.21 / -0.26±0.38	0.32±0.22 / 1.36±0.29	-0.38±0.24 / -0.02±0.31	1.26±0.35 / -0.26±0.4	-0.61±0.31 / -0.5±0.49
JER Effective NP 5	-0.23±0.39 / 0.03±0.22	0.82±0.26 / 0.56±0.2	-0.15±0.33 / 0.15±0.26	-0.53±0.36 / -0.05±0.32	-0.02±0.43 / -0.38±0.34
JER Effective NP 6	0.11±0.3 / -0.75±0.37	0.27±0.21 / 1.14±0.27	-0.44±0.29 / -0.0±0.3	-0.72±0.29 / -0.14±0.36	0.4±0.24 / -0.25±0.42
JER Effective NP 7	-0.86±0.25 / 0.69±0.27	0.51±0.21 / 0.55±0.19	-0.2±0.21 / -0.11±0.21	0.04±0.28 / -0.14±0.29	0.17±0.34 / -0.44±0.27
JER Effective NP 8	-0.03±0.21 / 0.35±0.14	0.19±0.19 / 0.17±0.14	0.3±0.2 / -0.62±0.22	-0.38±0.27 / -0.64±0.2	-0.11±0.32 / 0.44±0.17
JER Effective NP 9	-0.31±0.27 / 0.0±0.26	0.23±0.21 / 0.6±0.2	-0.23±0.22 / 0.11±0.19	-0.85±0.31 / -0.31±0.25	0.51±0.38 / -0.25±0.27
JER Effective NP 10	-0.28±0.24 / 0.1±0.18	-0.16±0.19 / 0.24±0.14	-0.62±0.18 / 0.53±0.16	-0.59±0.22 / -0.13±0.21	0.84±0.29 / -0.45±0.24
JER Effective NP 11	-0.34±0.21 / -0.22±0.2	0.58±0.18 / -0.26±0.15	0.76±0.16 / -0.67±0.19	-0.33±0.2 / -0.69±0.24	-0.5±0.24 / 0.95±0.3
JER Effective NP 12restTerm	-0.31±0.22 / 0.32±0.18	0.16±0.16 / 0.22±0.16	-0.64±0.17 / 0.37±0.16	-0.64±0.21 / 0.18±0.21	0.72±0.26 / -0.56±0.25
JES Effective NP Detector1	0.08±0.52 / -0.06±0.52	-0.04±0.44 / -0.03±0.43	-0.03±0.5 / -0.05±0.5	0.05±0.55 / 0.12±0.55	0.01±0.59 / 0.05±0.59
JES Effective NP Detector2	0.07±0.52 / 0.01±0.52	0.02±0.43 / 0.03±0.43	0.01±0.5 / 0.04±0.5	0.02±0.55 / 0.02±0.55	-0.02±0.59 / -0.02±0.59
JES Effective NP Modelling1	0.14±0.53 / -0.47±0.51	0.04±0.44 / -0.39±0.43	0.16±0.5 / -0.54±0.48	0.11±0.56 / -0.41±0.53	-0.18±0.59 / 0.93±0.58
JES Effective NP Modelling2	0.03±0.52 / 0.02±0.52	-0.02±0.43 / -0.04±0.44	-0.06±0.5 / 0.08±0.5	-0.02±0.55 / 0.14±0.55	0.08±0.59 / -0.07±0.59
JES Effective NP Modelling3	-0.02±0.52 / 0.07±0.52	0.0±0.43 / -0.01±0.43	0.03±0.5 / -0.02±0.5	0.17±0.55 / 0.01±0.55	-0.05±0.59 / 0.01±0.6
JES Effective NP Modelling4	0.04±0.52 / -0.06±0.52	0.0±0.43 / -0.04±0.43	-0.0±0.5 / -0.02±0.5	0.04±0.55 / 0.11±0.55	-0.0±0.59 / 0.04±0.59
JES Effective NP Mixed1	0.1±0.52 / -0.14±0.52	0.0±0.43 / -0.03±0.43	-0.02±0.5 / 0.0±0.5	-0.04±0.55 / 0.13±0.55	0.02±0.59 / 0.04±0.6
JES Effective NP Mixed2	-0.33±0.51 / 0.1±0.52	-0.17±0.43 / -0.03±0.43	-0.22±0.49 / -0.02±0.5	-0.14±0.53 / 0.05±0.55	0.44±0.58 / -0.0±0.59
JES Effective NP Mixed3	0.07±0.52 / -0.05±0.52	0.01±0.43 / -0.04±0.43	0.01±0.5 / -0.04±0.5	0.02±0.55 / 0.09±0.54	-0.02±0.59 / 0.06±0.59
JES Effective NP Statistical1	-0.01±0.52 / -0.0±0.52	0.03±0.44 / 0.03±0.44	0.03±0.5 / 0.05±0.5	0.02±0.55 / 0.03±0.55	-0.01±0.59 / -0.02±0.59
JES Effective NP Statistical2	-0.26±0.51 / 0.07±0.52	-0.12±0.43 / -0.07±0.43	-0.21±0.49 / 0.08±0.5	-0.21±0.53 / 0.04±0.55	0.42±0.58 / -0.03±0.59
JES Effective NP Statistical3	0.01±0.52 / 0.0±0.52	0.02±0.44 / 0.03±0.44	0.04±0.5 / 0.03±0.5	0.02±0.55 / 0.03±0.55	-0.01±0.59 / -0.01±0.59
JES Effective NP Statistical4	0.05±0.52 / -0.01±0.52	-0.01±0.43 / -0.01±0.43	-0.01±0.5 / 0.04±0.5	0.04±0.55 / 0.17±0.54	0.01±0.59 / -0.05±0.59
JES Effective NP Statistical5	-0.06±0.52 / 0.06±0.52	-0.03±0.43 / -0.02±0.43	-0.01±0.5 / -0.0±0.5	0.1±0.55 / 0.04±0.55	0.04±0.59 / 0.0±0.59
JES Effective NP Statistical6	0.06±0.52 / -0.05±0.52	-0.01±0.44 / -0.04±0.43	0.01±0.5 / -0.02±0.5	-0.0±0.55 / 0.11±0.55	0.01±0.59 / 0.04±0.59
JES Flavor Response	-0.61±0.5 / 0.02±0.53	-0.56±0.43 / 0.11±0.43	-0.61±0.48 / 0.04±0.49	-0.25±0.53 / -0.28±0.54	1.05±0.59 / 0.07±0.57
BJES Response	0.17±0.52 / 0.01±0.52	-0.02±0.43 / 0.1±0.44	-0.06±0.5 / -0.09±0.5	0.05±0.55 / 0.14±0.55	-0.01±0.59 / 0.04±0.59
JES Flavor Composition tq,tq	0.69±0.21 / -0.36±0.22	0.58±0.15 / -0.36±0.15	0.15±0.18 / -0.58±0.19	0.13±0.22 / -0.01±0.23	-0.74±0.21 / 0.71±0.22
JES Flavor Composition tt	0.1±0.05 / -0.1±0.05	0.04±0.04 / -0.04±0.04	0.03±0.04 / 0.05±0.05	0.06±0.05 / -0.03±0.05	-0.1±0.04 / 0.04±0.05
JES Flavor Composition tW + tW, tb/tb	0.02±0.02 / -0.01±0.02	0.01±0.02 / -0.01±0.02	-0.03±0.02 / -0.03±0.02	-0.02±0.02 / 0.0±0.02	0.02±0.02 / 0.02±0.02
JES pileup OffsetMu	-0.06±0.52 / -0.11±0.51	-0.02±0.43 / -0.39±0.43	0.44±0.47 / -0.51±0.47	-0.74±0.55 / 0.03±0.53	0.11±0.57 / 0.59±0.58
JES pileup OffsetNPV	0.04±0.53 / 0.04±0.5	0.24±0.43 / -0.46±0.44	0.05±0.5 / -0.42±0.48	-0.06±0.55 / -0.09±0.54	-0.11±0.61 / 0.54±0.58
JES pileup RhoTopology	-0.14±0.52 / -0.76±0.51	0.15±0.43 / -0.55±0.43	0.32±0.5 / -0.23±0.46	-0.48±0.54 / -0.76±0.54	0.03±0.57 / 1.08±0.58
JES pileup PtTerm	-0.19±0.53 / -0.08±0.5	0.1±0.43 / -0.26±0.43	-0.06±0.5 / -0.36±0.48	0.17±0.54 / -0.3±0.53	0.03±0.6 / 0.55±0.58
JES SingleParticle HighPt	-0.01±0.52 / -0.01±0.52	0.04±0.44 / 0.04±0.44	0.04±0.5 / 0.04±0.5	0.05±0.55 / 0.05±0.55	-0.03±0.59 / -0.03±0.59
JES PunchThrough MC16	0.0±0.52 / 0.0±0.52	0.03±0.44 / 0.03±0.44	0.04±0.5 / 0.04±0.5	0.03±0.55 / 0.01±0.55	-0.02±0.59 / -0.01±0.59
JES EtaIntercalibration Modelling	1.02±0.51 / -0.91±0.51	0.23±0.45 / -1.03±0.43	0.74±0.5 / -1.0±0.47	-0.36±0.55 / -0.47±0.52	-0.8±0.59 / 1.77±0.58
JES EtaIntercalibration TotalStat	0.13±0.52 / -0.19±0.51	0.03±0.44 / -0.16±0.43	0.31±0.5 / -0.37±0.49	-0.22±0.55 / -0.34±0.54	-0.12±0.59 / 0.56±0.58
JES EtaIntercalibration NonClosure highE	0.03±0.52 / 0.02±0.52	0.03±0.43 / 0.04±0.43	0.04±0.5 / 0.04±0.5	0.01±0.55 / 0.02±0.55	-0.02±0.59 / -0.02±0.59
JES EtaIntercalibration NonClosure negEta	0.0±0.52 / 0.04±0.52	0.0±0.44 / 0.03±0.43	0.03±0.5 / 0.04±0.49	0.02±0.55 / 0.06±0.55	0.0±0.59 / -0.05±0.59
JES EtaIntercalibration NonClosure posEta	-0.02±0.52 / -0.07±0.52	0.0±0.43 / 0.02±0.43	0.02±0.5 / 0.02±0.5	-0.03±0.55 / -0.06±0.55	0.04±0.6 / 0.06±0.59
JES EtaIntercalibration NonClosure 2018data	0.06±0.52 / -0.1±0.52	0.05±0.44 / -0.05±0.44	-0.03±0.5 / 0.05±0.5	0.03±0.55 / -0.07±0.54	-0.01±0.6 / 1.0±0.6
JVT	0.02±0.52 / 0.01±0.52	0.01±0.44 / 0.05±0.43	0.0±0.5 / 0.04±0.5	0.02±0.55 / 0.02±0.55	0.01±0.59 / -0.03±0.59
IJVT	-0.01±0.52 / 0.04±0.52	-0.03±0.44 / 0.09±0.43	0.02±0.5 / 0.02±0.5	0.04±0.55 / -0.0±0.55	0.02±0.59 / -0.03±0.59
tq μR	0.28±0.22 / -0.17±0.21	0.42±0.16 / -0.13±0.15	0.38±0.19 / -0.18±0.19	0.04±0.23 / -0.15±0.22	-0.47±0.22 / 0.25±0.22
tq μF	0.19±0.22 / -0.18±0.21	0.3±0.16 / -0.12±0.15	0.18±0.19 / -0.12±0.19	-0.11±0.23 / -0.09±0.22	-0.39±0.22 / 0.28±0.22
tq FSR	0.03±0.24 / -0.69±0.33	0.23±0.17 / -0.42±0.26	0.13±0.21 / 0.34±0.28	-0.06±0.25 / -0.25±0.37	-0.19±0.24 / 0.41±0.33
tq ISR αS	-0.04±0.22 / 0.07±0.22	0.11±0.16 / 0.07±0.16	0.06±0.19 / 0.01±0.19	-0.03±0.23 / -0.14±0.23	-0.06±0.22 / -0.02±0.22
tq Parton shower	-0.42±0.21 / (0.42±0.21)	0.42±0.16 / (-0.42±0.16)	0.31±0.19 / (-0.31±0.19)	0.87±0.24 / (-0.87±0.24)	-0.65±0.22 / (0.65±0.22)
tq NLO matching	0.35±0.44 / (-0.35±0.44)	-0.49±0.37 / (0.49±0.37)	-0.19±0.43 / (0.19±0.43)	0.27±0.46 / (-0.27±0.46)	0.02±0.48 / (-0.02±0.48)
tt μR	-0.05±0.05 / 0.03±0.05	-0.04±0.04 / 0.02±0.04	-0.0±0.05 / 0.0±0.05	0.0±0.05 / -0.0±0.05	0.04±0.05 / -0.02±0.04
tt μF	-0.03±0.05 / 0.02±0.05	-0.01±0.04 / -0.0±0.04	-0.0±0.05 / -0.0±0.05	-0.01±0.05 / 0.0±0.05	0.02±0.05 / -0.01±0.04
tt FSR	-0.08±0.06 / 0.47±0.12	0.05±0.05 / -0.26±0.11	0.04±0.06 / -0.12±0.11	-0.06±0.06 / 0.19±0.12	0.0±0.05 / -0.06±0.11
tt ISR αS	0.01±0.05 / -0.02±0.06	0.01±0.04 / -0.03±0.04	-0.0±0.05 / -0.0±0.05	-0.04±0.05 / 0.04±0.05	0.01±0.04 / 0.01±0.05
tW + tW, tb/tb μR	0.0±0.02 / 0.0±0.02	0.0±0.02 / -0.01±0.02	-0.0±0.02 / -0.0±0.02	0.0±0.02 / -0.0±0.02	-0.0±0.02 / 0.01±0.02
tW + tW, tb/tb μF	0.0±0.02 / 0.0±0.02	0.0±0.02 / -0.0±0.02	-0.0±0.02 / -0.0±0.02	-0.0±0.02 / -0.0±0.02	0.0±0.02 / 0.0±0.02
tW + tW DS	0.08±0.02 / (-0.08±0.02)	-0.03±0.02 / (0.03±0.02)	-0.09±0.02 / (0.09±0.02)	-0.06±0.02 / (0.06±0.02)	0.06±0.02 / (-0.06±0.02)
tW + tW, tb/tb FSR	0.03±0.03 / -0.03±0.04	-0.01±0.02 / -0.0±0.03	-0.0±0.03 / 0.05±0.03	0.05±0.03 / -0.06±0.04	-0.03±0.03 / 0.01±0.04
tW + tW, tb/tb ISR αS	0.03±0.02 / -0.02±0.03	-0.0±0.02 / -0.0±0.02	-0.01±0.02 / -0.01±0.02	-0.0±0.02 / 0.0±0.02	-0.02±0.02 / 0.02±0.02
tW + bbbμF	0.16±0.37 / -0.16±0.37	0.18±0.3 / -0.18±0.3	-0.08±0.34 / 0.08±0.34	0.41±0.41 / -0.41±0.41	-0.28±0.51 / 0.28±0.51
W + bbbμR	0.04±0.38 / -1.±0.38	0.03±0.29 / -0.9±0.29	0.22±0.32 / -0.13±0.33	0.11±0.38 / -0.55±0.41	-0.21±0.39 / 0.41±0.4
W + c(c)bμF	0.37±0.53 / -0.11±0.39	0.35±0.46 / -0.13±0.33	0.45±0.51 / 0.43±0.37	0.92±0.58 / -0.3±0.38	-1.1±0.96 / -0.03±0.43
W + c(c)bμR	0.29±0.39 / 0.19±0.44	0.25±0.31 / 0.5±0.35	0.08±0.35 / -0.34±0.41	0.32±0.41 / 0.36±0.45	-0.41±0.54 / -0.25±0.57
tW + tW, tb/tb Parton shower	0.11±0.02 / (-0.11±0.02)	0.04±0.02 / (-0.04±0.02)	-0.12±0.02 / (0.12±0.02)	0.06±0.02 / (-0.06±0.02)	-0.02±0.02 / (0.02±0.02)
tt Parton shower	0.03±0.09 / (-0.03±0.09)	0.03±0.06 / (-0.03±0.06)	-0.16±0.07 / (-0.16±0.07)	0.22±0.08 / (-0.22±0.08)	-0.22±0.07 / (0.22±0.07)
tt NLO matching	0.03±0.05 / (-0.03±0.05)	0.04±0.04 / (-0.04±0.04)	0.11±0.04 / (-0.11±0.04)	0.01±0.05 / (-0.01±0.05)	-0.11±0.04 / (0.11±0.04)
tW + tW NLO matching	0.16±0.02 / (-0.16±0.02)	-0.03±0.02 / (0.03±0.02)	-0.02±0.02 / (0.02±0.02)	0.04±0.02 / (-0.04±0.02)	-0.05±0.02 / (0.05±0.02)
t t hump	0.03±0.04 / (-0.03±0.04)	-0.07±0.03 / (-0.07±0.03)	0.07±0.04 / (-0.07±0.04)	-0.01±0.04 / 0.01±0.04	-0.09±0.03 / (0.09±0.03)

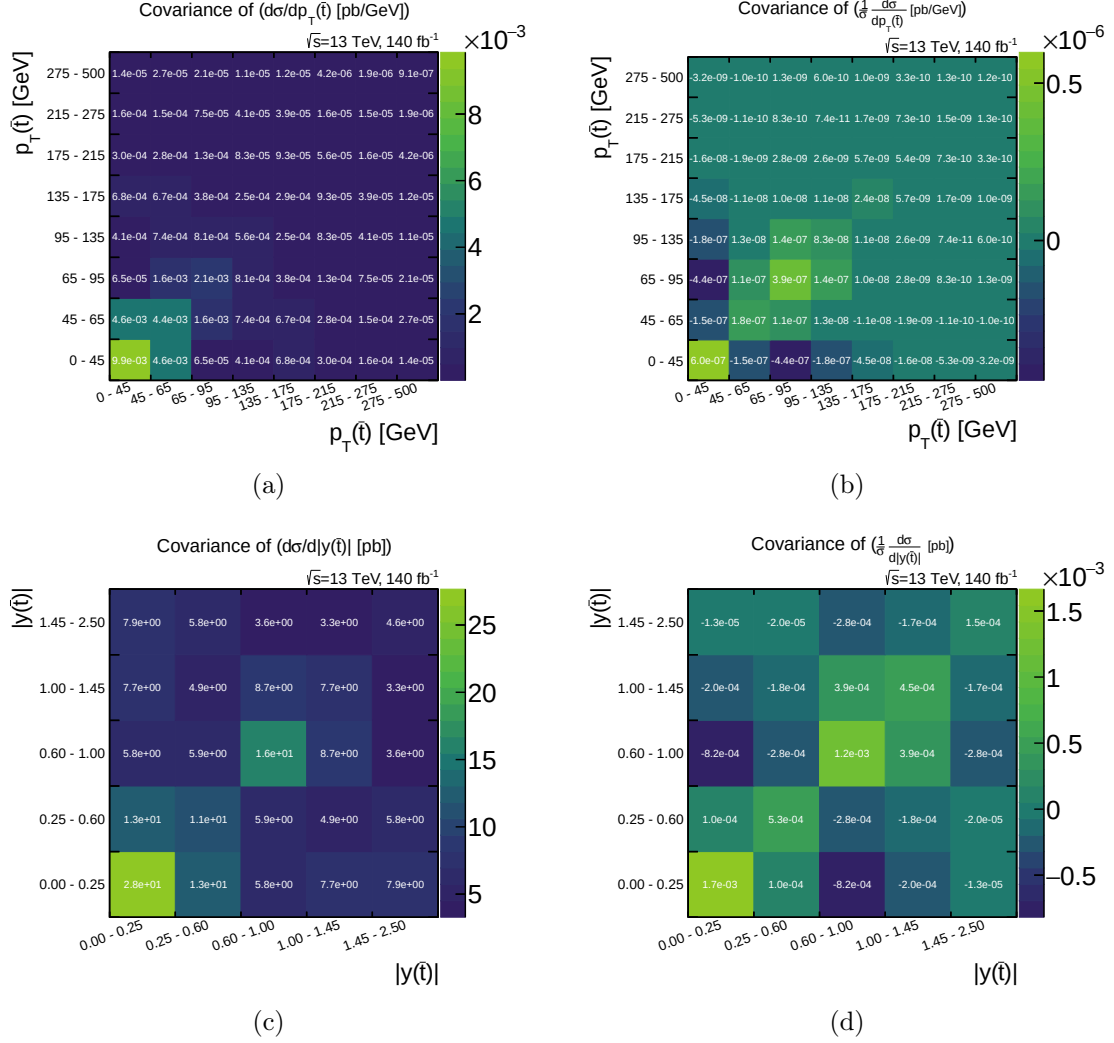


Table F.19.: Central values and statistical uncertainties of the systematic uncertainties in the normalised $\bar{t}q$ cross section, binned in $|\mathbf{y}(\bar{t})|$, evaluated with the bootstrap method. The uncertainties are given in % of the measured differential cross section. Brackets indicate that an uncertainty is symmetrised and entries highlighted in orange have a statistical uncertainty of 0.5 % or higher. The entries in the table read as: central value up variation $\pm$ statistical uncertainty / central value down variation $\pm$ statistical uncertainty.

Systematic	Systematic uncertainty in [%]				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
JER DataVsMC MC16	-1.75 $\pm$ 0.54 / 0.22 $\pm$ 0.47	0.78 $\pm$ 0.37 / -0.54 $\pm$ 0.34	1.72 $\pm$ 0.5 / 0.18 $\pm$ 0.44	-0.53 $\pm$ 0.49 / -0.67 $\pm$ 0.59	-0.66 $\pm$ 0.46 / 0.52 $\pm$ 0.52
JER Effective NP 1	1.75 $\pm$ 0.61 / -3.06 $\pm$ 0.59	-0.96 $\pm$ 0.49 / 0.39 $\pm$ 0.43	-0.18 $\pm$ 0.51 / 1.0 $\pm$ 0.53	1.81 $\pm$ 0.6 / -0.99 $\pm$ 0.54	-1.12 $\pm$ 0.56 / 1.12 $\pm$ 0.53
JER Effective NP 2	1.19 $\pm$ 0.56 / -2.18 $\pm$ 0.51	-0.73 $\pm$ 0.43 / 1.64 $\pm$ 0.41	-0.43 $\pm$ 0.51 / 1.21 $\pm$ 0.47	-0.38 $\pm$ 0.57 / 0.18 $\pm$ 0.57	0.48 $\pm$ 0.56 / -1.04 $\pm$ 0.43
JER Effective NP 3	-1.58 $\pm$ 0.54 / 1.41 $\pm$ 0.5	1.25 $\pm$ 0.36 / -0.7 $\pm$ 0.36	0.35 $\pm$ 0.43 / 0.0 $\pm$ 0.41	-0.26 $\pm$ 0.45 / 0.32 $\pm$ 0.48	-0.17 $\pm$ 0.38 / -0.43 $\pm$ 0.47
JER Effective NP 4	-1.82 $\pm$ 0.53 / 0.37 $\pm$ 0.47	0.4 $\pm$ 0.37 / -0.27 $\pm$ 0.34	-0.77 $\pm$ 0.38 / 1.65 $\pm$ 0.46	0.1 $\pm$ 0.55 / -0.01 $\pm$ 0.46	1.22 $\pm$ 0.39 / -1.29 $\pm$ 0.49
JER Effective NP 5	-1.07 $\pm$ 0.44 / 0.03 $\pm$ 0.46	-0.33 $\pm$ 0.34 / -0.18 $\pm$ 0.4	0.65 $\pm$ 0.4 / -0.35 $\pm$ 0.48	-0.45 $\pm$ 0.36 / -1.01 $\pm$ 0.5	0.56 $\pm$ 0.41 / 0.97 $\pm$ 0.43
JER Effective NP 6	-1.5 $\pm$ 0.44 / 0.48 $\pm$ 0.49	-0.35 $\pm$ 0.32 / -0.29 $\pm$ 0.35	0.85 $\pm$ 0.47 / 0.73 $\pm$ 0.47	-0.16 $\pm$ 0.45 / 0.29 $\pm$ 0.36	0.47 $\pm$ 0.39 / -0.78 $\pm$ 0.45
JER Effective NP 7	-0.4 $\pm$ 0.46 / -0.39 $\pm$ 0.34	-0.35 $\pm$ 0.28 / -0.14 $\pm$ 0.27	0.98 $\pm$ 0.39 / -0.22 $\pm$ 0.24	-0.19 $\pm$ 0.42 / 0.1 $\pm$ 0.43	-0.19 $\pm$ 0.39 / 0.42 $\pm$ 0.32
JER Effective NP 8	-0.42 $\pm$ 0.36 / -1.23 $\pm$ 0.32	0.79 $\pm$ 0.25 / 0.6 $\pm$ 0.26	0.56 $\pm$ 0.28 / -0.55 $\pm$ 0.22	-0.41 $\pm$ 0.39 / 0.47 $\pm$ 0.44	-0.54 $\pm$ 0.34 / 0.39 $\pm$ 0.29
JER Effective NP 9	-0.37 $\pm$ 0.31 / -0.62 $\pm$ 0.35	0.47 $\pm$ 0.21 / -0.71 $\pm$ 0.28	-0.26 $\pm$ 0.2 / 0.24 $\pm$ 0.34	-0.22 $\pm$ 0.22 / -0.12 $\pm$ 0.39	0.2 $\pm$ 0.22 / 0.71 $\pm$ 0.37
JER Effective NP 10	0.08 $\pm$ 0.27 / -0.69 $\pm$ 0.43	-0.17 $\pm$ 0.2 / 0.18 $\pm$ 0.2	0.01 $\pm$ 0.2 / -0.64 $\pm$ 0.22	0.75 $\pm$ 0.24 / -0.24 $\pm$ 0.35	-0.36 $\pm$ 0.31 / 0.89 $\pm$ 0.23
JER Effective NP 11	-0.89 $\pm$ 0.28 / -0.56 $\pm$ 0.37	-0.14 $\pm$ 0.19 / 0.35 $\pm$ 0.21	0.26 $\pm$ 0.29 / -0.62 $\pm$ 0.2	0.11 $\pm$ 0.34 / 0.54 $\pm$ 0.26	0.31 $\pm$ 0.25 / 0.22 $\pm$ 0.3
JER Effective NP 12restTerm	-0.18 $\pm$ 0.27 / -0.25 $\pm$ 0.43	-0.19 $\pm$ 0.18 / 0.04 $\pm$ 0.2	-0.01 $\pm$ 0.18 / -1.1 $\pm$ 0.22	0.47 $\pm$ 0.17 / -0.51 $\pm$ 0.36	-0.03 $\pm$ 0.15 / 1.26 $\pm$ 0.26
JES Effective NP Detector1	0.19 $\pm$ 0.66 / 0.15 $\pm$ 0.66	-0.26 $\pm$ 0.59 / 0.1 $\pm$ 0.58	0.01 $\pm$ 0.62 / 0.23 $\pm$ 0.62	0.17 $\pm$ 0.69 / 0.02 $\pm$ 0.69	0.08 $\pm$ 0.67 / -0.23 $\pm$ 0.67
JES Effective NP Detector2	0.01 $\pm$ 0.66 / 0.06 $\pm$ 0.66	0.03 $\pm$ 0.58 / 0.03 $\pm$ 0.58	0.05 $\pm$ 0.63 / 0.01 $\pm$ 0.63	0.03 $\pm$ 0.69 / 0.01 $\pm$ 0.69	0.04 $\pm$ 0.67 / 0.04 $\pm$ 0.68
JES Effective NP Modelling1	0.37 $\pm$ 0.67 / 0.67 $\pm$ 0.65	0.17 $\pm$ 0.58 / -0.08 $\pm$ 0.58	0.54 $\pm$ 0.62 / -0.26 $\pm$ 0.62	0.26 $\pm$ 0.7 / 0.02 $\pm$ 0.69	-0.78 $\pm$ 0.68 / -0.01 $\pm$ 0.68
JES Effective NP Modelling2	0.2 $\pm$ 0.66 / 0.07 $\pm$ 0.66	-0.05 $\pm$ 0.59 / 0.01 $\pm$ 0.58	0.14 $\pm$ 0.62 / 0.04 $\pm$ 0.63	0.15 $\pm$ 0.69 / 0.1 $\pm$ 0.69	-0.14 $\pm$ 0.67 / -0.01 $\pm$ 0.67
JES Effective NP Modelling3	0.03 $\pm$ 0.67 / 0.26 $\pm$ 0.66	-0.03 $\pm$ 0.58 / -0.12 $\pm$ 0.59	0.14 $\pm$ 0.62 / 0.07 $\pm$ 0.62	0.07 $\pm$ 0.69 / 0.2 $\pm$ 0.69	-0.03 $\pm$ 0.67 / -0.1 $\pm$ 0.67
JES Effective NP Modelling4	-0.03 $\pm$ 0.66 / 0.04 $\pm$ 0.66	0.04 $\pm$ 0.59 / 0.05 $\pm$ 0.58	0.02 $\pm$ 0.63 / -0.0 $\pm$ 0.63	0.02 $\pm$ 0.69 / -0.02 $\pm$ 0.69	0.07 $\pm$ 0.67 / 0.06 $\pm$ 0.67
JES Effective NP Mixed1	0.16 $\pm$ 0.66 / 0.05 $\pm$ 0.66	-0.25 $\pm$ 0.59 / 0.1 $\pm$ 0.58	0.09 $\pm$ 0.62 / 0.18 $\pm$ 0.62	0.16 $\pm$ 0.69 / -0.14 $\pm$ 0.69	0.04 $\pm$ 0.67 / -0.04 $\pm$ 0.67
JES Effective NP Mixed2	0.08 $\pm$ 0.66 / 0.06 $\pm$ 0.66	0.19 $\pm$ 0.58 / -0.22 $\pm$ 0.59	0.16 $\pm$ 0.62 / 0.16 $\pm$ 0.62	-0.02 $\pm$ 0.7 / 0.2 $\pm$ 0.69	-0.18 $\pm$ 0.67 / -0.02 $\pm$ 0.67
JES Effective NP Mixed3	0.17 $\pm$ 0.66 / 0.05 $\pm$ 0.66	-0.26 $\pm$ 0.59 / 0.03 $\pm$ 0.58	0.03 $\pm$ 0.62 / 0.2 $\pm$ 0.62	0.14 $\pm$ 0.69 / -0.09 $\pm$ 0.69	0.1 $\pm$ 0.67 / -0.05 $\pm$ 0.67
JES Effective NP Statistical1	0.01 $\pm$ 0.66 / 0.06 $\pm$ 0.66	0.03 $\pm$ 0.58 / 0.04 $\pm$ 0.58	0.04 $\pm$ 0.63 / 0.02 $\pm$ 0.63	0.02 $\pm$ 0.69 / -0.01 $\pm$ 0.69	0.04 $\pm$ 0.67 / 0.04 $\pm$ 0.67
JES Effective NP Statistical2	0.06 $\pm$ 0.66 / 0.07 $\pm$ 0.66	0.17 $\pm$ 0.58 / -0.23 $\pm$ 0.59	0.23 $\pm$ 0.62 / 0.14 $\pm$ 0.62	-0.0 $\pm$ 0.69 / 0.18 $\pm$ 0.69	-0.22 $\pm$ 0.67 / 0.0 $\pm$ 0.68
JES Effective NP Statistical3	0.01 $\pm$ 0.66 / 0.01 $\pm$ 0.66	0.03 $\pm$ 0.58 / 0.03 $\pm$ 0.58	0.04 $\pm$ 0.63 / 0.05 $\pm$ 0.63	0.02 $\pm$ 0.69 / 0.02 $\pm$ 0.69	0.04 $\pm$ 0.67 / 0.03 $\pm$ 0.67
JES Effective NP Statistical4	0.14 $\pm$ 0.66 / 0.1 $\pm$ 0.66	-0.21 $\pm$ 0.59 / 0.0 $\pm$ 0.58	0.07 $\pm$ 0.63 / 0.05 $\pm$ 0.63	0.15 $\pm$ 0.69 / 0.02 $\pm$ 0.69	0.05 $\pm$ 0.67 / 0.01 $\pm$ 0.67
JES Effective NP Statistical5	0.03 $\pm$ 0.66 / 0.17 $\pm$ 0.67	-0.05 $\pm$ 0.58 / -0.21 $\pm$ 0.59	0.16 $\pm$ 0.62 / 0.05 $\pm$ 0.62	0.05 $\pm$ 0.69 / 0.15 $\pm$ 0.69	-0.02 $\pm$ 0.67 / 0.05 $\pm$ 0.67
JES Effective NP Statistical6	0.01 $\pm$ 0.66 / 0.1 $\pm$ 0.66	0.01 $\pm$ 0.58 / 0.03 $\pm$ 0.58	0.08 $\pm$ 0.63 / 0.01 $\pm$ 0.63	0.06 $\pm$ 0.69 / -0.02 $\pm$ 0.69	0.0 $\pm$ 0.67 / 0.04 $\pm$ 0.67
JES Flavor Response	0.16 $\pm$ 0.65 / 0.25 $\pm$ 0.67	-0.58 $\pm$ 0.59 / 0.1 $\pm$ 0.58	0.41 $\pm$ 0.61 / 0.58 $\pm$ 0.62	-0.15 $\pm$ 0.7 / 1.16 $\pm$ 0.67	0.22 $\pm$ 0.68 / -1.22 $\pm$ 0.69
BJES Response	-0.08 $\pm$ 0.66 / 0.07 $\pm$ 0.67	-0.12 $\pm$ 0.6 / -0.21 $\pm$ 0.58	0.2 $\pm$ 0.63 / 0.11 $\pm$ 0.63	0.4 $\pm$ 0.7 / 0.31 $\pm$ 0.69	-0.18 $\pm$ 0.69 / -0.05 $\pm$ 0.68
JES Flavor Composition tq, tq	0.56 $\pm$ 0.21 / -0.26 $\pm$ 0.21	0.38 $\pm$ 0.17 / -0.37 $\pm$ 0.18	0.42 $\pm$ 0.19 / 0.26 $\pm$ 0.2	0.23 $\pm$ 0.24 / -0.06 $\pm$ 0.24	-1.03 $\pm$ 0.25 / 0.23 $\pm$ 0.26
JES Flavor Composition tt	-0.04 $\pm$ 0.1 / -0.11 $\pm$ 0.1	0.08 $\pm$ 0.08 / -0.11 $\pm$ 0.08	0.23 $\pm$ 0.09 / 0.0 $\pm$ 0.09	0.07 $\pm$ 0.09 / 0.04 $\pm$ 0.09	-0.26 $\pm$ 0.1 / -0.11 $\pm$ 0.1
JES Flavor Composition $tW + tW, tb/tb$	0.01 $\pm$ 0.04 / 0.02 $\pm$ 0.04	-0.03 $\pm$ 0.03 / 0.01 $\pm$ 0.03	0.02 $\pm$ 0.04 / 0.03 $\pm$ 0.04	-0.04 $\pm$ 0.04 / 0.02 $\pm$ 0.05	0.02 $\pm$ 0.05 / -0.05 $\pm$ 0.05
JES pileup OffsetMu	0.12 $\pm$ 0.68 / 0.42 $\pm$ 0.65	-0.63 $\pm$ 0.61 / -0.04 $\pm$ 0.57	0.87 $\pm$ 0.64 / -0.43 $\pm$ 0.64	0.89 $\pm$ 0.7 / 0.08 $\pm$ 0.68	-0.69 $\pm$ 0.7 / 0.21 $\pm$ 0.66
JES pileup OffsetNPV	0.45 $\pm$ 0.67 / -0.4 $\pm$ 0.67	0.17 $\pm$ 0.58 / 0.08 $\pm$ 0.57	0.23 $\pm$ 0.63 / 0.36 $\pm$ 0.62	0.16 $\pm$ 0.69 / 0.21 $\pm$ 0.7	-0.51 $\pm$ 0.7 / -0.14 $\pm$ 0.68
JES pileup RhoTopology	0.71 $\pm$ 0.66 / 0.65 $\pm$ 0.64	0.62 $\pm$ 0.59 / -0.09 $\pm$ 0.58	0.57 $\pm$ 0.64 / 0.44 $\pm$ 0.63	0.53 $\pm$ 0.7 / -0.27 $\pm$ 0.73	-1.49 $\pm$ 0.7 / -0.41 $\pm$ 0.67
JES pileup PtTerm	0.46 $\pm$ 0.67 / 0.26 $\pm$ 0.65	-0.35 $\pm$ 0.59 / 0.01 $\pm$ 0.58	0.43 $\pm$ 0.62 / 0.12 $\pm$ 0.62	0.34 $\pm$ 0.69 / 0.07 $\pm$ 0.7	-0.45 $\pm$ 0.68 / -0.16 $\pm$ 0.68
JES SingleParticle HighPt	-0.01 $\pm$ 0.66 / -0.01 $\pm$ 0.66	0.04 $\pm$ 0.58 / 0.04 $\pm$ 0.58	0.05 $\pm$ 0.63 / 0.05 $\pm$ 0.63	0.03 $\pm$ 0.69 / 0.03 $\pm$ 0.69	0.04 $\pm$ 0.67 / 0.04 $\pm$ 0.67
JES PunchThrough MC16	0.02 $\pm$ 0.66 / 0.01 $\pm$ 0.66	0.02 $\pm$ 0.58 / 0.02 $\pm$ 0.58	0.06 $\pm$ 0.63 / 0.06 $\pm$ 0.63	0.04 $\pm$ 0.69 / 0.03 $\pm$ 0.69	0.02 $\pm$ 0.67 / 0.03 $\pm$ 0.67
JES EtaIntercalibration Modelling	0.66 $\pm$ 0.66 / 0.36 $\pm$ 0.65	0.35 $\pm$ 0.59 / -0.93 $\pm$ 0.6	1.13 $\pm$ 0.63 / -0.39 $\pm$ 0.63	0.52 $\pm$ 0.68 / 0.9 $\pm$ 0.68	-1.67 $\pm$ 0.7 / 0.36 $\pm$ 0.67
JES EtaIntercalibration TotalStat	0.1 $\pm$ 0.67 / 0.28 $\pm$ 0.66	-0.11 $\pm$ 0.58 / -0.01 $\pm$ 0.58	0.29 $\pm$ 0.63 / 0.06 $\pm$ 0.62	0.02 $\pm$ 0.7 / 0.05 $\pm$ 0.7	-0.1 $\pm$ 0.67 / -0.11 $\pm$ 0.67
JES EtaIntercalibration NonClosure highE	0.0 $\pm$ 0.66 / 0.01 $\pm$ 0.66	0.03 $\pm$ 0.58 / 0.02 $\pm$ 0.58	0.04 $\pm$ 0.63 / 0.04 $\pm$ 0.63	0.04 $\pm$ 0.69 / 0.03 $\pm$ 0.69	0.04 $\pm$ 0.67 / 0.04 $\pm$ 0.67
JES EtaIntercalibration NonClosure negEta	0.15 $\pm$ 0.66 / 0.04 $\pm$ 0.66	0.17 $\pm$ 0.58 / -0.04 $\pm$ 0.58	-0.24 $\pm$ 0.64 / 0.08 $\pm$ 0.63	0.12 $\pm$ 0.7 / 0.09 $\pm$ 0.69	0.05 $\pm$ 0.67 / 0.0 $\pm$ 0.67
JES EtaIntercalibration NonClosure posEta	-0.04 $\pm$ 0.66 / 0.03 $\pm$ 0.66	0.05 $\pm$ 0.58 / 0.05 $\pm$ 0.58	0.05 $\pm$ 0.63 / 0.05 $\pm$ 0.63	0.05 $\pm$ 0.69 / 0.01 $\pm$ 0.69	0.02 $\pm$ 0.67 / 0.0 $\pm$ 0.67
JES EtaIntercalibration NonClosure 2018data	0.21 $\pm$ 0.66 / 0.04 $\pm$ 0.66	-0.01 $\pm$ 0.58 / -0.19 $\pm$ 0.58	0.03 $\pm$ 0.63 / -0.0 $\pm$ 0.63	-0.12 $\pm$ 0.69 / -0.07 $\pm$ 0.7	0.05 $\pm$ 0.68 / 0.28 $\pm$ 0.68
JVT	-0.02 $\pm$ 0.66 / 0.01 $\pm$ 0.66	0.02 $\pm$ 0.58 / 0.04 $\pm$ 0.58	0.1 $\pm$ 0.62 / -0.0 $\pm$ 0.63	-0.01 $\pm$ 0.69 / 0.06 $\pm$ 0.69	0.04 $\pm$ 0.67 / 0.04 $\pm$ 0.67
IJVT	0.01 $\pm$ 0.66 / -0.01 $\pm$ 0.67	-0.12 $\pm$ 0.58 / 0.17 $\pm$ 0.58	0.02 $\pm$ 0.62 / 0.06 $\pm$ 0.63	-0.01 $\pm$ 0.69 / 0.07 $\pm$ 0.69	0.16 $\pm$ 0.68 / -0.08 $\pm$ 0.67
$tq \mu_R$	-0.19 $\pm$ 0.21 / -0.32 $\pm$ 0.21	0.12 $\pm$ 0.18 / 0.0 $\pm$ 0.17	-0.02 $\pm$ 0.2 / -0.06 $\pm$ 0.19	-0.14 $\pm$ 0.25 / -0.26 $\pm$ 0.25	0.06 $\pm$ 0.26 / 0.41 $\pm$ 0.26
$tq \mu_F$	0.05 $\pm$ 0.21 / -0.56 $\pm$ 0.21	0.29 $\pm$ 0.17 / -0.18 $\pm$ 0.17	0.09 $\pm$ 0.2 / -0.17 $\pm$ 0.19	-0.21 $\pm$ 0.25 / -0.24 $\pm$ 0.24	-0.31 $\pm$ 0.26 / 0.8 $\pm$ 0.26
$tq \text{ FSR}$	-0.17 $\pm$ 0.23 / 0.08 $\pm$ 0.33	0.22 $\pm$ 0.19 / -0.24 $\pm$ 0.29	-0.33 $\pm$ 0.22 / -0.26 $\pm$ 0.31	-0.8 $\pm$ 0.28 / -0.31 $\pm$ 0.39	0.65 $\pm$ 0.29 / 0.5 $\pm$ 0.41
$tq \text{ ISR } \alpha_S$	-0.28 $\pm$ 0.21 / -0.28 $\pm$ 0.21	0.01 $\pm$ 0.17 / 0.06 $\pm$ 0.17	-0.08 $\pm$ 0.2 / -0.06 $\pm$ 0.2	-0.34 $\pm$ 0.25 / -0.09 $\pm$ 0.25	0.4 $\pm$ 0.26 / 0.2 $\pm$ 0.26
tq Parton shower	-1.09 $\pm$ 0.22 / (1.09 $\pm$ 0.22)	-0.02 $\pm$ 0.17 / (0.02 $\pm$ 0.17)	1.34 $\pm$ 0.2 / (-1.34 $\pm$ 0.2)	0.9 $\pm$ 0.23 / (-0.9 $\pm$ 0.23)	-1.08 $\pm$ 0.27 / (1.08 $\pm$ 0.27)
tq NLO matching	-1.16 $\pm$ 0.61 / (1.16 $\pm$ 0.61)	0.25 $\pm$ 0.5 / (-0.25 $\pm$ 0.5)	1.92 $\pm$ 0.58 / (-1.92 $\pm$ 0.58)	1.93 $\pm$ 0.63 / (-1.93 $\pm$ 0.63)	-2.14 $\pm$ 0.7 / (2.14 $\pm$ 0.7)
$tt \mu_R$	-0.02 $\pm$ 0.1 / -0.04 $\pm$ 0.1	-0.02 $\pm$ 0.08 / 0.01 $\pm$ 0.08	-0.01 $\pm$ 0.09 / 0.02 $\pm$ 0.09	-0.0 $\pm$ 0.1 / -0.01 $\pm$ 0.09	0.03 $\pm$ 0.1 / -0.02 $\pm$ 0.1
$tt \mu_F$	-0.01 $\pm$ 0.1 / -0.01 $\pm$ 0.1	-0.03 $\pm$ 0.08 / 0.02 $\pm$ 0.08	-0.06 $\pm$ 0.09 / 0.07 $\pm$ 0.09	-0.04 $\pm$ 0.09 / 0.02 $\pm$ 0.09	0.09 $\pm$ 0.1 / -0.07 $\pm$ 0.1
$tt \text{ FSR}$	-0.14 $\pm$ 0.12 / -0.46 $\pm$ 0.25	0.0 $\pm$ 0.09 / -0.05 $\pm$ 0.16	0.3 $\pm$ 0.11 / -0.33 $\pm$ 0.2	0.03 $\pm$ 0.11 / -0.25 $\pm$ 0.21	-0.18 $\pm$ 0.12 / 0.68 $\pm$ 0.17
$tt \text{ ISR } \alpha_S$	-0.0 $\pm$ 0.1 / -0.02 $\pm$ 0.1	0.02 $\pm$ 0.08 / -0.01 $\pm$ 0.08	0.04 $\pm$ 0.09 / -0.02 $\pm$ 0.09	0.03 $\pm$ 0.09 / -0.03 $\pm$ 0.1	-0.06 $\pm$ 0.1 / 0.05 $\pm$ 0.1
$tW + tW, tb/tb \mu_R$	-0.01 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.04 $\pm$ 0.03 / -0.01 $\pm$ 0.03	0.01 $\pm$ 0.04 / -0.04 $\pm$ 0.04	0.04 $\pm$ 0.04 / -0.04 $\pm$ 0.04	-0.04 $\pm$ 0.05 / 0.01 $\pm$ 0.05
$tW + tW, tb/tb \mu_F$	0.0 $\pm$ 0.04 / -0.01 $\pm$ 0.04	-0.0 $\pm$ 0.03 / -0.01 $\pm$ 0.03	0.01 $\pm$ 0.04 / -0.01 $\pm$ 0.04	-0.01 $\pm$ 0.04 / 0.01 $\pm$ 0.04	0.0 $\pm$ 0.05 / 0.01 $\pm$ 0.05
$tW + tW \text{ DS}$	0.03 $\pm$ 0.04 / (-0.03 $\pm$ 0.04)	-0.03 $\pm$ 0.03 / (0.03 $\pm$ 0.03)	0.11 $\pm$ 0.04 / (-0.11 $\pm$ 0.04)	-0.29 $\pm$ 0.05 / (0.29 $\pm</$	



F.7. Covariance matrices

Figure F.6: Covariance matrices of the (a), (c) absolute and (b), (d) normalised differential $t\bar{t}$ cross sections.

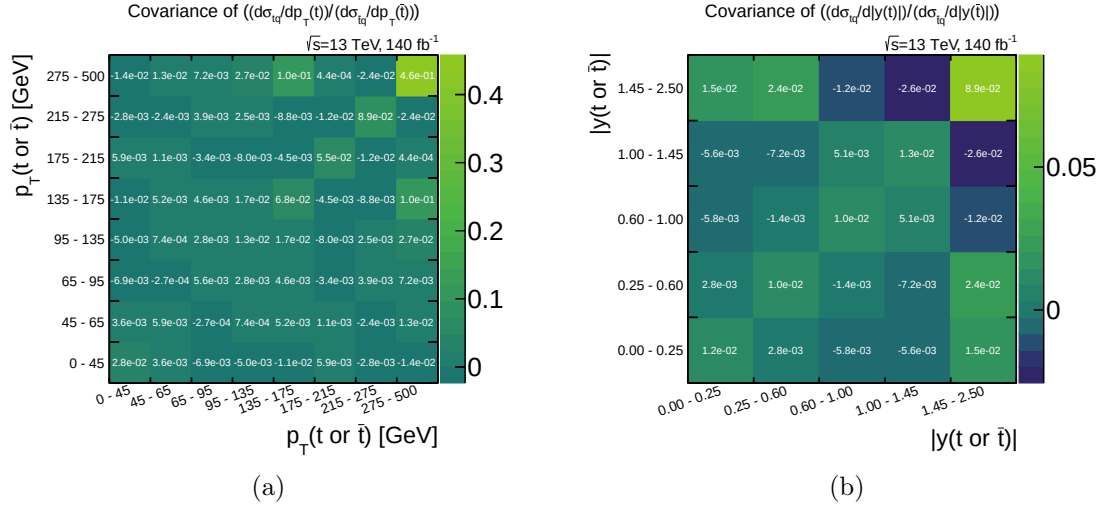


Figure F.7: Covariance matrices of the ratios of the differential cross sections as a function of (a) $p_T(t \text{ or } \bar{t})$ and (b) $|y(t \text{ or } \bar{t})|$.

F.8. Correlation matrices

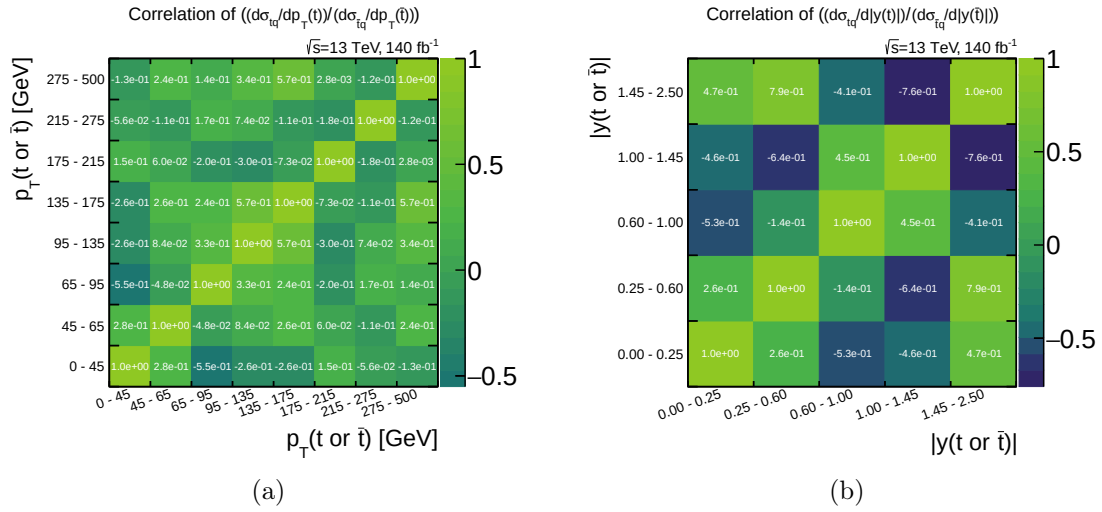


Figure F.8: Correlation matrices of the ratios of the differential cross sections as a function of (a) $p_T(t \text{ or } \bar{t})$ and (b) $|y(t \text{ or } \bar{t})|$.

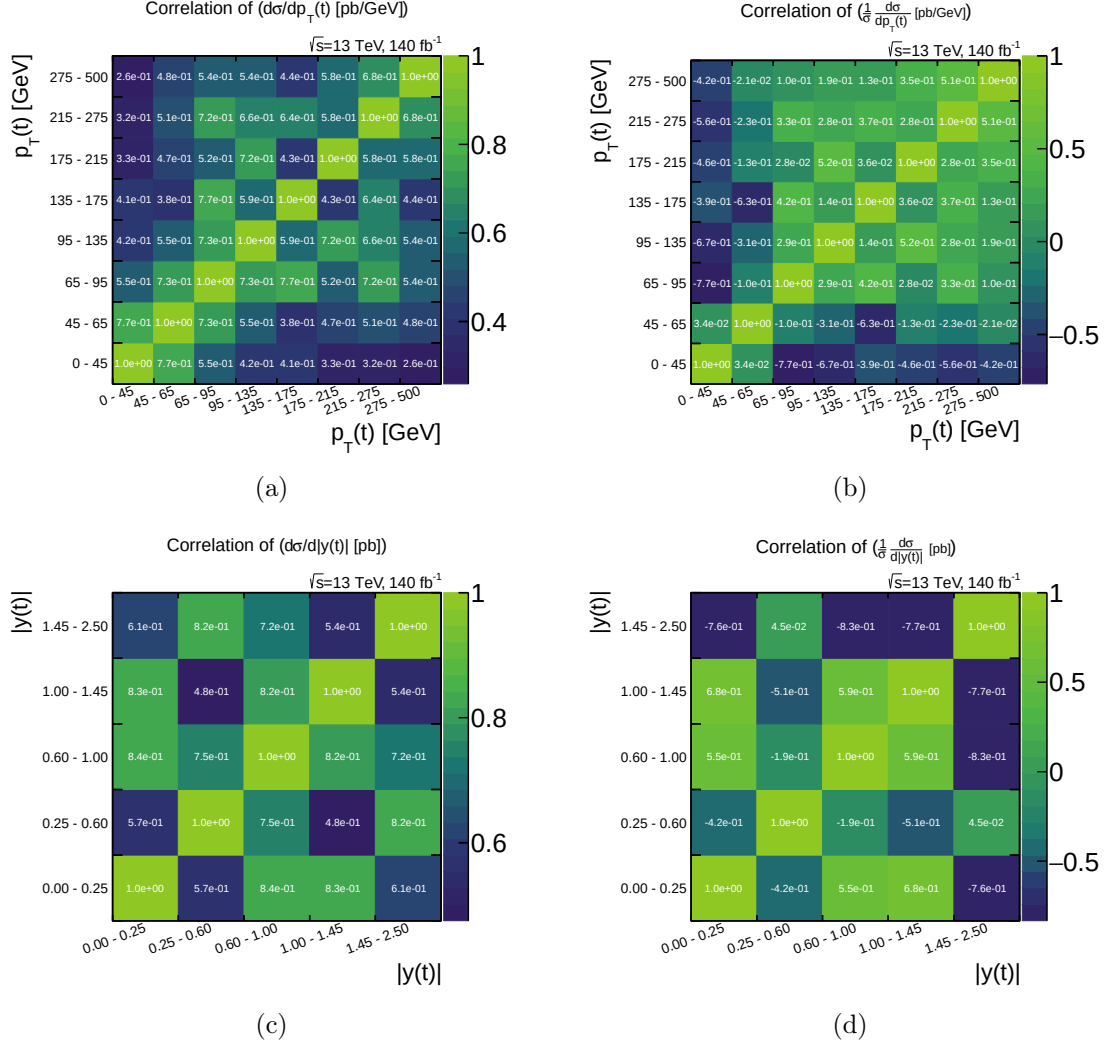


Figure F.9: Correlation matrices of the absolute and normalised differential tq cross sections measured as a function of (a),(b) $p_T(t)$ and (c),(d) $|y(t)|$.

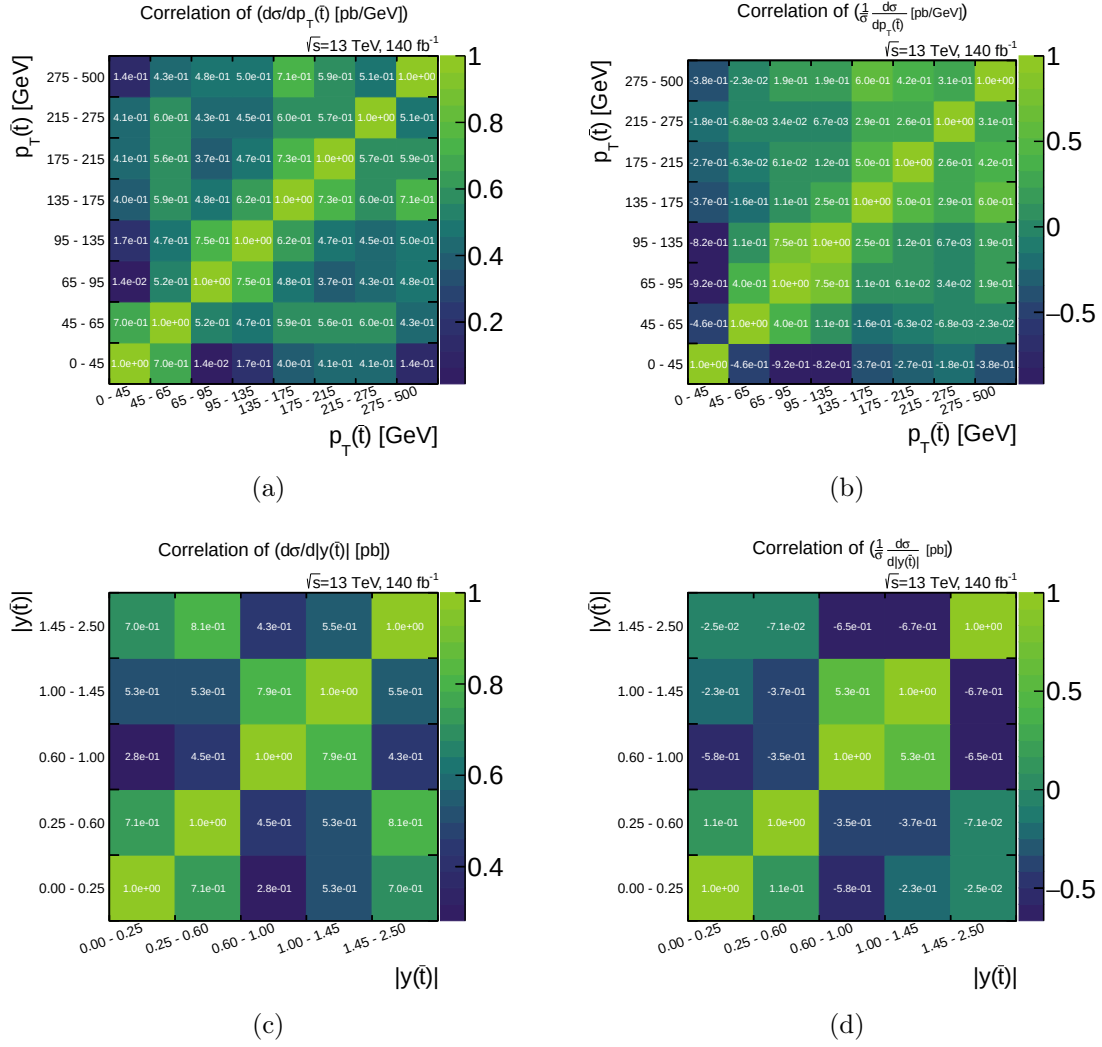


Figure F.10: Correlation matrices of the (a), (c) absolute and (b), (d) normalised differential $t\bar{q}$ cross sections.



G. Results

Comparisons between the measured differential cross sections and the various theory predictions, which are not shown in the discussion of the analysis results in Chapter 11, are presented in Appendix G.1. The numerical values of the measured cross sections are listed in Appendix G.2. The predicted distributions of signal events in the plane of both observables are shown in Appendix G.3. For the EFT interpretation presented in Section 11.2, a least-squares is performed whose results are listed in Appendix G.4.



G.1. Distributions of the differential cross sections

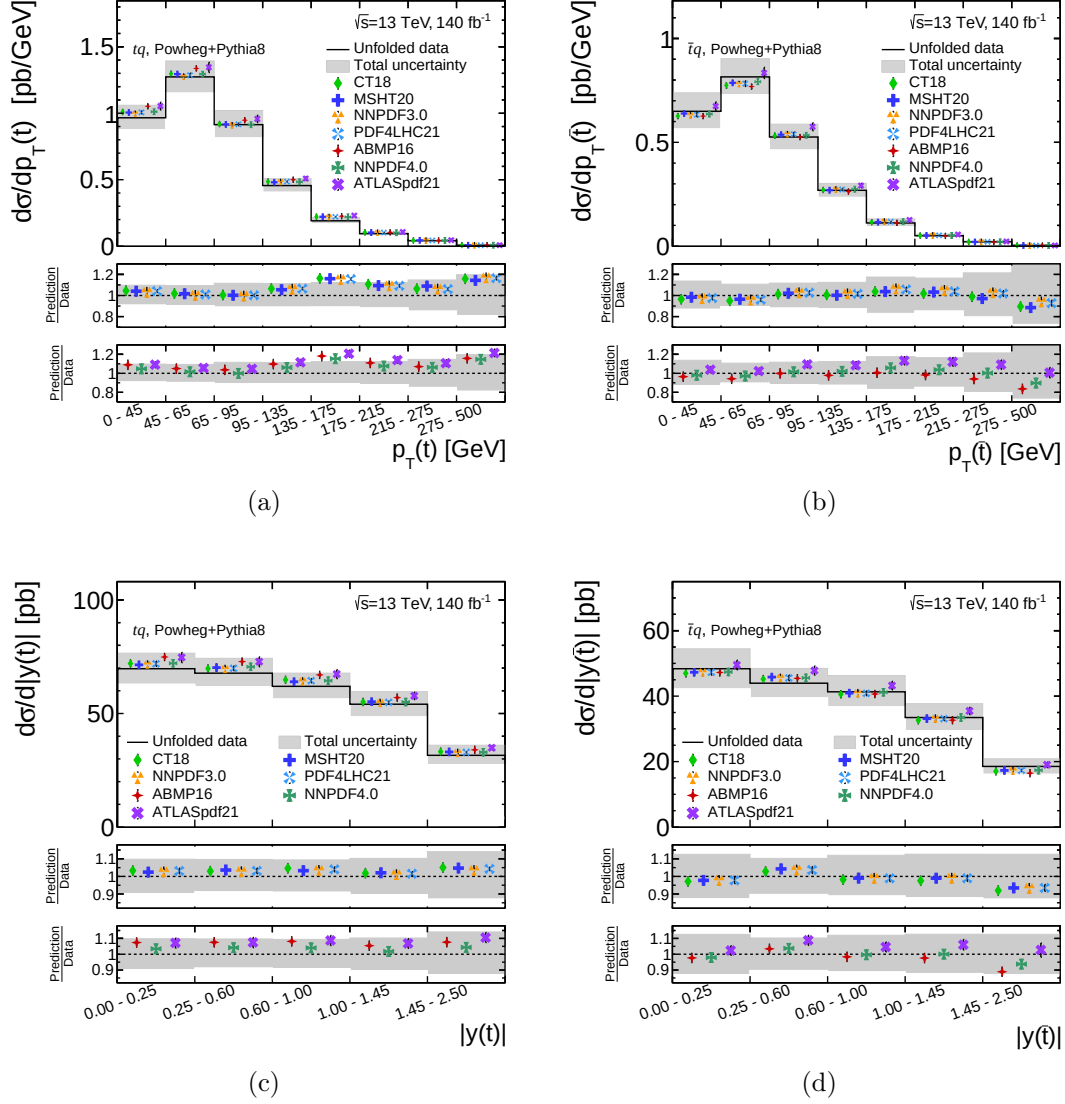


Figure G.1: Absolute differential (a) (c) tq and (b) (d) $\bar{t}q$ cross sections as a function of (a) (b) $p_{T(t)}$ or $p_{T(\bar{t})}$ and (c) (d) $|y(t)|$ or $|y(\bar{t})|$ compared to the predictions from POWHEG + PYTHIA 8 with different PDF sets. The shaded band indicates the total measurement uncertainty. The uncertainty in the theoretical predictions comprises the MC statistical uncertainty and the PDF uncertainty.

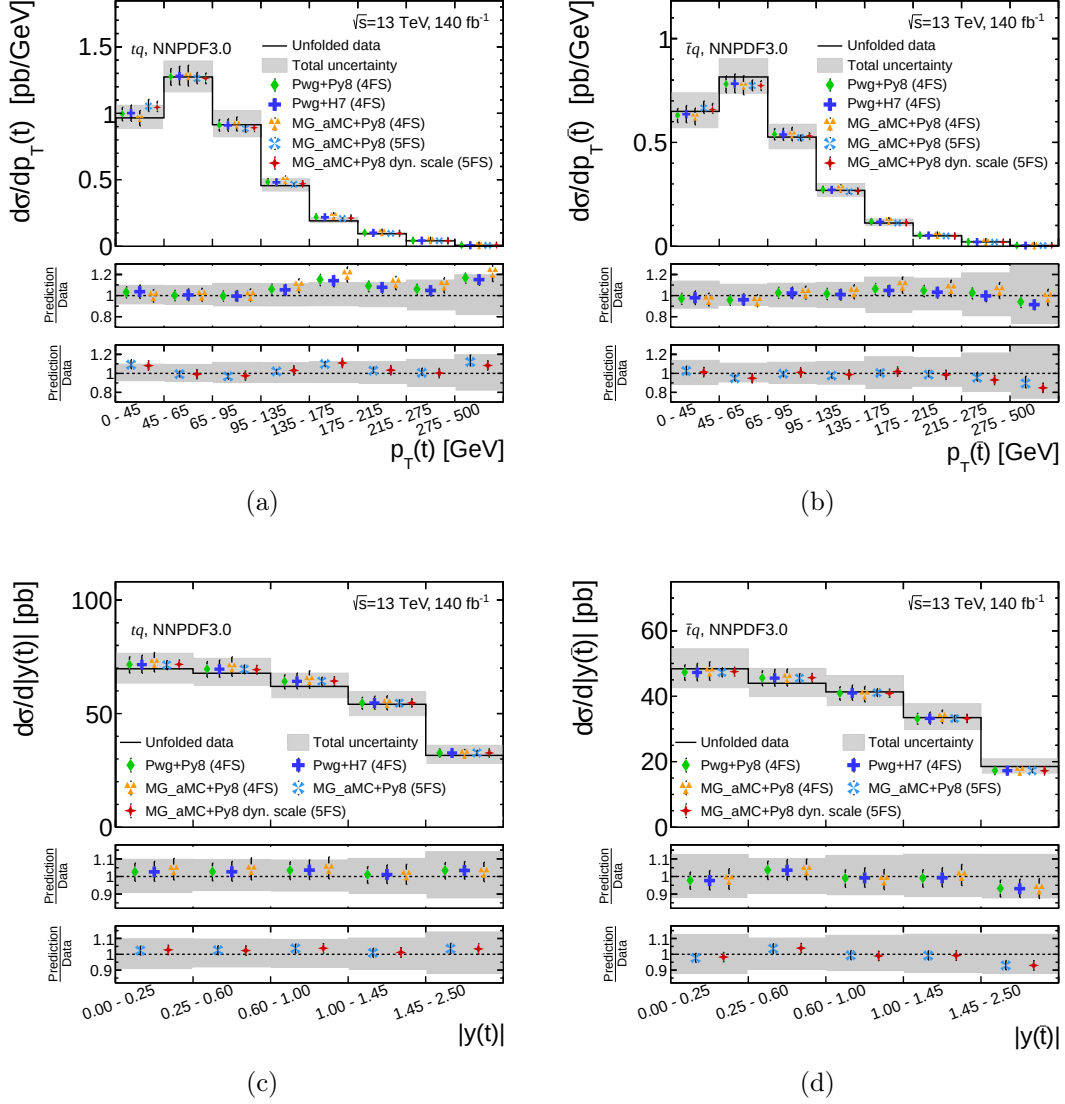


Figure G.2: Absolute differential (a) (c) tq and (b) (d) $\bar{t}q$ cross sections as a function of (a) (b) $p_{T(t)}$ or $p_{T(\bar{t})}$ and (c) (d) $|y(t)|$ or $|y(\bar{t})|$. The shaded band indicates the total measurement uncertainty. The cross sections are compared with the predictions from different MC event generators and parton-shower programs. All predictions are generated with the NNPDF3.0 PDF set. The uncertainty in the theoretical predictions comprises the MC statistical uncertainty, the uncertainty in the renormalisation and factorisation scale choice and the PDF uncertainty.

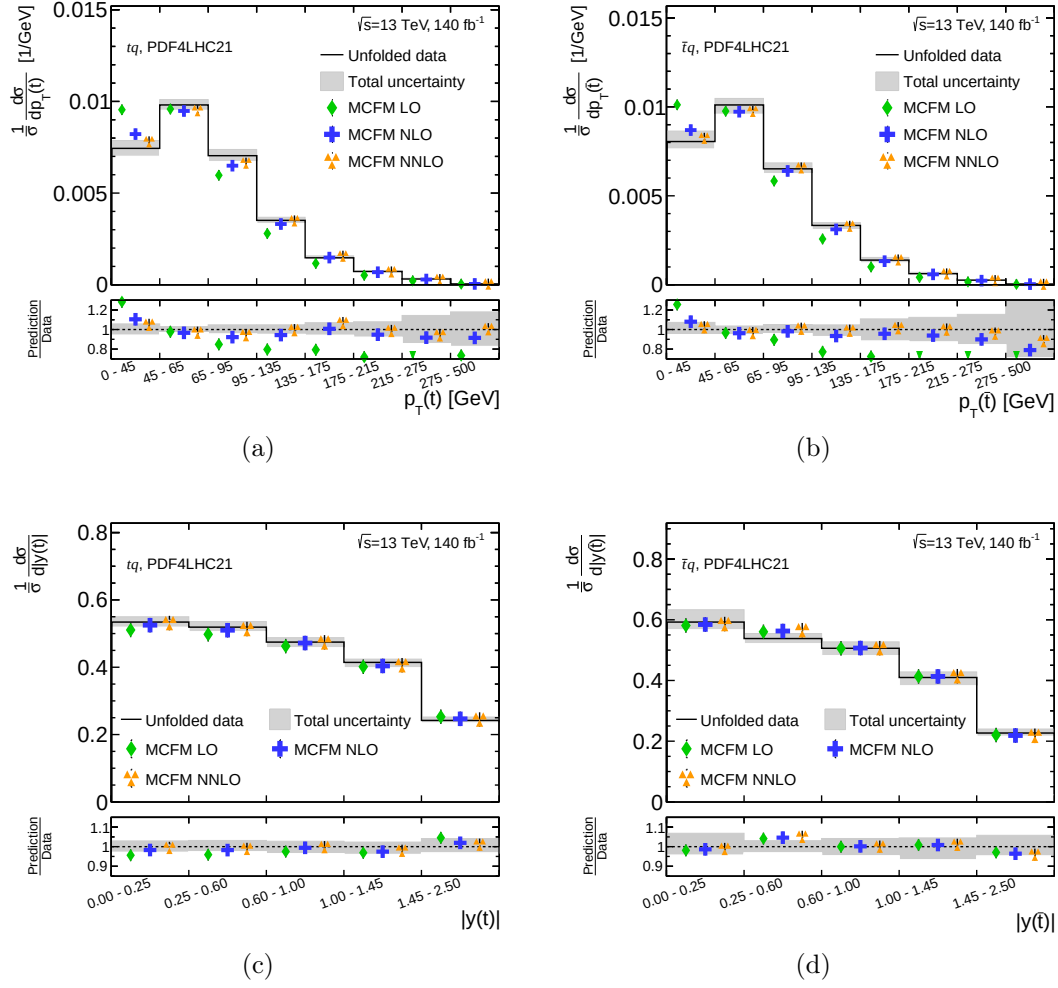


Figure G.3: Normalised differential (a) (c) tq and (b) (d) $\bar{t}q$ cross sections as a function of (a) (b) $p_T(t)$ or $p_T(\bar{t})$ and (c) (d) $|y(t)|$ or $|y(\bar{t})|$. The shaded band indicates the total measurement uncertainty. The cross sections are compared with the theoretical predictions from FO calculations done with MCFM at LO, NLO and NNLO. The uncertainty in the theoretical predictions comprises the uncertainty in the renormalisation and factorisation scale choice and the uncertainty in the value of α_S .

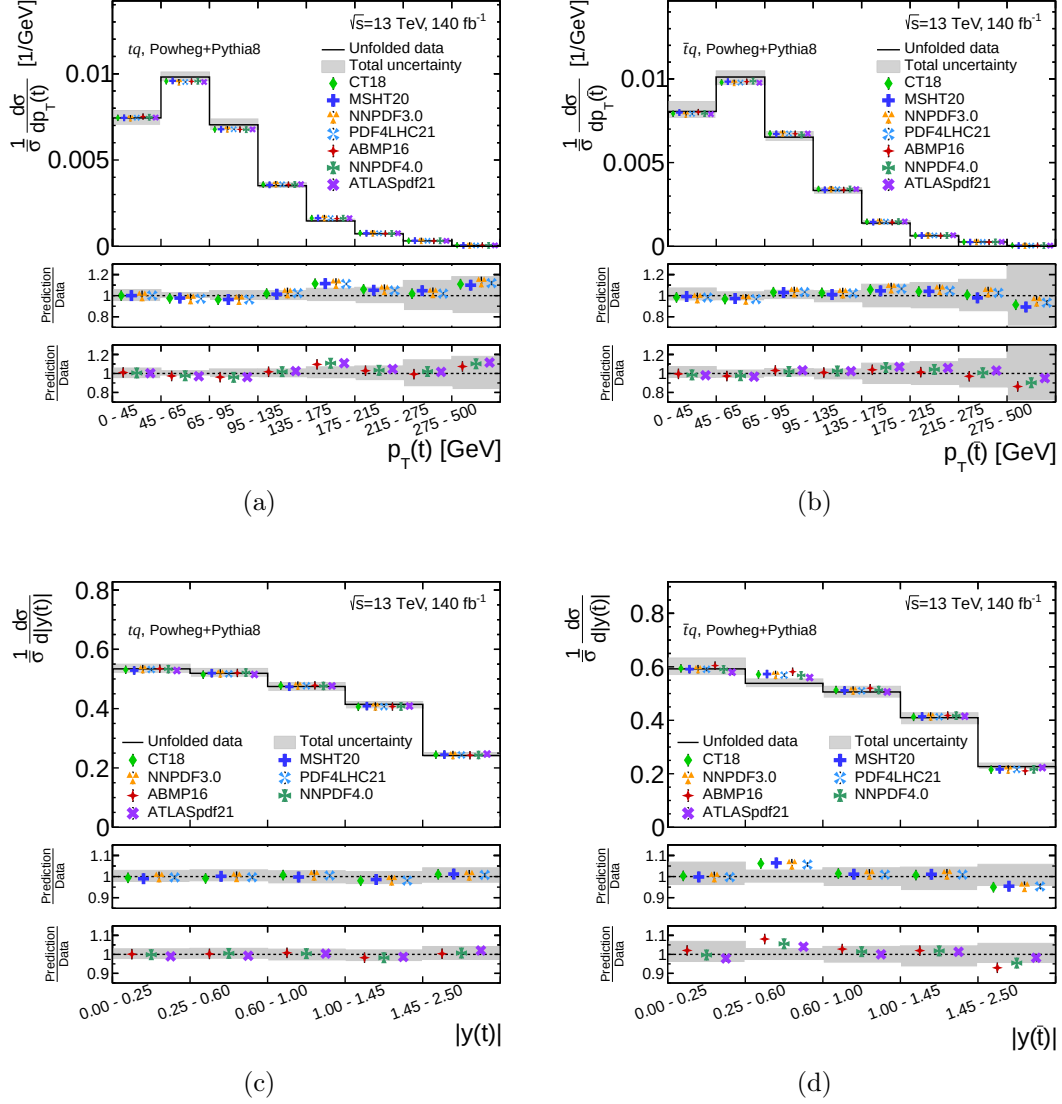


Figure G.4: Normalised differential (a) (c) tq and (b) (d) $\bar{t}q$ cross sections as a function of (a) (b) $p_T(t)$ or $p_T(\bar{t})$ and (c) (d) $|y(t)|$ or $|y(\bar{t})|$. The shaded band indicates the total measurement uncertainty. The cross sections are compared with the predictions from POWHEG + PYTHIA8 with different PDF sets. The uncertainty in the theoretical predictions comprises the MC statistical uncertainty and the PDF uncertainty.

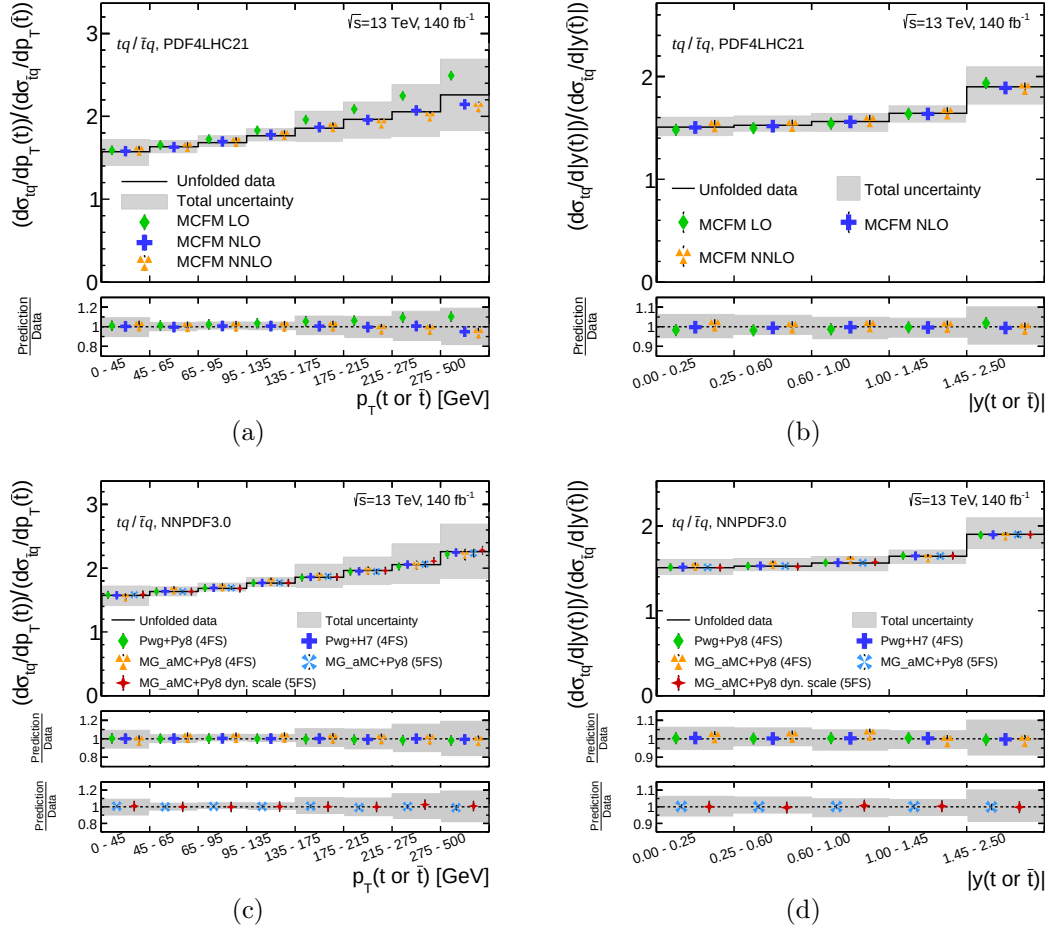


Figure G.5: Ratio of the differential cross sections as a function of (a) (c) $p_T(t \text{ or } \bar{t})$ and (b) (d) $|y(t \text{ or } \bar{t})|$. The shaded band indicates the total measurement uncertainty. The cross sections are compared with theoretical predictions obtained from (a) (b) FO calculations done with MCFM at LO, NLO and NNLO and (c) (d) different MC event generators and parton-shower programs with the NNPDF3.0 PDF set. The uncertainty in the FO calculations comprises the uncertainty in the renormalisation and factorisation scale choice and the uncertainty in the value of α_S . The uncertainty in the predictions from different event generators comprises the MC statistical uncertainty, the uncertainty in the renormalisation and factorisation scale choice and the PDF uncertainty.



G.2. Numerical values of the differential cross sections

Table G.1.: Absolute and normalised differential tq production cross sections as a function of $p_T(t)$.

$p_T(t)$ [GeV]	$\frac{d\sigma_{tq}}{dp_T(t)}$ [fb GeV ⁻¹]	$\frac{1}{\sigma_{tq}} \frac{d\sigma_{tq}}{dp_T(t)}$ [10 ⁻³ GeV ⁻¹]
	syst. $\pm$ stat.	syst. $\pm$ stat.
0 – 45	966 $^{+90}_{-83} \pm 18$	7.44 $^{+0.37}_{-0.34} \pm 0.15$
45 – 65	1274 $^{+95}_{-98} \pm 16$	9.81 $^{+0.28}_{-0.32} \pm 0.13$
65 – 95	914 $^{+67}_{-58} \pm 12$	7.04 $^{+0.26}_{-0.24} \pm 0.09$
95 – 135	456 $^{+37}_{-35} \pm 9$	3.51 $^{+0.16}_{-0.17} \pm 0.07$
135 – 175	191 $^{+18}_{-15} \pm 7$	1.470 $^{+0.095}_{-0.075} \pm 0.052$
175 – 215	93.6 $^{+9.3}_{-8.7} \pm 4.9$	0.721 $^{+0.043}_{-0.047} \pm 0.038$
215 – 275	40.4 $^{+5.6}_{-5.6} \pm 2.7$	0.311 $^{+0.032}_{-0.032} \pm 0.021$
275 – 500	6.1 $^{+1.1}_{-1.1} \pm 0.6$	0.0470 $^{+0.0068}_{-0.0065} \pm 0.0043$

Table G.2.: Absolute and normalised differential tq production cross sections as a function of $|y(t)|$.

$ y(t) $	$\frac{d\sigma_{tq}}{d y(t) }$ [pb]	$\frac{1}{\sigma_{tq}} \frac{d\sigma_{tq}}{d y(t) }$
	syst. $\pm$ stat.	syst. $\pm$ stat.
0.0 – 0.25	69.7 $^{+4.6}_{-4.6} \pm 1.2$	0.534 $^{+0.012}_{-0.020} \pm 0.009$
0.25 – 0.6	67.7 $^{+5.2}_{-4.4} \pm 0.9$	0.519 $^{+0.018}_{-0.011} \pm 0.007$
0.6 – 1.0	62.0 $^{+4.5}_{-4.2} \pm 1.0$	0.475 $^{+0.010}_{-0.013} \pm 0.007$
1.0 – 1.45	54.1 $^{+3.6}_{-3.6} \pm 1.0$	0.414 $^{+0.011}_{-0.016} \pm 0.008$
1.45 – 2.5	31.6 $^{+3.5}_{-3.1} \pm 0.8$	0.2420 $^{+0.0100}_{-0.0075} \pm 0.0064$



Table G.3.: Absolute and normalised differential $\bar{t}q$ production cross sections as a function of $p_T(\bar{t})$.

$p_T(\bar{t})$ [GeV]	$\frac{d\sigma_{\bar{t}q}}{dp_T(\bar{t})}$ [fb GeV ⁻¹]	$\frac{1}{\sigma_{\bar{t}q}} \frac{d\sigma_{\bar{t}q}}{dp_T(\bar{t})}$ [10 ⁻³ GeV ⁻¹]
	syst. $\pm$ stat.	syst. $\pm$ stat.
0 – 45	649 $^{+76}_{-71}$ ± 16	8.05 $^{+0.56}_{-0.51}$ ± 0.20
45 – 65	815 $^{+60}_{-57}$ ± 14	10.11 $^{+0.34}_{-0.34}$ ± 0.18
65 – 95	526 $^{+40}_{-41}$ ± 10	6.52 $^{+0.35}_{-0.41}$ ± 0.13
95 – 135	269 $^{+20}_{-21}$ ± 8	3.33 $^{+0.13}_{-0.18}$ ± 0.10
135 – 175	112 $^{+16}_{-15}$ ± 6	1.38 $^{+0.14}_{-0.14}$ ± 0.07
175 – 215	50.1 $^{+6.9}_{-5.8}$ ± 3.8	0.621 $^{+0.061}_{-0.058}$ ± 0.047
215 – 275	20.6 $^{+3.4}_{-3.1}$ ± 2.3	0.256 $^{+0.031}_{-0.030}$ ± 0.028
275 – 500	3.42 $^{+0.87}_{-0.78}$ ± 0.47	0.0425 $^{+0.0091}_{-0.0082}$ ± 0.0058

Table G.4.: Absolute and normalised differential $\bar{t}q$ production cross sections as a function of $|y(\bar{t})|$.

$ y(\bar{t}) $	$\frac{d\sigma_{\bar{t}q}}{d y(\bar{t}) }$ [pb]	$\frac{1}{\sigma_{\bar{t}q}} \frac{d\sigma_{\bar{t}q}}{d y(\bar{t}) }$
	syst. $\pm$ stat.	syst. $\pm$ stat.
0.0 – 0.25	48.4 $^{+4.8}_{-4.9}$ ± 1.1	0.592 $^{+0.025}_{-0.037}$ ± 0.014
0.25 – 0.6	43.9 $^{+3.4}_{-3.3}$ ± 0.8	0.538 $^{+0.017}_{-0.016}$ ± 0.010
0.6 – 1.0	41.3 $^{+3.1}_{-2.4}$ ± 0.9	0.506 $^{+0.025}_{-0.018}$ ± 0.011
1.0 – 1.45	33.5 $^{+2.5}_{-2.2}$ ± 0.9	0.410 $^{+0.018}_{-0.014}$ ± 0.011
1.45 – 2.5	18.5 $^{+2.0}_{-2.2}$ ± 0.7	0.2268 $^{+0.0082}_{-0.0120}$ ± 0.0084



Table G.5.: Ratio of the absolute differential tq and $\bar{t}q$ production cross sections as a function of $p_T(t \text{ or } \bar{t})$.

$p_T(t \text{ or } \bar{t}) \text{ [GeV]}$	$\left(\frac{d\sigma(tq)}{dp_T(t)} \right) / \left(\frac{d\sigma(\bar{t}q)}{dp_T(\bar{t})} \right)$
	syst. $\pm$ stat.
0 – 45	$1.573^{+0.137}_{-0.172} \pm 0.048$
45 – 65	$1.634^{+0.063}_{-0.081} \pm 0.035$
65 – 95	$1.683^{+0.072}_{-0.047} \pm 0.039$
95 – 135	$1.766^{+0.059}_{-0.049} \pm 0.060$
135 – 175	$1.86^{+0.17}_{-0.13} \pm 0.11$
175 – 215	$1.96^{+0.11}_{-0.16} \pm 0.18$
215 – 275	$2.06^{+0.20}_{-0.18} \pm 0.26$
275 – 500	$2.26^{+0.23}_{-0.25} \pm 0.36$

Table G.6.: Ratio of the absolute differential tq and $\bar{t}q$ production cross sections as a function of $|y(t \text{ or } \bar{t})|$.

$ y(t \text{ or } \bar{t}) $	$\left(\frac{d\sigma(tq)}{d y(t) } \right) / \left(\frac{d\sigma(\bar{t}q)}{d y(\bar{t}) } \right)$
	syst. $\pm$ stat.
0.0 – 0.25	$1.507^{+0.085}_{-0.085} \pm 0.043$
0.25 – 0.6	$1.525^{+0.083}_{-0.060} \pm 0.034$
0.6 – 1.0	$1.562^{+0.065}_{-0.099} \pm 0.040$
1.0 – 1.45	$1.642^{+0.050}_{-0.083} \pm 0.052$
1.45 – 2.5	$1.90^{+0.17}_{-0.16} \pm 0.08$



G.3. Parton-level predictions for $|y|$ vs. p_T

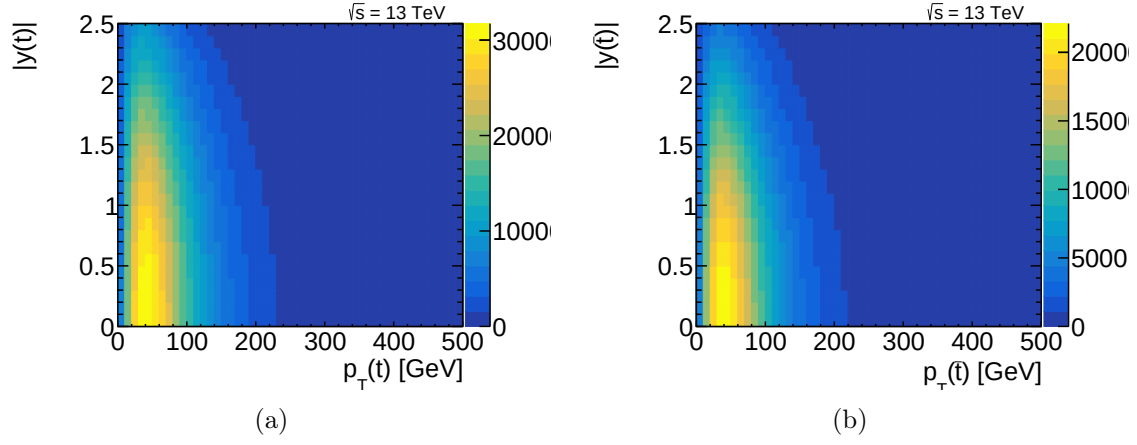


Figure G.6: Predictions for the parton-level distribution of (a) tq and (b) $\bar{t}q$ production in the $p_T(t)-|y(t)|$ and $p_T(\bar{t})-|y(\bar{t})|$ plane respectively.



G.4. EFT interpretation

Table G.7.: Best fit values for the expected relative change in the differential cross sections obtained from least-squares fits. According to Equation 11.1, the expected relative change is parameterised per bin as $\sigma_{EFT}/\sigma_{SM} = \left(1 + p_0 \cdot C_{Qq}^{3,1}/\Lambda^2 + p_1 \cdot (C_{Qq}^{3,1}/\Lambda^2)^2\right)$.

$p_T(t)$ or $p_T(\bar{t})$ range	$\frac{d\sigma}{dp_T(t)} (C_{Qq}^{3,1}/\Lambda^2)$		$\frac{d\sigma}{dp_T(\bar{t})} (C_{Qq}^{3,1}/\Lambda^2)$	
	p_0	p_1	p_0	p_1
$0 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 45 \text{ GeV}$	-0.175	0.0	-0.260	0.142
$45 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 65 \text{ GeV}$	-0.145	0.0	-0.205	0.187
$65 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 95 \text{ GeV}$	-0.263	0.050	-0.216	0.014
$95 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 135 \text{ GeV}$	-0.389	0.0	-0.429	0.063
$135 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 175 \text{ GeV}$	-0.735	0.143	-0.593	0.231
$175 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 215 \text{ GeV}$	-0.813	0.099	-1.107	0.695
$215 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 275 \text{ GeV}$	-0.897	0.043	-1.184	0.640
$275 \text{ GeV} \leq p_T(t) \text{ or } p_T(\bar{t}) \leq 500 \text{ GeV}$	-2.452	1.694	-2.576	3.426

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