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**Measurement of the differential $W \rightarrow \mu + \nu$
cross section at high transverse masses
at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector**

**Thesis zur Erlangung des akademischen Grades
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Abstract

In this thesis, the measurement of the cross section of the charged-current Drell-Yan process in the muonic decay channel is presented. The cross section is measured differentially in the transverse mass of the W boson, m_T^W , while covering the high mass tail in a range from 130 GeV to 2000 GeV. Separate results for both charges of the W boson as well as their combination are presented. The analysis is based on proton-proton collisions at the LHC at a center-of-mass-energy of $\sqrt{s} = 13$ TeV, recorded at the ATLAS detector in 2015 and 2016.

The modeling of background processes plays a key role, in particular the estimation of the multijet background, which consists of fake muons. This background is obtained data-driven via the Matrix Method. The number of signal events in the data is unfolded to the born level using the technique of Iterative Bayesian Unfolding. Dedicated corrections for the detector smearing, measurement efficiency and acceptance are applied. The final calculated cross sections include statistical as well as systematic uncertainties. At high transverse masses, the statistical uncertainty dominates, whereas at low m_T^W the uncertainty associated with the E_T^{miss} is the most significant. Finally, the results are compared to the born level of the signal POWHEG-BOX+PYTHIA 8 MC. Overall, the theory and unfolded cross section are in good agreement, with the exception of the first m_T^W bin, ranging from 130 – 170 GeV, where an underestimation in the MC is visible.

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1. Introduction

Physicists have always sought to describe our universe and understand the structure of matter. In order to have a complete theory at very small scales, the Standard Model of Elementary Particle Physics (SM) was developed. It describes all fundamental particles and their interaction very well. The SM is a very powerful theory and its predictions are tested and verified to very high precision. Nevertheless, the SM still has some flaws, for instance, dark matter can not be explained yet. In order to search for new physics in the field of elementary particles, huge particle colliders are built, such as the Large Hadron Collider (LHC) at CERN. In the circular accelerator, with a circumference of 27 km, protons are accelerated to near speed of light and brought to collisions at a center-of-mass-energy of $\sqrt{s} = 13$ TeV. A large variety of particles get produced in these collisions, which are measured at multi-purpose particle detectors, such as the ATLAS detector.

In order to understand the physics at the LHC, a precise prediction of the outcome of all processes at the collider is indispensable. This thesis deals with the charged-current Drell-Yan (DY) process, which is one of the benchmark processes at the LHC. A W boson is produced from quark-quark interactions within the proton collisions and its decay into a muon and neutrino is studied. Data taken at the ATLAS detector in 2015 and 2016 is analyzed, corresponding to an integrated luminosity of 36.2 fb^{-1} . The aim of this thesis is the measurement of an unfolded differential cross section of the DY process at high transverse masses. While the inclusive cross section is well-studied, a differential measurement at the high mass region is done for the first time. A precise measurement will give important insights into the structure of the proton, since constraints on its parton distribution functions can be concluded. A complete and precise understanding of the structure of the proton is essential for further measurements and searches at the LHC. In addition, the results of this analysis provide sensitivity to electroweak parameters and allow effective field theory interpretations.

This thesis is structured as follows. At first, a short introduction into the theoretical context is given and the LHC as well as the ATLAS detector are presented in Chapter 2 and 3, respectively. The following Chapter 4 gives an overview of the used data and simulations. While in Chapter 5 the important objects measured in the ATLAS detector are presented, Chapter 6 presents the analysis specific event selection. A crucial step is good background modeling, which is described in Chapter 7. In particular, the estimation of the multijet background via the Matrix Method plays a key role. After that, simulation and data are compared in Chapter 8. The following Chapter 9 addresses the measurement of the unfolded differential cross section. It is divided into the process of optimizing the binning of the discriminant variable m_T^W and a description of the unfolding procure via Iterative Bayesian Unfolding. After a breakdown of the systematic uncertainties in Chapter 10 the measurement results are finally presented in Chapter 11.

2. Theoretical context

The current knowledge about fundamental particles, so-called elementary particles, and their interaction is formulated in the Standard Model of Elementary Particle Physics [1]. Its main constituents and principles are presented below. Since the main focus of this analysis is on the W boson, its properties, production in proton-proton collisions and decay are discussed in more detail. Lastly, the theoretical basis of estimating a differential cross section is presented.

2.1. The Standard Model of Elementary Particle Physics

The Standard Model of Elementary Particle Physics (SM) is a relativistic quantum-field-theory which was developed in the 1960s and 1970s. It describes the known elementary particles and their interaction very well and covers three of the four fundamental forces, with the electromagnetic, weak and strong interaction. Only the gravitational force is not included, which is, with respect to the other forces, very weak. Instead, this is described by the theory of general relativity. An overview of all elementary particles of the SM and their properties is shown in Fig. 2.1. The particles can be divided into several groups. At first, the particles are differentiated with regard to their spin. Particles with a spin of integer value are called bosons, while particles with a spin of $1/2$ are called fermions. The latter can be further divided into quarks and leptons. There are up-type quarks (up, charm, top) with a charge of $+2/3 e$ as well as down-type quarks (down, strange, bottom) with a charge of $-1/3 e$. Quarks occur in three generations, where the lightest particles are found in the first and the heaviest in the third generation. All naturally observed matter consists of the first generation (up and down quarks), whereas heavier quarks can be e.g. produced in particle accelerators. They are, however, not stable and decay into the lighter particles.

In addition, the SM contains six leptons which are sorted into three generations as well. On the one hand, there are the charged leptons electron, muon and tau (e , μ , τ) which carry the negative elementary charge each. Besides their increasing mass with a higher generation, all three charged leptons show analogous properties and behavior. This is called lepton universality. On the other hand, there are three so-called neutrinos. Each one corresponds to one of the charged leptons (ν_e , ν_μ , ν_τ). The neutrinos do not carry an electrical charge and are massless in the SM. This is, in addition to e.g. the excluded gravitational force, one of the flaws of the SM. It was observed that neutrinos have, in fact, a very low mass [1]. For each fermion, there is an anti-particle that has the same mass as the particle but an opposite charge. As a result, there are 24 different fermions defined in the SM.

Interactions between particles are propagated by gauge bosons. The mediator of the electromagnetic (em) interaction, which is described by quantum electrodynamics (QED), is the photon. It does not carry an electrical charge itself and couples to all charged particles, i.e. all quarks and the three charged leptons. Photons are massless and do not directly self-interact, as a result the em interaction has an infinite range.

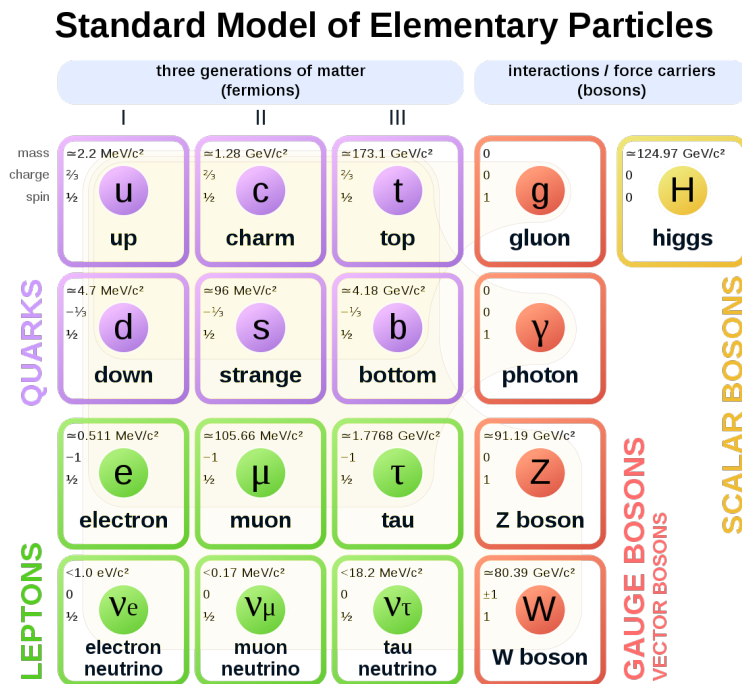


Figure 2.1.: Schematic overview of all elementary particles of the SM and their properties. [2]

In contrast, the force carriers of the weak force are massive. These are the electrically neutral Z boson and the charged W^+ and W^- bosons. A result of the mass of the mediator is that the strength of the weak interaction is small compared to the other two fundamental interactions (em and strong interaction). The weak gauge bosons couple to all particles that carry a weak charge. These are besides all quarks, the electrically charged leptons and the neutrinos as well. In fact, neutrinos interact only via the weak force. The third fundamental force in the SM is the strong force. It is mediated by the massless gluons. In contrast to photons, gluons carry a so-called color-charge by themselves. The strong interaction is described by quantum chromodynamics (QCD) where this additional color-charge is introduced. There are three color-charges, arbitrarily represented by red, green and blue, and corresponding anti-charges (anti-red, anti-green, anti-blue). Gluons always carry a color-charge and an anti-color-charge simultaneously. Because of this, self-interaction between gluons is possible and, unlike all other forces, the strength of the strong force increases with distance. Quarks are the only fermions that carry a color-charge and, hence, they are the only fermions that interact via the strong force. As a result of the increasing strong force, no isolated quarks can be observed, which is called confinement. Instead, hadronization of the quarks takes place, which means that color-neutral (white) states are formed. There are two possibilities to form these states. On the one hand, from quark-anti-quark pairs (color+anti-color=white), these particle states are called mesons. On the other hand, three quark states (red+blue+green=white) can be formed, which are called baryons. The most famous representatives of baryons are the proton and the neutron.

At short distances, e.g. smaller than the proton radius, the strong force is modest which is called asymptotic freedom.

The last aspect of the SM is the Higgs boson, which couples to all massive particles and is the mediator of the Higgs field. It was the last particle of the SM to be discovered experimentally, namely in 2012, as a collaborative effort of the experiments ATLAS and CMS at CERN [3, 4].

2.2. The W boson in proton-proton collisions

The W boson is the mediator of the charged-current weak interaction and exists in two forms, with a charge of $+e$ or $-e$. It has a spin of one and belongs to the gauge bosons. In contrast to the em or strong interaction, the mediating particles of the weak interaction are massive. The mass of the W boson is measured precisely and amounts to $m_W = (80.385 \pm 0.015) \text{ GeV}^1$ [5]. The W boson is an unstable particle that can decay either hadronically or leptonically with a branching ratio of $\mathcal{BR}_{had} = 2/3$ and $\mathcal{BR}_{lep} = 1/3$, respectively. In a hadronic decay, the boson decays into an up-type and a down-type quark, where one of the quarks has to be an anti-particle in order to conserve charge. Most probably, the decay residuals are within the same generation but a cross-generation coupling to the W boson is possible as well, e.g. an up and anti-bottom quark in the final state. However, this is highly suppressed, as described in the CKM-matrix [1]. On the other hand, the final decay products of the W boson can be a charged lepton and the corresponding lepton neutrino. Also in this decay mode, one of the two particles is an anti-particle, in order to conserve charge and lepton flavor, e.g. a W^+ boson can decay into a positively charged anti-muon μ^+ and a muon-neutrino ν_μ . Due to the instability of the W boson, its mass is not fixed but it is described by a Breit-Wigner distribution. It has a measured width of $\Gamma_W = (2.085 \pm 0.042) \text{ GeV}$ [5]. This means that there is a certain probability that a W boson with a very large mass, far off the peak of 80 GeV, can be produced. The production cross section for exactly these high mass W bosons is measured in this analysis.

Clearly, a lot of energy is needed in order to produce such high masses. A common way to achieve and study this is by proton-proton collisions (pp collisions) at particle accelerators, such as the LHC at CERN. At sufficiently high energies, not the protons themselves collide but their constituents, which are called partons. In general, the proton consists of three valence quarks, two up quarks and one down quark, which add up to the proton charge of $+1e$ but, at increasing energy scales, so-called sea quarks become relevant as well. These are fluctuating quarks with a very small lifetime produced via gluon radiation inside the proton. The valence and sea quarks represent, together with the radiated gluons themselves, the partons of the proton. Of course, the colliding partons can not carry the whole momentum of the accelerated protons but the momentum is split up between all partons. The fraction of the proton's total momentum that a parton carries is given by the Bjorken-x. The probability that a given parton has a certain Bjorken-x is shown in Fig. 2.2. These distributions are

¹Natural units are used which implies that c is set to 1.

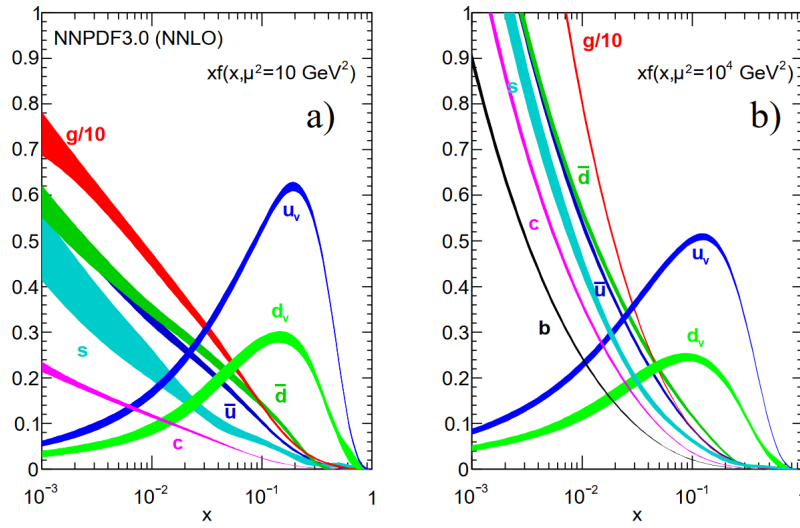


Figure 2.2.: Parton distribution functions of the proton at two different energy scales [6].

called parton distribution functions (PDFs) and are crucial in experiments based on pp collisions. An energy-dependency can be observed. At a rather small energy scale of $\mu^2 = 10 \text{ GeV}^2$, it is still clearly visible that the valence quarks in the proton, i.e. up and down quarks, dominate and are most likely to carry a rather large fraction of the proton's momentum. At higher energies, as seen in the right plot with $\mu^2 = 10^4 \text{ GeV}^2$, the impact of gluon radiation and sea quarks becomes more relevant and these partons can carry a larger fraction of the proton's momentum.

In this analysis, the charged-current Drell-Yan [7,8] process is studied, whose Feynman graph is shown in Fig. 2.3. A W boson is produced by the annihilation of two quarks, which are the colliding partons of the accelerated protons. The short-lived boson decays after an average lifetime² of around $\tau_W = 3 \times 10^{-25} \text{ s}$. A leptonic decay mode is studied in this analysis because it shows a more significant signature in the detector. Due to quark confinement and hadronization a final state consisting of quarks can not be measured as distinctively. The analysis presented in this thesis deals with the decay

²The lifetime of a particle is directly related to its width via $\Gamma \cdot \tau = \hbar$.

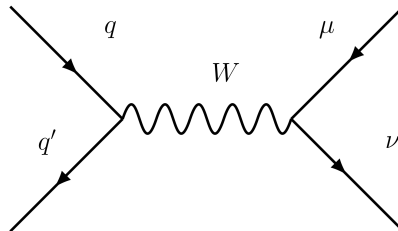


Figure 2.3.: The charged-current Drell-Yan process in the muonic decay channel. The mediating W boson as well as the final state muon can be charged positively or negatively. The neutrino ν is a muon neutrino.

of the W boson into a muon and muon neutrino³. At a later point, the results of this thesis can be combined with a parallel electron channel analysis.

2.3. Cross section measurement

The aim of this thesis is a differential cross section measurement of the charged-current Drell-Yan process. In addition to a short motivation, an explanation of how a differential cross section can be estimated from measured data is given here.

A cross section is, in general, a measure for the probability of a process, e.g. the production of a particle. It can be either calculated theoretically or measured experimentally. Nevertheless, one difficulty at hadron colliders arises from the fact that the proton is not an elementary particle. In high-energy pp collisions, not the protons themselves but their partons interact, as discussed in Sec. 2.2. The estimation of the cross section in pp collisions is based on the factorization theorem [9]. It states that, at a given factorization scale μ_f , the cross section σ for two protons, p_A and p_B , to collide can be expressed by a convolution of the hard-scattering cross section of the partons a and b with the parton distribution functions (PDFs) $f_{a|p_A}$ of a parton a inside the proton p_A (analogously for proton p_B). A summation over all pairs of partons (a, b) inside the protons is done.

$$\sigma_{p_A, p_B} = \sum_{a, b} \int dx_a dx_b f_{a|p_A}(x_a, \mu_f^2) f_{b|p_B}(x_b, \mu_f^2) \sigma_{a, b}(s, \mu_r^2) \quad (2.1)$$

The partonic cross section $\sigma_{a, b}$ can be calculated via perturbation theory at a given center-of-mass energy s and renormalization scale μ_r , where the matrix element $\mathcal{M}$ and the available phase space are taken into account. These calculations are done very precisely by theoreticians [10]. The convoluted cross section σ_{p_A, p_B} , however, can be measured in experiments. A high precision will provide, together with the known partonic cross section, thus direct constraints on the PDFs of the proton. This insight into the proton's PDFs is one of the main motivations for a precision measurement of a SM process, as it is done in this analysis. A good understanding and modeling of the structure inside the proton are essential for further measurements and searches for new physics at proton colliders. Moreover, the results of this measurement provide sensitivity to the running electroweak coupling α_2 at high energy scales [11]. Lastly, they can be used in precise effective field theory calculations, as discussed in detail in [12].

In principle, the experimental measurement of a cross section is based on a counting experiment. The number of events N of a given process is estimated by the product of the cross section σ and the integrated luminosity $\mathcal{L}_{int}$, which is a measure for the number of interactions per unit area and dependent on the experiment.

$$N = \sigma \cdot \mathcal{L}_{int} \cdot \epsilon \cdot \mathcal{BR} \quad (2.2)$$

³In the following, the muon neutrino is referred to as neutrino and the abbreviation ν instead of ν_μ is made.

The factor ϵ includes measurement inefficiencies as well as a limited acceptance. Additionally, if only a part of the possible final states is considered, a correction for the branching ratio $\mathcal{BR}$ is done. For instance in this analysis, only the muonic decay of the W boson is measured, although there are, in general, further decay modes of the W boson.

In this analysis, a differential cross section is measured, i.e. as a function of a certain variable x_j . The following definition is used, where Δx_j is the bin width.

$$\frac{d\sigma}{dx_j} = \frac{1}{\Delta x_j \cdot \mathcal{L}_{int} \cdot \mathcal{BR} \cdot \epsilon_j} \sum_i R_{ij}^{-1} \cdot f_{in}^i \cdot (N_{data}^i - N_{bkg}^i) \quad (2.3)$$

The number of signal events per bin is estimated by subtracting all background events from the measured data, $(N_{data}^i - N_{bkg}^i)$. Thus, a good modeling of the background processes is essential. A differentiation between the measured reconstruction level (bin index i in eq. 2.3) and generated truth level (bin index j) is made. The latter equals the parton level, i.e. without efficiency and acceptance effects induced by the measurement. For a cross section that is comparable with other measurements and theoretical predictions, it is essential to correct the measured data to the truth level because this level is not dependent on the given detector. At first, an acceptance correction for events that are selected on reconstruction level but not on truth level within the fiducial phase space is made, in the form of a bin-wise factor f_{in}^i . In a binned measurement, there is a probability that an event is generated in a certain bin but measured in a different one. This effect is called migration and the bin-wise probability for this can be summarized in a response matrix R_{ij} . In order to correct for the migration in the data, the matrix is inverted and applied to the measured data per bin. This process is called unfolding. Lastly, the unfolded truth level distribution is further corrected for events that are generated on truth level but not considered in the reconstruction. Reasons for this are, on the one hand, muons that are not measured in the detector because of e.g. interruptions in the detecting material, or, on the other hand, the acceptance induced by a limited phase space on reconstruction level. This means measured events need to fulfill certain criteria to be considered, e.g. exceed an energy threshold or lay within a well-defined region of the detector. A bin-by-bin correction is made by dividing with the efficiency factor ϵ_j .

3. LHC and the ATLAS experiment

Accelerators are a powerful tool to explore and understand the broad field of particle physics. Particles get accelerated nearly to the speed of light and are then brought to collisions, in which a vast variety of further particles gets produced. Large and complex detectors are built in order to measure all these particles. By reconstructing and analyzing the taken data many conclusions concerning the SM and beyond can be made. In addition to the search for new particles, accelerators are an important tool for high precision measurements within the SM, such as the one presented in this analysis. The analyzed data was recorded from pp collisions at the Large Hadron Collider at CERN by the ATLAS detector. The accelerator and detector are presented in the following.

3.1. The Large Hadron Collider

The Large Hadron Collider (LHC) [13] is a circular particle accelerator and collider located at the European Organization for Nuclear Research (CERN), near Geneva. With a circumference of 26.7 km and a center-of-mass energy of 13 TeV, it is the largest and most powerful particle accelerator in the world. Protons and heavy ions are collided at a velocity near the speed of light at four interaction points, where the four major experiments ATLAS [14], CMS [15], LHCb [16] and ALICE [17] are located. The ATLAS and CMS detectors are multi-purpose detectors and cover a broad spectrum of SM measurements and searches for new physics. The LHCb experiment is designed to study the physics of b-hadrons¹ explicitly. While all these three experiments rely on pp collisions, the ALICE experiment studies collisions of heavy ions.

Before the particles can be accelerated to such high energies, several pre-accelerators are needed. A schematic of the LHC complex with all its pre-accelerators and detectors can be seen in Fig. 3.1. As the first step, the protons are extracted from hydrogen gas using an electric field and are accelerated by a linear accelerator (LINAC 2) up to an energy of 50 MeV. After that, the protons are subsequently transferred into four synchrotron accelerators. The Proton-Synchrotron-Booster (PSB), Proton-Synchrotron (PS) and Super-Proton-Synchrotron (SPS) are further sub-accelerators, while the last acceleration step is in the LHC itself. Protons are launched into the LHC with an energy of 450 GeV and accelerated in opposite directions up to an energy of 6.5 TeV in order to collide them at a center-of-mass-energy of $\sqrt{s} = 13$ TeV.

The LHC and three of the four pre-accelerators follow the principle of a synchrotron. These accelerators are rings in which the particles are held in a circular trajectory by superconducting magnets. Further quadrupole magnets are used to focus the proton beams. The acceleration takes place over small, straight sections where a radio-frequency (RF) is applied. The charged particles undergo a small acceleration every time they cross these RF-cavities and travel many rounds in the synchrotron in order to achieve their final energy. Due to the design of the accelerator, the beams are not continuous but consist of proton bunches, containing on average 1.5×10^{11} particles

¹A b-hadron is a hadron that contains a bottom quark.

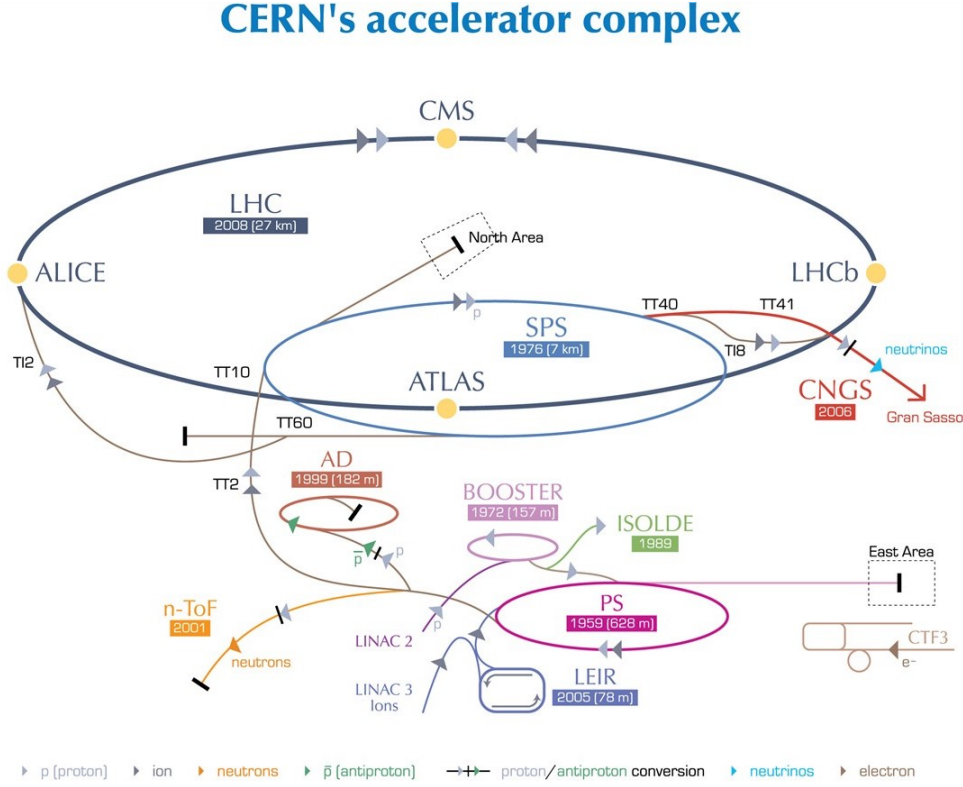


Figure 3.1.: Schematic of the accelerator and detector complex at CERN [18].

each. The bunches are spaced by 25 ns, which corresponds to a maximum collision frequency of 40 MHz.

A characteristic parameter of accelerators is the instantaneous luminosity $\mathcal{L}$, which is a measure of the number of interactions per time and unit area and is given by the following equation.

$$\mathcal{L} = \frac{N_b^2 n_b f_r}{4\pi \sigma_x \sigma_y} \quad (3.1)$$

Here, N_b is the number of particles per bunch, n_b the number of bunches, f_r the revolution frequency and $\sigma_{x/y}$ the width of the beam profile. In this equation, a Gaussian beam profile and head-on-collisions are assumed. In practice, this is not always the case and the luminosity is corrected.

By integrating the instantaneous luminosity over time the total number of expected events N that are produced in the collider for a given process can be estimated when multiplied with the cross section σ .

$$N = \sigma \cdot \int \mathcal{L} dt =: \sigma \cdot \mathcal{L}_{int} \quad (3.2)$$

The other way around, a cross section can be measured at a collider experiment by measuring the number of signal events as well as the integrated luminosity $\mathcal{L}_{int}$, as discussed in Sec. 2.3.

3.2. The ATLAS experiment

The ATLAS² [14] experiment is the largest of the four major experiments at CERN and aims at precision measurements of SM properties as well as searches for new physics. A schematic of the ATLAS detector is shown in Fig. 3.2. The detector has a cylindrical structure with a length of 46 m, diameter of 25 m and weight of over 7000 t. It is a multi-purpose detector with three sub-detector systems layered around the interaction point. These are the Inner Detector, the calorimeters and the Muon Spectrometer, which are presented below. They are crucial in order to measure and distinguish different particles produced in the pp collisions. Electrons, muons, photons and so-called jets, which are a consequence of confinement and hadronization of quarks, can be detected.

The layered cylindrical structure around the beamline is called barrel region. In addition, there are so-called end-caps at both ends of the detector which are perpendicular to the beamline (see Fig. 3.2). They have the purpose to detect particles within a small angle to the beamline. As a result, the ATLAS detector covers nearly the full solid angle of 4π .

3.2.1. Coordinate system

The ATLAS coordinate system is a right-handed cartesian coordinate system with its origin in the interaction point (IP). The z-direction is defined by the beam direction

²A Toroidal LHC ApparatuS.

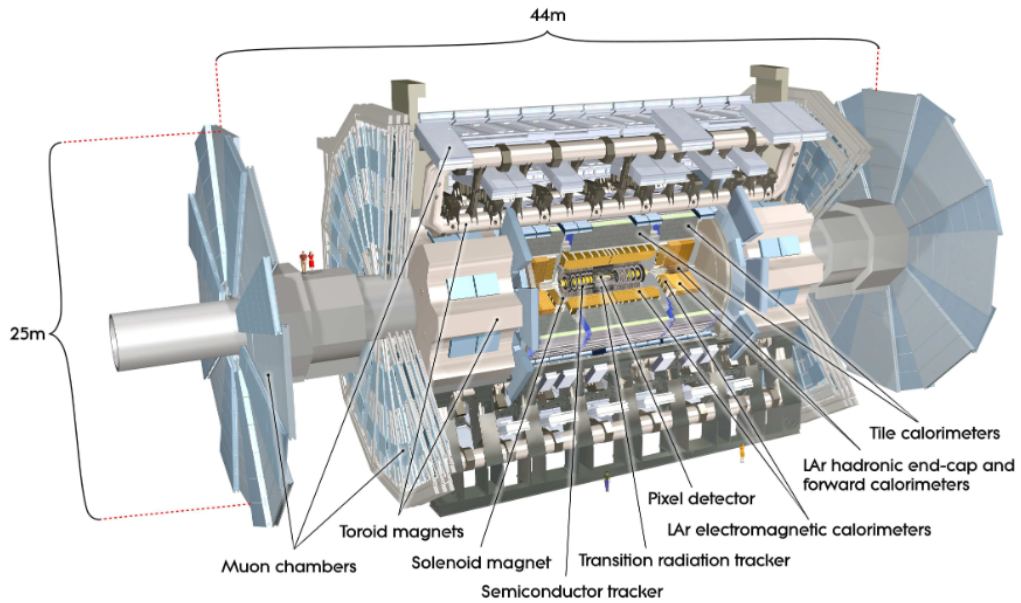


Figure 3.2.: Overview of the ATLAS detector including the different sub-detectors.

and the x-y-plane is perpendicular to the beamline. The positive x-direction points from the IP to the center of the LHC ring and the positive y-direction points upwards. Due to the form of the detector, cylindrical coordinates (z, r, ϕ) are introduced, where ϕ is the angle between the positive x-axis and the transverse momentum vector $\vec{p}_T = (p_x, p_y)$ of a particle. Because the initial transverse momentum of the colliding protons is approximately zero and momentum is conserved, the transverse momentum is an important measure in ATLAS events. Its absolute value is defined as follows.

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (3.3)$$

The polar angle θ is defined as the angle between the particle vector $\vec{p} = (p_x, p_y, p_z)$ and the z-axis. An alternative to describe the deviation from the z-axis is to use the rapidity y of a particle, which is given by its energy E and longitudinal momentum p_z .

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \quad (3.4)$$

It can be seen easily that the rapidity is zero for $p_z = 0$ and increases when p_z approaches the total energy E , which corresponds to arbitrary small transverse components p_x, p_y , in the limit. For a particle with a small mass compared to its energy ($m \ll E$), the rapidity can be approximated by the pseudorapidity η as in the following.

$$\eta = \frac{1}{2} \ln\left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}\right) = \frac{1}{2} \ln\left(\tan \frac{\theta}{2}\right) \quad (3.5)$$

As a result, the angular distance between two particles ΔR in the ATLAS detector can be expressed by the azimuthal angle and pseudorapidity as follows.

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \quad (3.6)$$

Throughout this thesis, the azimuthal angle $\Delta\phi$ between two objects is always positively defined, i.e. it refers, in fact, to the absolute value $|\Delta\phi|$.

3.2.2. Inner Detector

The Inner Detector (ID) is the innermost part of the ATLAS detector and is attached directly to the beam pipe. It measures the direction and momenta of all charged particles coming from the pp collisions, i.e. leptons and quarks which hadronize in the form of jets. The ID is embedded in a strong solenoid magnetic field of 2 T that leads to a bent path of all charged particles in the plane perpendicular to the beam. From the bent trajectory, the particle type and momentum might be concluded because the radius is directly dependent on the particle's momentum and charge as well as the given strength of the magnetic field³.

³This can be seen easily when Lorentz- and centripetal force are set equal.

There are three subsystems in the ID which are designed to measure the track of a particle with high precision. The innermost part is the pixel-detector which consists of a large number of cylindrically organized semiconducting detection elements, the so-called pixels. During a shutdown in 2014, a new layer, called Insertable B-Layer [19], was inserted between the existing pixel-detector and beam pipe in order to further improve the tracking of particles close to the interaction point. The pixel-detector is enclosed by the silicon microstrip detector that also relies on the semiconductor detection principle but provides a slightly less precise measurement. The third part of the ID is the transition radiation tracker. It consists of drift tubes filled with Xenon gas. Passing particles produce em radiation which is transferred into an electrical signal.

3.2.3. Calorimeters

Calorimeters are placed around the ID and aim at measuring the energy of particles. They are divided into an electromagnetic and a hadronic calorimeter. The former measures the energy of electrons and photons. It consists of alternating layers of absorbing lead or stainless steel and liquid argon. The particles lose energy in the absorber material in the form of bremsstrahlung or pair production. This results in a particle shower that is measured in the liquid argon layer. The material gets ionized and an electrical signal is extracted that is proportional to the energy of the incoming particle. In general, the functionality of the hadronic calorimeter is analogous. In contrast to the em calorimeter, hadronic objects, such as jets, are measured in this part of the detector and the showering in the absorbing material is caused by inelastic hadronic interaction. The hadronic calorimeter consists of alternating layers of steel and scintillators in the barrel region and of copper and liquid argon in the end-caps.

3.2.4. Muon Spectrometer

The outermost sub-detector of ATLAS is the Muon Spectrometer (MS). It is designed in order to measure muons explicitly. Due to their substantially larger mass than electrons, the muons produce nearly no bremsstrahlung in the calorimeter system but pass it basically without any interaction. In order to still be able to measure the energy of muons produced in the pp collisions at a sufficient precision, the track of a muon is measured not only in the ID but also in the MS. Such as the ID, the MS is embedded in a large magnetic field. It is produced by eight superconducting toroidal magnets and leads to a curvature of the trajectories of the muons. The tracks get measured mostly by Monitored Drift Tubes (MDTs). For absolute pseudorapidities larger than two, Cathode Strip Chambers (CSCs) with a higher granularity are used. In general, the MS is able to measure muons up to $|\eta| < 2.7$. In addition, there are Resistive Plate Chambers (RPCs) in the barrel and Thin Gap Chambers (TGCs) in the end-caps, which measure with less precision and are used for triggering. The muon trigger

system covers only an absolute pseudorapidity of 2.4.

Since the muon system is the outermost part of the detector, muons can not be measured with full efficiency in some regions due to the architecture of the detector. For instance, at the central region ($\eta = 0$), there is a small gap for services and cables spanning to the solenoid magnets, the ID and the calorimeters. Furthermore, the feet of the detector lead to measurement inefficiencies at certain values of the detector coordinates ϕ and η . Further information can be found in the technical design report [20] of the MS.

3.2.5. Trigger system

At design value, the LHC provides collisions every 25 ns, which corresponds to a rate of 40 MHz. However, this results in an amount of data that is too large to read out and store. Hence, a trigger system is implemented in order to pre-select only the events that are physically interesting. A two-stage trigger system is used [21,22]. The first stage is the hardware-based L1 trigger, which uses only parts of the information provided by the ATLAS detector. As a result, it is able to make a very fast decision, i.e. within less than 2.5 μ s, on whether or not to store an event. The L1 trigger lowers the frequency of recorded events to 100 kHz. The second stage consists of software-based High-Level-Triggers (HLT). These triggers use all information provided by the ATLAS detector and lower the frequency to 1 kHz. This is a reasonable rate of events, which can be stored and analyzed at a later point. The information about which trigger has fired is stored and helps to select events for a certain physical process, e.g. in this analysis, an event has to be triggered by a muon.

4. Data and simulated samples

This chapter gives an overview of the data used recorded at the ATLAS detector as well as the modeling of the signal and most background processes. These are simulated using Monte Carlo (MC) generators, which are based on theoretical predictions given by the SM. The idea is to imitate the behavior of real experiments very precisely and then compare the simulated MC to data.

4.1. Data

The analyzed data is based on pp collisions measured by the ATLAS detector at the LHC. The data was recorded in 2015 and 2016 corresponding to an integrated luminosity of 36.2fb^{-1} at a center-of-mass energy of $\sqrt{s} = 13\text{TeV}$. As discussed in Sec. 3.2.5, a trigger system is used in order to pre-select the measured data. Events used in this analysis are triggered by the muon. A logical ‘or’ between the single lepton triggers HLT_mu50 and HLT_mu20_iloose_L1MU15 (HLT_mu26_ivarmedium) is used for data recorded in 2015 (2016), as summarized in Tab. 4.1. The HLT_mu50 is a High-Level-Trigger that is fired by a muon exceeding a p_T threshold of 50 GeV. At lower p_T the other two triggers, assigned to the respective data taking period, fire with a threshold of 20 GeV (26 GeV). For these lower p_T triggers a loose isolation of the muon is required, in addition. There are several further general requirements that the data has to fulfill in order to be considered in this analysis. All sub-detectors had to work properly during the periods of data acquisition in order to consider the recorded data, this information is stored in a Good Run List (GRL). Moreover, events have to pass an event veto that takes care of errors in the calorimeter system and they need to have a primary vertex¹.

4.2. Monte Carlo samples

The prediction of the outcome of events produced in the ATLAS detector is a challenging task. On the one hand, these events are hard to predict from a theoretical point of view and, on the other hand, the experimental setup, including many sub-detectors,

¹The vertex that has at least two tracks associated to it, and these tracks have the highest sum of transverse momenta, is called primary vertex.

Table 4.1.: Overview of the single muon triggers used in this analysis.

Year	Trigger
2015	HLT_mu50 or HLT_mu20_iloose_L1MU15
2016	HLT_mu50 or HLT_mu26_ivarmedium

must be simulated sufficiently well. The simulation is based on MC generation and can be divided into several steps. At first, the matrix element is calculated to a certain order in perturbation theory. As the next step, a shower simulation using another generator that includes further radiation and hadronization processes takes place. Lastly, the detector response is simulated by **GEANT4** [23].

It is essential that not only the signal but also important background processes are predicted by simulations. As seen in eq. 2.3, the number of background events is subtracted from the data for a cross section measurement and, thus, should be well-estimated. The following backgrounds are taken into account in the MC simulations. First of all, top-anti-top ($t\bar{t}$) events make up a huge background, which is one of the benchmark processes at the LHC. Each top quark decays most likely into a bottom quark and a W boson. In order to have a single muon final state resembling the signal process, one W boson decays into a muon and neutrino, whereas the other one decays hadronically. However, there is the possibility that also the second W boson decays into a neutrino and a lepton that is not measured in the detector. Analogously, the neutral-current Drell-Yan process, where a Z boson is produced from quark-quark interaction and decays into a lepton pair, is considered as a substantial background if one of the two leptons is not reconstructed. It is referred to as Z+jets in the course of this analysis. In general, top quarks are not always produced in pairs and single top production in the s- and t-channel as well as the Wt process are a further source of background. Moreover, the production of a weak boson pair, i.e. WW, ZZ or WZ, that decays such that exactly one muon is measured is taken into account (diboson). Lastly, a small contribution is given by the charged-current Drell-Yan process decaying into a tau and tau neutrino. It yields a similar signature to the signal process if the short-lived tau decays into a muon and muon neutrino. However, there is one background that is not simulated in MC, which is called multijet background. Its production is purely via QCD interactions, nevertheless so-called fake muons might occur from e.g. a heavy flavor decay inside a jet. The estimation of this particular background is done data-driven, as explained in detail in Sec. 7.3.

A list of the MC generators used for the signal process as well as all simulated real muon backgrounds is shown in Tab. 4.2, divided into matrix element and showering simulation step. The signal $W \rightarrow \mu\nu$ process is simulated using a combination of

Table 4.2.: List of samples simulated in MC, including each generator used for the matrix element and showering simulation.

process	Matrix element	Parton shower/hadronization
$W \rightarrow \mu\nu$	POWHEG-BOX	PYTHIA 8
$t\bar{t}$	POWHEG-BOX	PYTHIA 8
single top	POWHEG-BOX	PYTHIA 8
Z+jets	POWHEG-BOX	PYTHIA 8
Diboson	SHERPA	SHERPA
$W \rightarrow \tau\nu$	POWHEG-BOX	PYTHIA 8

POWHEG-BOX [24] for the matrix element and PYTHIA 8 [25] for the showering. Analogously, the same generators are used for all simulated backgrounds, except the diboson background that is generated using SHERPA [26] for both, the matrix element and the showering [27, 28]. All matrix element calculations are done to next-to-leading order (NLO) precision in perturbative QCD. Additionally, the inclusive cross section of the $t\bar{t}$ process is calculated to next-to-next-to-leading order (NNLO), with a resummation to next-to-next-to-leading log (NNLL) order of soft-gluons [29]. However, the signal process is re-weighted to NNLO using a mass-dependent k-factor weight [27]. Lastly, pileup and lepton scale factors (SFs) are applied to all MC samples in order to match them with the data. These SFs are provided from dedicated measurements in which the simulation is compared to data in well-understood physical events, such as $Z \rightarrow \mu\mu$ or $J/\Psi \rightarrow \mu\mu$ [30].

The MC of the signal process is divided into an inclusive ("peak") sample and several high mass samples ("slices"). This holds as well for the $W \rightarrow \tau\nu$ and Z +jets backgrounds but is discussed exemplarily for the signal process here. The different samples are separated by the invariant mass of the W boson. Even though the inclusive sample is generated over the full kinematic range, it is cut to cover an invariant mass below 120 GeV only, while the region of higher masses is divided into several slices. A representation of the different samples is shown in Fig. 4.1, exemplarily for the W^+ MC. The number of events, binned in the invariant mass of the W boson, is shown, where each color corresponds to one sub-sample. This slicing is done for the following reason: The probability for the production of a W boson with a very large mass is extremely small compared to the peak region. In order to still have a sufficiently low MC statistical uncertainty in the high mass region, the number of generated events is enhanced there. Later, it is scaled down by the cross section in order to get a smooth stitching of all samples. The black line in Fig. 4.1 shows the composed $W^+ \rightarrow \mu^+\nu$ sample multiplied by a factor of two in order to discriminate from the single sample lines. It can be observed that the inclusive sample and all high mass slices form a smooth distribution.

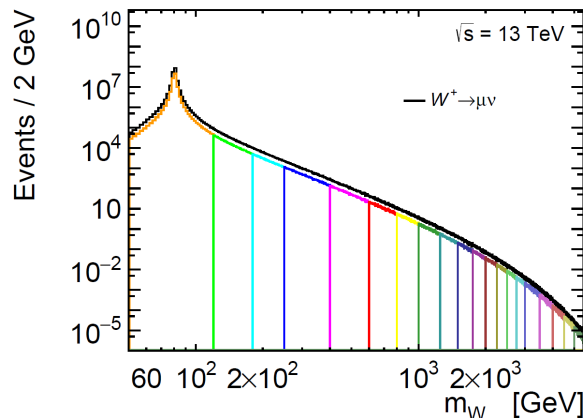


Figure 4.1.: Distribution of the invariant W^+ mass, where each colored line represents one $W^+ \rightarrow \mu^+\nu$ MC sub-sample. The black line is the combination of all samples and is scaled by a factor of two.

5. Object definitions and reconstruction

There are several kinds of objects produced in the pp collisions that can be measured in the ATLAS detector directly. This chapter gives an overview of all objects considered in this analysis. These are electrons, muons, jets and the missing transverse momentum, which can be used as a measure for the neutrino. Even though the signature of the signal process consists of a muon and neutrino only, all these objects are important at some point and the correct identification and reconstruction are essential. Finally, the reconstruction of the W boson is described, as the short-lived particle can not be measured directly.

5.1. Electrons

Particles are perceived as electron candidates if they leave a bent track in the ID as well as an isolated cluster in the em calorimeter [31]. Electron candidates in this analysis are required to have a transverse momentum larger than 20 GeV and need to be detected within an absolute pseudorapidity smaller than 2.47. Due to the architecture of the em calorimeter electrons within $1.37 < |\eta| < 1.52$ are excluded. In order to ensure that an electron originates from a primary vertex, two track-based cuts are applied: $|d_0^{sig}| < 5$ and $|z_0 \sin \theta| < 0.5$ mm, while d_0 (z_0) is the transverse (longitudinal) track impact parameter. They give the shortest distance between the trajectory of a particle and the z-axis. By d_0^{sig} the transverse impact parameter divided by its uncertainty is indicated. The electron candidates need to fulfill certain identification (id) and isolation criteria while a loose and tight level are defined. On the loose level, the electrons are required to meet the `LooseAndBLayerLH` id as well as the `FCLoose` isolation. On the tight level, the `TightLH` id with the `FixedCutHighPtCaloOnly` isolation is required [31]. Moreover, for tight electrons the $p_T(e)$ cut is raised to 30 GeV. Lastly, electrons are vetoed if they have bad calorimeter clusters associated with them in order to further improve the quality of selected electrons.

5.2. Muons

In general, the identification and selection procedure of muons is similar to the one of electrons. However, one large difference arises from the fact that muons do not leave a cluster in the calorimeters, as discussed in Sec. 3.2.4. In most parts of the analysis, muon candidates are selected if they leave a track in the ID and in the MS¹. Muons whose tracks are detected in both detector parts are called combined (CB) [30]. The selected muon candidates are required to have a transverse momentum of at least 20 GeV and an absolute pseudorapidity smaller than 2.4. Even though the MS is able

¹An exception holds on the muon veto level where only `Medium` quality instead of the analysis' default `HighPt` quality is required. Then, also extrapolated muons are considered.

to measure muons within $|\eta| < 2.7$, the muon trigger system ranges only up to 2.4. Since events in this analysis are triggered by muons, this limits the pseudorapidity range. Moreover, each muon has to fulfill cuts on the track parameters, namely an absolute d_0 significance smaller than three and $|z_0 \sin \theta| < 0.5$ mm. Just like for electrons, there are two identification levels defined for muons. The loose level is defined by `HighPt` quality² with no explicit isolation requirement. The tight level can be distinguished from the loose level by requiring an additional isolation of the muon, namely `FCTightTrackOnly_FixedRad` [30]. Furthermore, the p_T cut for tight muons is raised to 30 GeV.

5.3. Jets

One of the main principles of the strong interaction is confinement, i.e. quarks (and gluons) can not exist independently but form hadronic states. As a result, quarks can not be measured directly in the ATLAS detector but are perceived in the form of particle showers, which are called jets. In order to extrapolate from a jet to the momentum and energy of the initial particle, a reconstruction algorithm is used. The jet is reconstructed from topological clusters built from energy deposits in the calorimeter system. In this analysis, the anti- k_t algorithm [32], with a radius parameter of 0.4, is used. Jet candidates are selected if they have a transverse momentum of at least 25 GeV and are found within a pseudorapidity of 2.5.

Jets originating from bottom quarks behave differently from the ones that originate from light quarks. E.g. the longer lifetime of bottom quarks leads to a second vertex a few millimeters away from the primary vertex. Together with other criteria, multivariate algorithms decide with a certain probability whether a jet originates from a bottom quark. In this analysis, the DL1r algorithm [33] with a 70 % efficiency working point is used. A jet coming from a bottom quark is referred to as a b-jet.

5.4. Missing transverse momentum

The ATLAS coordinate system, as defined in Sec. 3.2.1, is constructed such that the colliding protons' momentum has nearly only a longitudinal component along the z-axis and a negligible transverse component. The principle of momentum conservation postulates that the vectorial sum of the transverse momenta of all final state objects should thus be approximately zero. However, due to the nature of neutrinos, they barely interact with matter and can not be seen in the ATLAS detector. As a result, there can be an imbalance of the measured transverse momenta present after

²The id is called quality for muons.

the collision. This missing transverse momentum, called E_T^{miss} , is associated with the transverse component of the neutrino³ and defined the following.

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2} \quad (5.1)$$

The x- and y-components of the missing transverse momentum are given by the negative vectorial sum of all reconstructed objects as well as a track-based soft term [34].

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,\mu} + E_{x(y)}^{miss,soft} \quad (5.2)$$

In this analysis, photons and taus are not considered in the reconstruction. The soft term $E_{x(y)}^{miss,soft}$ incorporates all energy deposits that are not associated with any of the calibrated objects. If an object has different identification levels defined, as e.g. the muon, the tight level is propagated into the calculation of the E_T^{miss} in this analysis.

5.5. Overlap removal

The reconstruction of objects is based on tracks in the ID and MS as well as energy deposits in the calorimeters. These tracks or energy deposits may be associated with more than one reconstructed object. In order to describe the underlying physics correctly, it is important to avoid double-counting. Therefore, an overlap removal is applied. The following objects are removed subsequently, i.e. each discarded element is no longer considered.

- Any electron with a track overlapping with another electron,
- Any calorimeter muon⁴ found with a shared track with an electron,
- Any electron with a shared track with a muon,
- Any jet found within a ΔR of 0.2 of an electron,
- Any electron found within a ΔR of 0.4 of a jet,
- Any jet with less than three associated tracks, which is found within a ΔR of 0.2 of a muon or has a track in the ID that is ghost-associated⁵.

In principle, there can be one further subsequent step that removes any muon found within a ΔR of 0.4 of a jet. However, this particular step is not applied in this analysis. This was necessary in order to get a proper estimation of the multijet background. A detailed discussion on this will be given in Sec. 7.3.3.

³Under the assumption that all other objects are, in fact, detected correctly.

⁴A calorimeter muon leaves a track in the ID and the calorimeter but not in the MS due to a detector gap.

⁵A ghost is a single infinitely soft particle whose track is added in the jet reconstruction. [35]

5.6. Reconstruction of the W boson

Since the W boson is a very short-lived particle, it can not be measured directly in the ATLAS detector but is reconstructed from its decay products. In this analysis, these are a muon and its corresponding neutrino. In MC simulations, the truth level properties of the muon and, in particular, the neutrino are available, so that the W boson can be reconstructed from the 4-vectors of both.

$$P_W = P_\mu + P_\nu \quad \text{with} \quad P_i = (E_i, p_i^x, p_i^y, p_i^z) \quad i = W, \mu, \nu \quad (5.3)$$

Hence, e.g. the mass of the W boson is defined as follows.

$$m_W^2 = m_{inv}^2 = (P_\mu + P_\nu)^2 \quad (5.4)$$

This is a Lorentz-invariant measure and, therefore, also called invariant mass m_{inv} . In measured data, however, not the whole information about the neutrino is available. Only the transverse component of the momentum of the neutrino can be measured in form of the missing transverse momentum E_T^{miss} (see Sec. 5.4). With this, the transverse mass m_T^W is defined as follows.

$$m_T^W = \sqrt{2p_T(\mu)E_T^{\text{miss}}(1 - \cos \phi_{\mu,\nu})} \quad (5.5)$$

Here, $p_T(\mu)$ expresses the transverse momentum of the muon and $\phi_{\mu,\nu}$ the angle between the muon and the neutrino in the transverse plane. Furthermore, the approximation of negligible particle masses is made. The quantity m_T^W is the discriminant variable in this analysis and the cross section is measured differentially in it.

6. Event selection

After the pre-selection of the data, as discussed in Sec. 4.1, there are several requirements applied to data and MC, which are summarized in the general event selection. These criteria aim to match the final state of the signal process and its kinematics in order to suppress background events while maintaining a sufficiently high signal efficiency. Several studies concerning the choice of working points were made and are presented in the following as well.

6.1. General event selection

The event selection used in this analysis is summarized in Tab. 6.1 and discussed in the following. Matching the final state of the signal process, events are selected if they contain exactly one muon and missing transverse momentum. The muon has to fulfill the tight working point, as presented in Sec. 5.2, i.e. the **HighPt** quality and **FCTightTrackOnly_FixedRad** isolation. For both, the choice of the working point is based on a study which is discussed below. The additional loose level definition of the muon is important for the multijet background estimation, in particular. Since the final state consists of exactly one muon, events with an additional lepton (muon or electron) are vetoed with a threshold of $p_T(\ell) > 20 \text{ GeV}$. For a smaller transverse momentum, the additional lepton is not considered as significant. In addition to the momentum threshold, the additional leptons need to meet certain identification and isolation criteria for the event to be vetoed. Electrons need to fulfill the loose level given in the object definition in Sec. 5.1. For muons, however, the veto level is extended to **Medium** quality. Otherwise, there would be a substantial rise in background. A study showing this issue is presented in the following. Furthermore, an event is vetoed if the muon candidate is considered a bad muon. This veto is designed to reject muons that have problems in the CB fit tracks [36].

Table 6.1.: Definitions of the two muon working points as well as the event selection criteria.

Criterion	Requirement
Loose level	HighPt quality No isolation
Tight level	HighPt quality FCTightTrackOnly_FixedRad isolation
Final state	Exactly one tight muon and E_T^{miss}
Veto	Loose electrons and HighPt / Medium quality muons Bad muons
$p_T(\mu)$	$> 65 \text{ GeV}$
E_T^{miss}	$> 65 \text{ GeV}$
m_T^W	$> 130 \text{ GeV}$

Since the goal of this analysis is measuring the cross section at the high mass tail of the mass distribution of the W boson, cuts are placed in order to get rid of the mass peak at around 80 GeV. The transverse mass m_T^W is demanded to be larger than 130 GeV. As it can be assumed that m_T^W is built evenly from the transverse momentum of the muon and the missing transverse momentum, a matching cut value on these would be $m_T^W/2$. Hence, both kinematic variables are required to be larger than 65 GeV.

If all cuts and requirements as presented here are applied, it is referred to as signal region in the following. Nevertheless, in some studies, not the full selection is applied and the differences with respect to the signal region are indicated in the corresponding chapter. Moreover, the abbreviation p_T instead of $p_T(\mu)$ is used in the further course of this thesis because the muon is the only real measured object in the final state. If the p_T of another object is meant, it will be stated explicitly. The same is valid for the detector coordinates η and ϕ of the muon.

6.2. Studies concerning the choice of working points

A working point (WP) optimized for the special needs of an analysis is essential. Therefore, the choice of the muon quality and isolation as well as the additional muon veto were studied. The following studies were performed subsequently, hence the final event selection given in Sec. 6.1 might not be applied fully in these studies.

6.2.1. Muon quality

Two quality working points for the tight muon level were studied, on the one hand, **Medium** quality and, on the other hand, **HighPt** quality [30, 36]. Among other things, the **Medium** WP is defined by requiring at least two hits in the MS. Opposed to this, the **HighPt** WP is characterized by requiring at least three hits in the MS, which yields an optimized measurement of muons with a large p_T . By requiring three hits in the MS the sagitta¹, and thus momentum, measurement is improved, in particular at high p_T . Furthermore, the **HighPt** WP distinguishes from other WPs by vetoing against muons in the transition region between barrel and end-caps, i.e. in the region $1.01 < |\eta| < 1.1$, since no optimal reconstruction of the muon track is possible there.

A comparison between both qualities on the tight muon level was done with respect to the detector resolution and efficiency. By increasing the muon quality to **HighPt**, an improved resolution is expected but, at the same time, a drop in efficiency because of the harsher requirement of at least three hits in the MS. The study is performed on

¹The sagitta is defined as the distance from the center of an arc to its chord and can be e.g. used to conclude to the radius of the circle. Since the charged muons are flying on circular tracks due to the magnetic field across the detector, the momentum of the muon can be determined by measuring the sagitta.

the signal MC, where the cuts on p_T , E_T^{miss} and m_T^W of the standard event selection² are omitted. Moreover, only the high mass slices, as defined in Sec. 4.2, are considered because the peak sample introduced non-physical fluctuations. A further discussion of this issue is given in appendix A.1.

The procedure of estimating the resolution of the transverse momentum of the muon is presented exemplarily for the **HighPt** WP in the following. At first, a two-dimensional histogram of the truth level against the reconstructed muon transverse momentum is made, as shown in Fig. 6.1a. The truth level is given in the simulation before any detector effects are applied, hence this comparison yields the explicit impact of the reconstruction. As a next step, for each bin of the truth p_T distribution, which is given on the y-axis, the distribution of the reconstructed p_T is taken. An example is shown in Fig. 6.1b where it can be observed how the reconstructed p_T distributes around its truth value. For each truth bin, the RMS of the distribution of the reconstructed variable is calculated. It is defined as the standard deviation of the distribution and, hence, not dependent on the chosen binning. The RMS is taken as a measure of the resolution, whereas a large RMS corresponds to a worse resolution, i.e. the reconstruction is not as close to the truth value.

A comparison between the resolution when requiring **HighPt** or **Medium** quality is shown in Fig. 6.2a. It is visible that the RMS increases with p_T . This is expected, since a muon is measured only track-based in the ID and MS. For a track-based momentum measurement, the relative uncertainty due to the resolution increases linearly with the energy [30]. As seen in the ratio plot in Fig. 6.2a, the resolution improves when using the **HighPt** WP, as it is expected. The effect is more pronounced at increasing p_T , up

²This study was one of the earlier studies of this analysis, meaning the final event selection was not yet found. In this study, the **FCTightTrackOnly_VarRad** isolation is used and the full overlap removal (see Sec. 5.5) is still applied. The veto level requires **Loose/HighPt** quality for the **Medium/HighPt** WP.

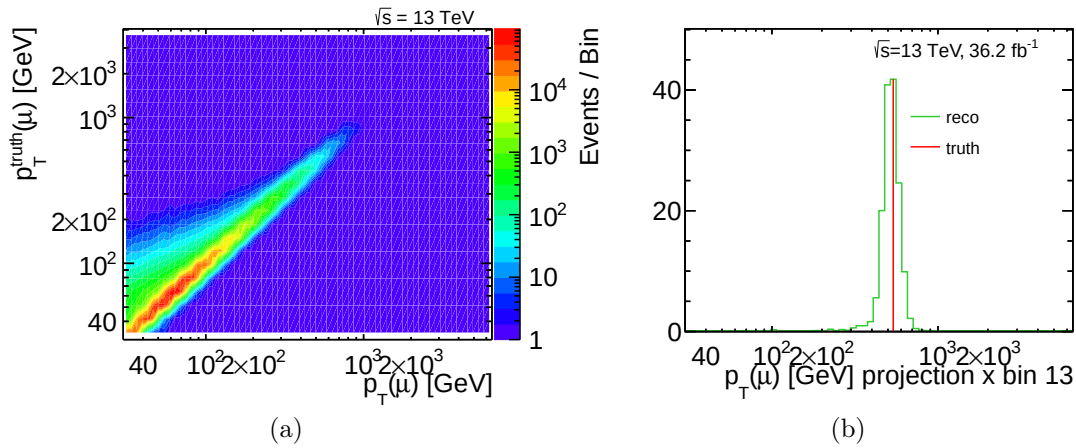


Figure 6.1.: (a) Truth level transverse momentum of the muon against the corresponding reconstruction level transverse momentum. (b) Distribution of the reconstructed transverse momentum of the muon, exemplarily for one truth bin.

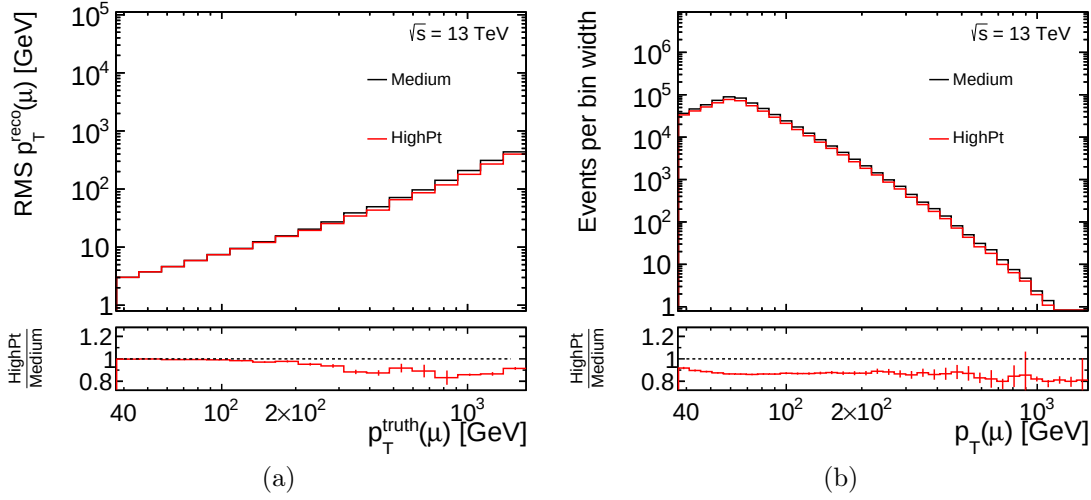


Figure 6.2.: Comparison of the (a) resolution and (b) efficiency for the two muon qualities **HighPt** and **Medium**.

to an improvement of around 15 % at $p_T = 1$ TeV. Clearly, an optimized resolution is important, since a more precise measurement can be made. However, the measurement efficiency must not decrease too heavily by having additional requirements. Hence, an efficiency comparison is done by comparing the event yield on reconstruction level per p_T bin for both WPs. It can be observed in Fig. 6.2b that the change of the WP from **Medium** to **HighPt** quality induces an efficiency loss of nearly constantly around 15 % over the measurement range. However, the effect is slightly more pronounced at high transverse momenta. Nevertheless, the muon efficiency is perceived as high enough to get a sufficiently large amount of events, even in the high p_T tail. Particularly in the low m_T^W region, the systematic uncertainty is expected to be dominant instead of the statistical uncertainty anyways. As a conclusion of this study, the expectation can be confirmed that the use of **HighPt** quality, instead of **Medium** quality on the tight muon level, results in an improved resolution but at the same time tolerable loss of measurement efficiency. Thus, it is chosen to use the **HighPt** working point over the whole analysis.

6.2.2. Muon isolation

Different isolation working points are available, each optimized for the special needs of certain analysis types. Two WPs were studied in detail in order to see which one is best for this particular analysis. These are **FCTightTrackOnly_VarRad** and **FCTightTrackOnly_FixedRad** (referred to as **VarRad** and **FixedRad** in the following) [30, 37]. Both isolations are track-based, which means that only an isolation around the muon's track is required and no further isolation in the calorimeter systems. A track-based isolation is quantified by adding up the transverse momenta of

nearby particles³ around the particle of interest, in this case the muon. The scalar sum of these p_T within a given cone size around the muon must not exceed a certain threshold. The difference between the two studied isolations is given by the cone size. In the **VarRad** isolation, the cone size is variable and gets smaller with increasing momentum of the muon ($\Delta R = \min(10 \text{ GeV}/p_T(\mu), 0.3)$). In contrast, the **FixedRad** isolation has the cone size fixed to $\Delta R = 0.2$ above 50 GeV, below it is defined exactly as the **VarRad** isolation. In general, an isolation with a fixed cone size is expected to have a better background rejection than one with a variable size because in the latter case the cone size gets arbitrary small for high p_T and nearby particles might not be considered for the isolation criterion any more⁴.

The chosen measure to judge the performance of an isolation is the efficiency for a loose level muon to pass the tight WP. As seen in Sec. 6.1, the only difference between the two levels is exactly the additional isolation requirement. An important criterion for an isolation is a good background rejection while the signal efficiency stays reasonably large. Hence, two different efficiencies are investigated which are called real and fake efficiency. These will be introduced and discussed in detail in Chapter 7.3 and are important for the modeling of the multijet background. At this point, it is sufficient to give a short overview of the two of them in order to understand the differences in the studied isolations. The real efficiency is a measure for the signal efficiency and defined by the efficiency for a real, prompt muon to be isolated. The fake efficiency, however, is based on fake muons, which are among the further decay products in jets. Thus, fake muons are clearly expected not to be isolated and the isolation should be an important criterion in estimating and rejecting events coming from the fake muon background. In summary, the real and fake efficiency should be a valid measure for the isolation performance. Both efficiencies comparing the two studied isolations are shown in Fig. 6.3. Below 50 GeV, the two isolations are per definition the same and, therefore, only above this value a difference can be observed. The fake muon efficiency shows a decrease by 5-8 % percent when using the **FixedRad** instead of the **VarRad** isolation. This means, the isolation with a fixed cone size shows a better background rejection in this analysis, as it was expected. The effect is slightly more pronounced for low p_T . In contrast, the real efficiency varies only by a few permille for both isolations. This agrees with the expectation as well, since signal muons are expected to be isolated anyway. Thus, the efficiency is in both cases very high and not strongly dependent on the definition of the isolation criterion. Concluding, the **FCTightTrackOnly_FixedRad** isolation shows overall a slightly better performance and, therefore, is chosen for this analysis.

6.2.3. Additional muon veto

The final state considered in this analysis consists of exactly one lepton and missing transverse momentum. Hence, events are vetoed if additional leptons are present. A

³Here, only particles with a p_T of at least 1 GeV are considered.

⁴In a very boosted and busy environment, an isolation with a p_T dependent cone size might be more adequate. In general, this environment is not expected for events selected in this analysis.

lepton has to meet certain criteria to be considered an additional lepton. For additional electrons, the veto level corresponds to the loose level given in Sec. 5.1. For additional muons, however, a study was performed comparing different definitions of this veto level. In one case, the veto level equals the loose level given in the muon object definition (Sec. 5.2) where the muon quality is **HighPt**. This is tested against a level where the additional muon has to fulfill only the lower **Medium** quality for the event to be vetoed.

Comparisons of the event yield in the signal region binned in m_T^W , using each definition of the veto level, are shown in Fig. 6.4 and Fig. 6.5. The histograms are sub-divided per process in order to see the impact of a different veto level on each background, signal and data, explicitly. The most striking effect can be observed in the Z+jets background, which is shown in Fig. 6.4a. The use of **Medium** quality on the veto level reduces this background substantially, in particular for increasing m_T^W . For instance, the number of events in the last m_T^W bin, from 1400 GeV to 2000 GeV, is reduced by a factor of more than four. The fact that there is such a high impact on this particular background is expected. Since the **HighPt** quality has a tighter definition, the efficiency for measuring **HighPt** muons is smaller than for **Medium** muons (see Sec. 6.2.1). Therefore, it is more likely that the second muon of the dileptonic final state of the Z+jets background is not detected in that case. As a result, more events of this process contribute to the single lepton final state.

In addition, the impact of the choice of veto level can be observed in other backgrounds. As seen in Fig. 6.4b, 6.4c and 6.4d the $t\bar{t}$, single top and diboson background are lowered by vetoing against **Medium** muons instead of **HighPt** muons. The effect is more pronounced at increasing m_T^W for these backgrounds as well. However, there is no large difference observable in the signal process, which is shown in Fig. 6.5a. There, only very few events are expected to be cut away by the additional lepton veto because the $W \rightarrow \mu\nu$ process is single-leptonic at leading order (EW) anyway. Thus, it can be

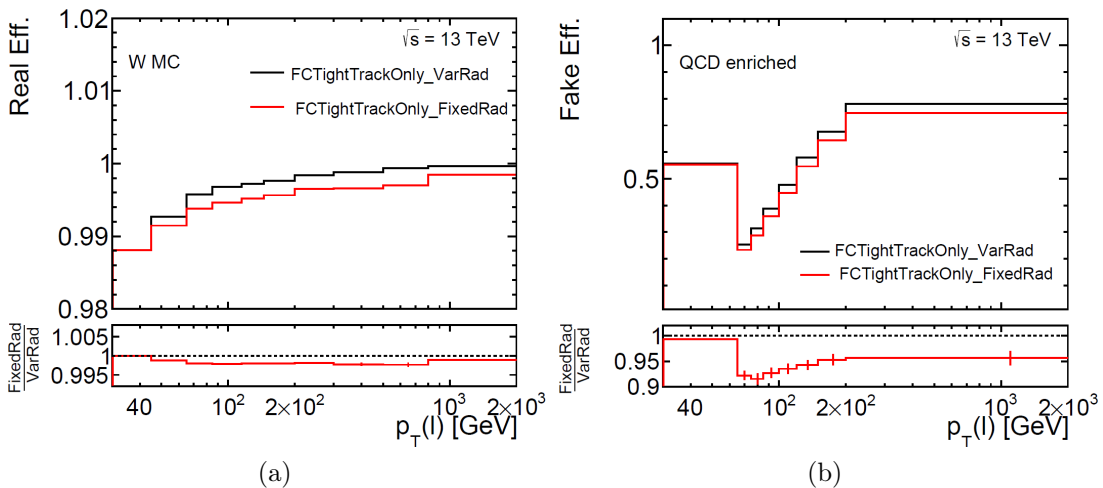


Figure 6.3.: The (a) real and (b) fake efficiency binned in the transverse momentum of the muon for two different isolations.

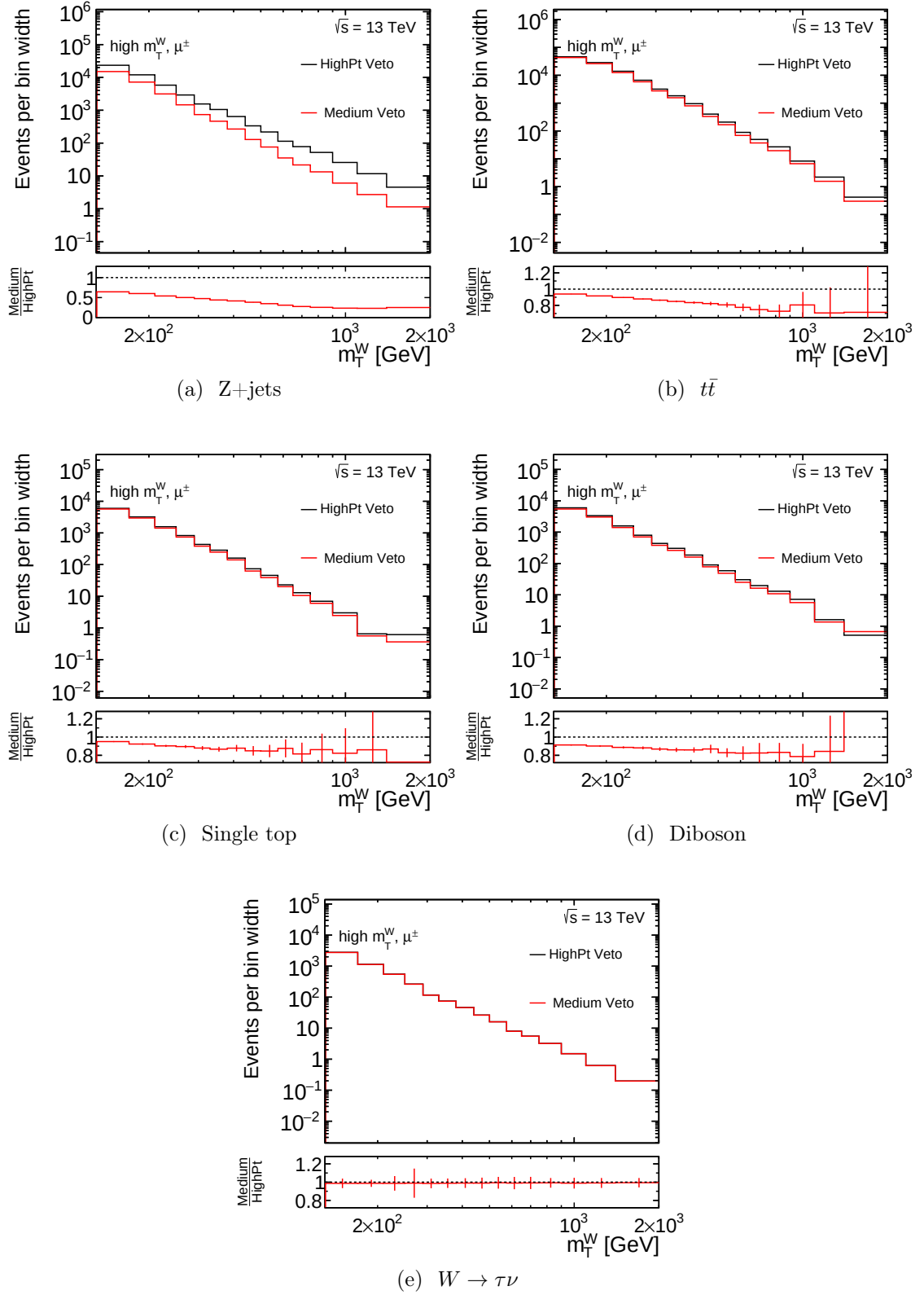


Figure 6.4.: Real muon background event yields binned in the transverse mass for two different muon qualities on the veto level.

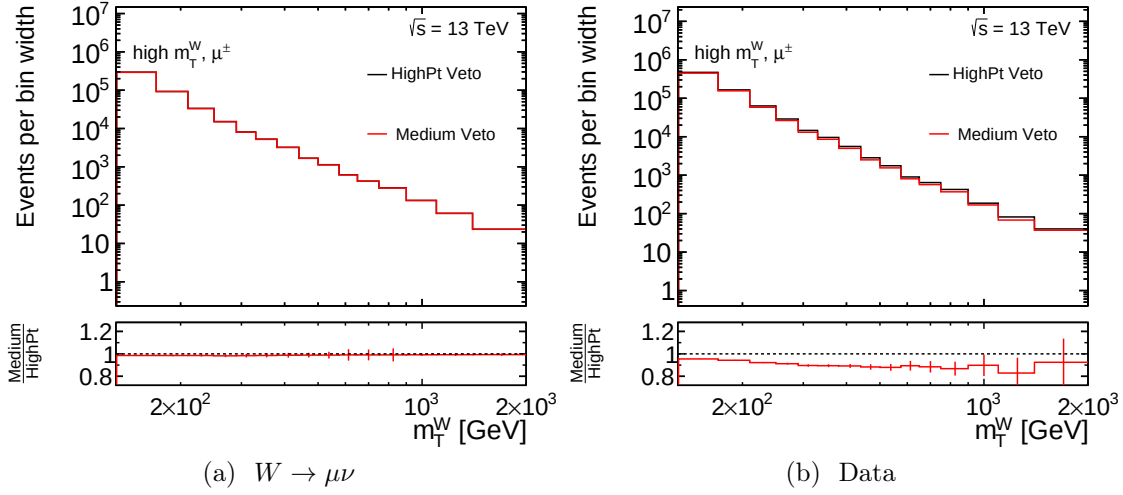


Figure 6.5.: The number of (a) signal MC events and (b) data events as a function of the transverse mass for two different muon qualities on the veto level.

understood that the choice of the veto level has no large impact on the signal. The same effect is visible in the $W \rightarrow \tau\nu$ background shown in Fig. 6.4e. Looking at data in Fig. 6.5b, the number of events is reduced by around 15% at maximum, i.e. the general amount of statistics in the data is still at a reasonable magnitude. However, basically only background events are expected to be cut away in the data, as the comparisons in the MC have shown.

As a conclusion, there is a substantial decrease of background, particularly at high m_T^W , while the signal efficiency is found to be essentially unaffected when requiring **Medium** instead of **HighPt** quality on the veto level. Because of this, it is chosen to veto against additional **Medium** muons throughout this analysis.

7. Background modeling

In a cross section measurement, all backgrounds are subtracted from the data to get the signal contribution (see equation 2.3). Hence, a good background estimation is essential in addition to the modeling of the signal process. All background processes were introduced briefly in Chapter 4 but important aspects in their modeling are discussed in this chapter. A large fraction of background events originates from $t\bar{t}$ events. A control region, called top control region, is defined to ensure this particular process is well-modeled. A further, rather large background is given by Z+jets events. There, a charge-asymmetry is observed, which is discussed in detail. Lastly, one background is distinct from the others, namely the multijet background. For this, a data-driven approach, namely the Matrix Method, is used to estimate the number of events, as opposed to all other processes that are simulated in MC. After a short theoretical introduction into this method, the procedure of estimating the multijet background is discussed. At the end of this chapter, two control regions for this particular background are presented.

7.1. Top control region

A large contribution to the background in this analysis is given by $t\bar{t}$ events. Therefore, a top control region (CR) is defined, which is enriched in top events and allows the comparison of the $t\bar{t}$ production MC to the data. At first, it is checked how different decay channels contribute to the $t\bar{t}$ process in the signal region. Each top quark decays into a bottom quark and a W boson, where the W boson itself can decay either leptonically or hadronically. A final state containing exactly one muon is perceived if one W boson decays into a muon and a neutrino, whereas the other one decays either hadronically into a quark and an anti-quark (semileptonic $t\bar{t}$ decay ($\ell\nu/qq$)), or in a neutrino and a second lepton that is not measured (dileptonic ($\ell\nu/\ell\nu$)). Therefore, a categorization of the $t\bar{t}$ MC according to the decay of the W boson is implemented. Fig. 7.1 shows the fractions of each decay category of the $t\bar{t}$ production in the signal region. It can be observed that roughly 30 % of the events decay dileptonically and 30 % semileptonically. An extra category is implemented if a tau is involved, since the tau itself decays leptonically or hadronically. A dileptonic decay where one lepton is a tau makes up most of the rest (30 % leptonic, 10 % hadronic tau decay). A control region containing exactly one muon and one electron is chosen. Hence, the only difference to the signal region is the additional lepton which makes the CR close to the signal region but at the same time enriched in dileptonic decaying $t\bar{t}$ events. Moreover, leptonic final states show a very clear signature in the detector.

In the top CR, data¹ taken in 2015 and 2016 and the corresponding MC is used. The CR is defined by requiring exactly one tight level muon as well as exactly one tight level electron, both with a transverse momentum larger than 30 GeV. The tight level of both leptons is defined as given in Chapter 5. A logical ‘or’ between all used single muon

¹However, a tiny part of the data, namely 0.2% of period I in 2016, is missing due to a recurring error while processing the data. This would have lead to a non-reasonable extension of computing time for such a small and probably negligible part of the data.

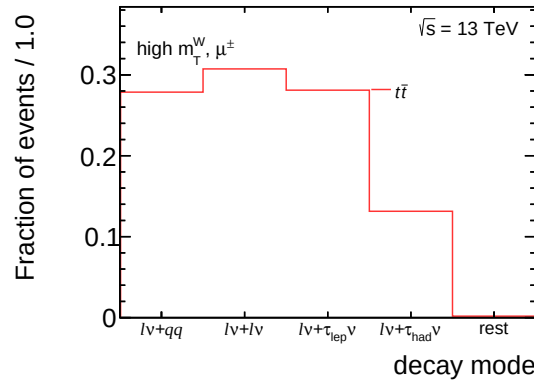


Figure 7.1.: A categorization of the $t\bar{t}$ MC according to the decay of the W boson in the signal region.

and single electron triggers is used². Since two leptons are selected in the top control region, the calculation of m_T^W according to eq. 5.5 is not determined. It is chosen to use the leading lepton, i.e. the lepton with the highest p_T measured, to reconstruct the transverse mass. It should be noted that also the missing transverse momentum can no longer be linked clearly to one neutrino, so the transverse mass defined here can not be linked to the signal m_T^W directly. To keep the top CR close to the signal region, the leading lepton is demanded to have a transverse momentum larger than 65 GeV. Three slightly different regions are defined.

1. $E_T^{\text{miss}} > 65 \text{ GeV}$ and $m_T^W > 130 \text{ GeV}$.
2. No cuts on E_T^{miss} and m_T^W .
3. No cuts on E_T^{miss} and m_T^W and at least one b-jet.

MC-data comparison plots for different kinematic variables for all three regions are presented in the following. In each figure, a ratio between data and MC is shown. The uncertainty band in the ratio includes the MC statistical uncertainty as well as systematic uncertainties. Experimental systematic uncertainties are applied to all MC processes and cover the measurement of the electron, muon, jets, and E_T^{miss} , the lepton SF as well as the b-tagging for the last region. Further information on all experimental systematic uncertainties can be found in Chapter 10, in which these are discussed exemplarily for the signal region³. In addition, the following theoretical systematic uncertainties for the $t\bar{t}$ process are included: initial and final state radiation, variations of the scales μ_R and μ_F , different PDFs and generators for the shower/matrix element

²In the top control region not only the muon triggers defined in Sec. 4.1 are used but also the following electron triggers: HLT_e24_lhmedium_L1EM20VH, HLT_e60_lhmedium, HLT_e120_lhloose for 2015 data and HLT_e26_lhtight_nod0_ivarloose, HLT_e60_lhmedium_nod0 and HLT_e140_lhloose_nod0 for 2016 data.

³Some experimental uncertainties, namely for the electron and b-tagging, are not important in the signal region. Here, these uncertainties are in line with Ref. [38], while the FULL_ETACORRELATED_v1 model is used for the electron uncertainties. The b-tagging systematic uncertainties are obtained by varying a dedicated b-tagging SF.

simulation. These uncertainties are discussed in Sec. 7.1.1 in more detail.

Fig. 7.2 and Fig. 7.3 show MC-data comparisons for the first region, which is defined to be closest to the signal region. In Fig. 7.2a the contributions from the different MC processes is shown in a pie plot. The $t\bar{t}$ purity, i.e. the fraction of the $t\bar{t}$ events in the total MC prediction, is 84.6%. Therefore, the requirement that the CR is highly top enriched is satisfied. It is noticeable in Fig. 7.2b that the electron is observed to be the leading lepton in a slightly higher number of events. Naively, this is against the physical expectation of lepton universality. This small asymmetry, however, can be explained by the fact that the reconstruction efficiency in the ATLAS detector is superior for an electron than for a muon at high p_T , since electrons are measured in the calorimeter system as well. In both bins of the histogram shown in Fig. 7.2b, the

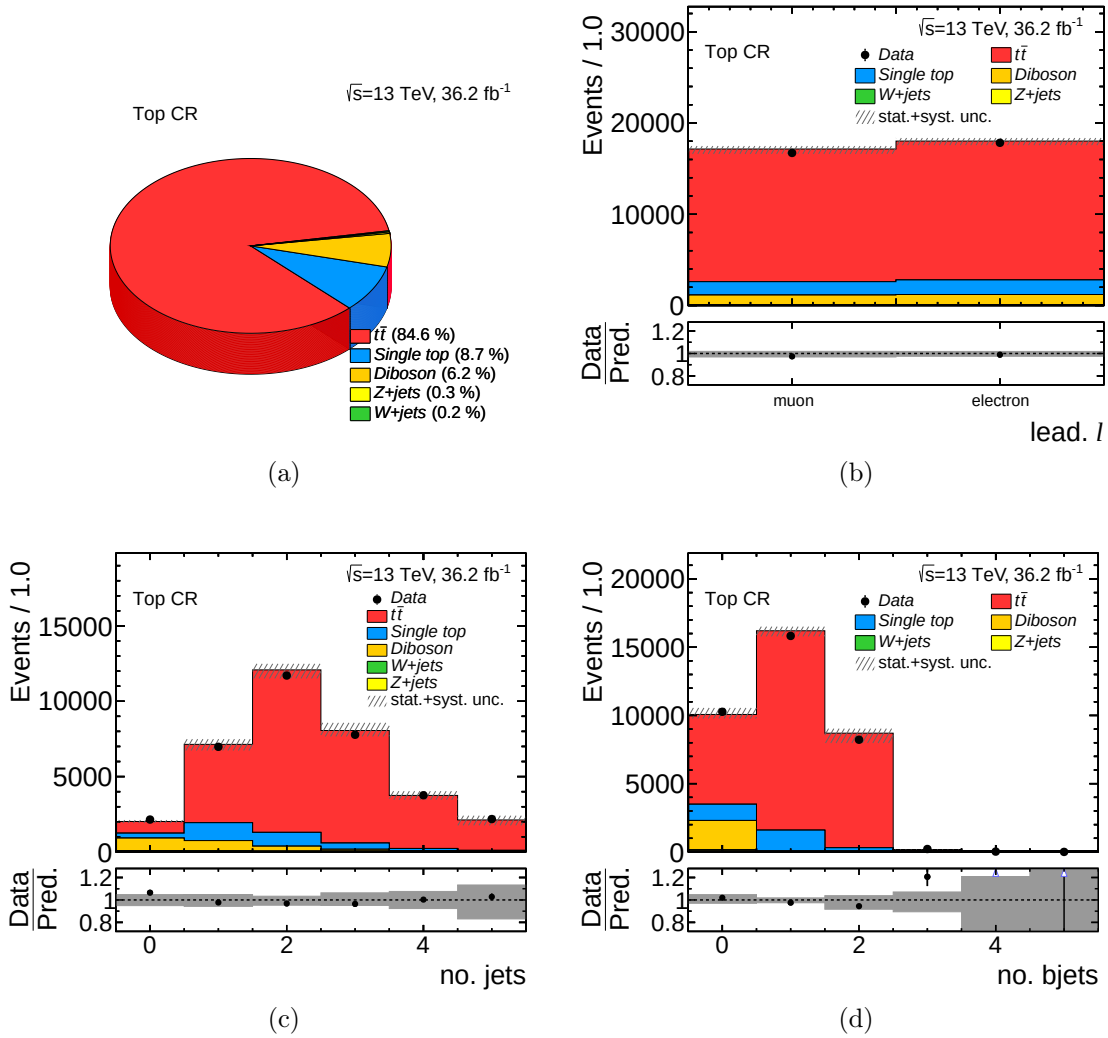


Figure 7.2.: The (a) contribution of the different processes to the total MC yield, (b) the distribution of the leading lepton among the lepton flavors, (c) the number of jets and (d) b-jets are shown in the first top control region ($m_T^W > 130$ GeV and $E_T^{miss} > 65$ GeV).

MC-data agreement is very good. The overall statistical and systematic uncertainty on the MC is in the order of a few percent and covers the tiny disagreement.

The jet and b-jet multiplicity are shown in Fig. 7.2c and Fig. 7.2d, respectively. The distribution of the number of jets has its maximum at two jets as expected for a dileptonic $t\bar{t}$ decay where both W bosons decay leptonically while the two b-quarks form jets. Nevertheless, the measured number of b-jets has its maximum at one b-jet only. This can be explained by the used 70% b-tagging efficiency working point and further jet efficiency and acceptance effects. As a result, not every bottom quark forms a jet which is identified as a b-jet. Fig. 7.3 shows more kinematic variables for the first region. Overall, all distributions look as expected and no significant deviation between simulation and data can be observed. At increasing energies, i.e. high p_T ,

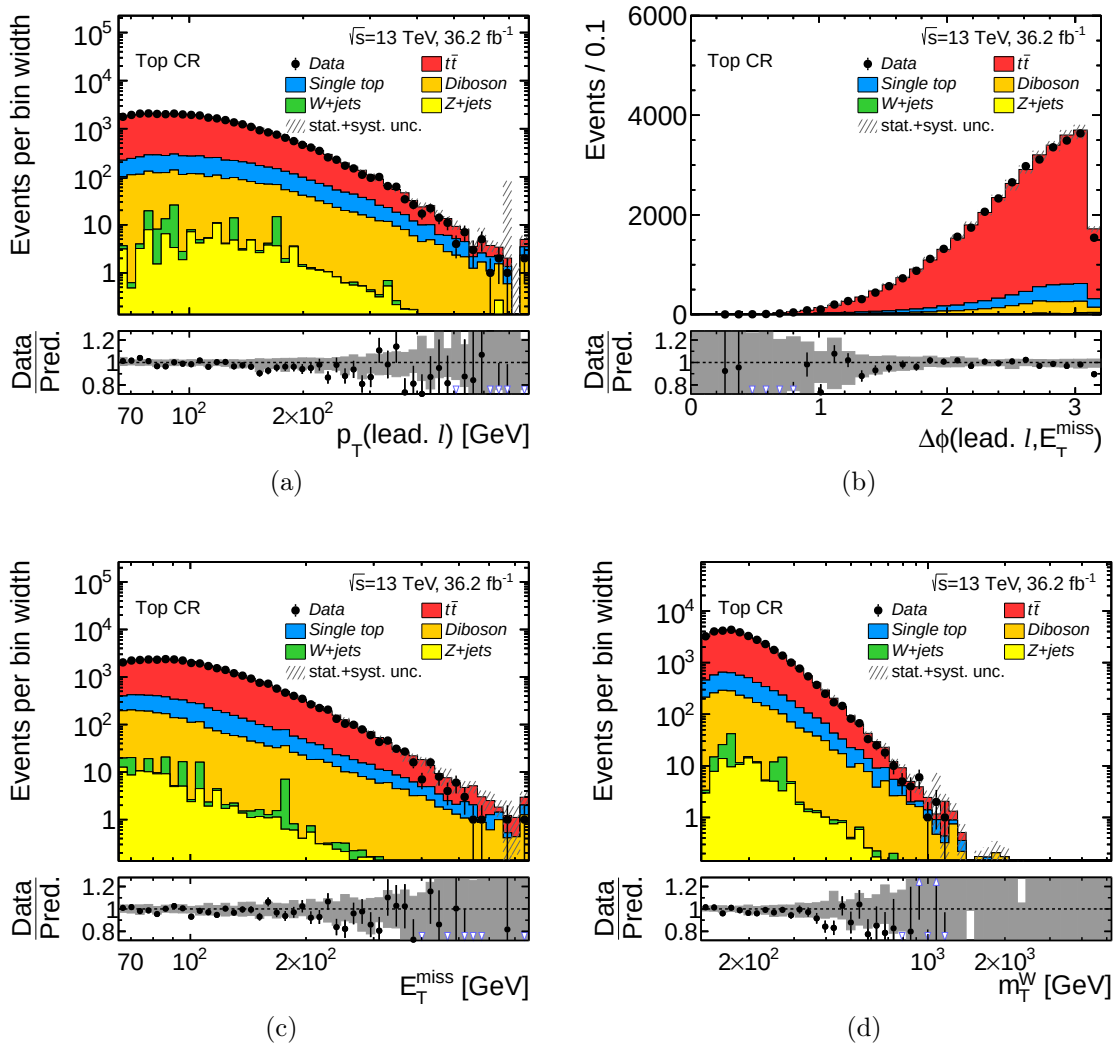


Figure 7.3.: The (a) transverse momentum of the leading lepton, (b) opening angle in the transverse plane between leading lepton and missing transverse momentum, (c) missing transverse momentum and (d) transverse mass are shown in the first top control region ($m_T^W > 130$ GeV and $E_T^{miss} > 65$ GeV).

E_T^{miss} and m_T^W , the statistical uncertainty becomes dominant. Additional distributions of the transverse momentum, the pseudorapidity and azimuthal angle of the muon and electron, respectively, are shown in Fig. A.10 in the appendix. In general, a reasonable agreement between data and MC is observed in all plots of this region and the given uncertainties cover all deviations.

The second region is defined without restricting m_T^W and E_T^{miss} . Distributions for this region are shown in Fig. 7.4 and Fig. 7.5 as well as Fig. A.11 in the appendix. Regions without these cuts are used for example for the multijet background estimation, as discussed in Sec. 7.3. Therefore, it is important that the $t\bar{t}$ background is also well-described there.

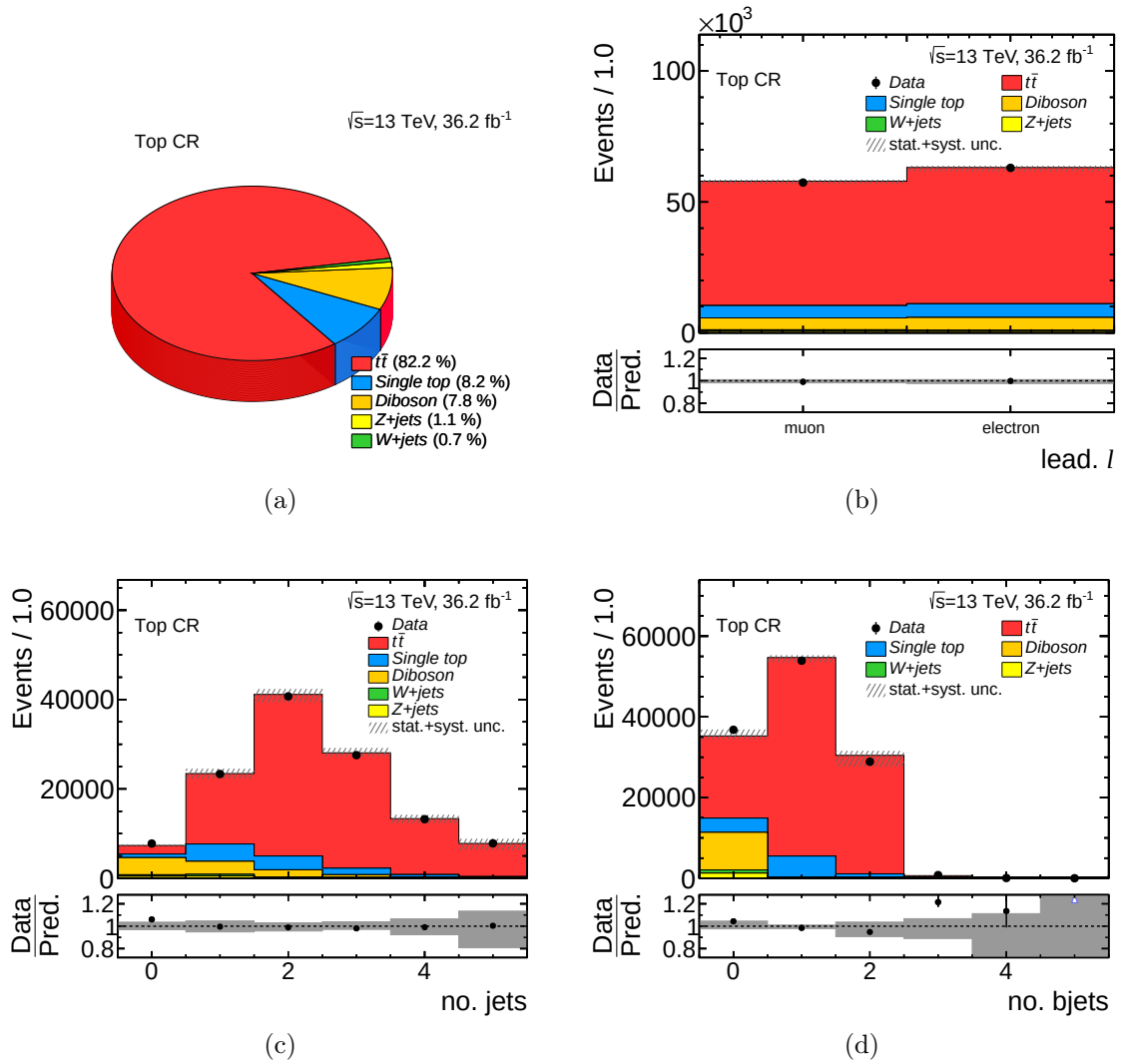


Figure 7.4.: The (a) contribution of the different processes to the total MC yield, (b) the distribution of the leading lepton among the lepton flavors, (c) the number of jets and (d) b-jets are shown in the second top control region (no m_T^W and E_T^{miss} cuts).

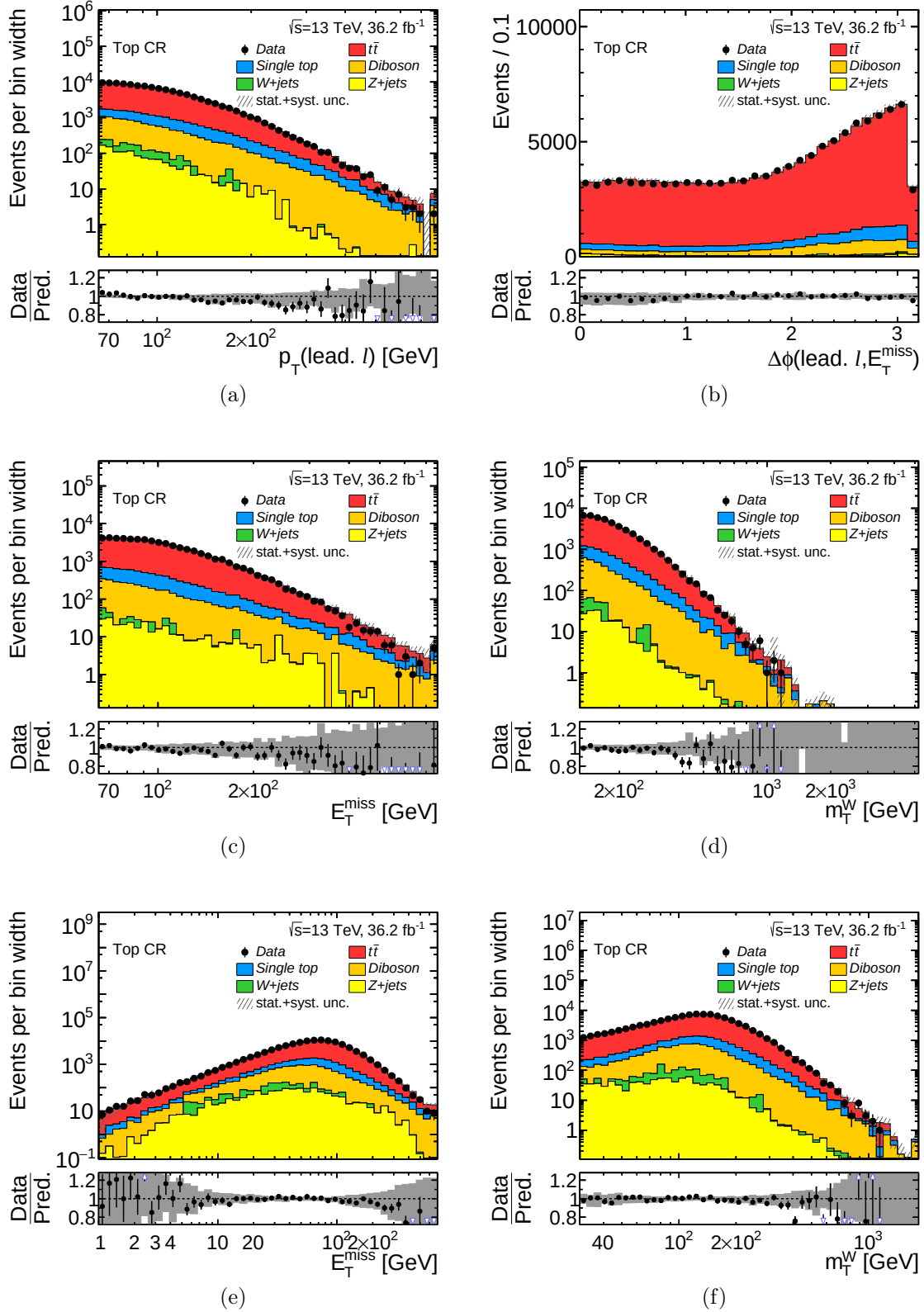


Figure 7.5.: The (a) transverse momentum of the leading lepton, (b) opening angle in the transverse plane between leading lepton and missing transverse momentum, (c)/(e) missing transverse momentum and (d)/(f) transverse mass are shown in the second top control region (no m_T^W and E_T^{miss} cuts). In (c)/(e) and (d)/(f), respectively, only the range shown on the x-axis is different.

In general, all variables show a similar behavior to the ones shown in the region before. The ratio is slightly more stable over the course of most variables, which is as expected because the statistical power increases when omitting the cuts on m_T^W and E_T^{miss} . Overall, a slight tendency of an overestimated prediction is noticeable for increasing p_T , E_T^{miss} and m_T^W . However, this is covered reasonably by the systematic and statistical uncertainties. Additionally, the distributions of m_T^W and E_T^{miss} in the regions below 130 GeV and 65 GeV, respectively, are shown explicitly in Fig. 7.5e and Fig. 7.5f. Also, in these regions, the MC-data agreement is good.

Fig. 7.6 and 7.7 show all discussed variables for the third region, which aims to achieve an even larger fraction of $t\bar{t}$ events by requiring at least one b-jet, in addition. Just like in the second region, no cuts on E_T^{miss} and m_T^W are placed.

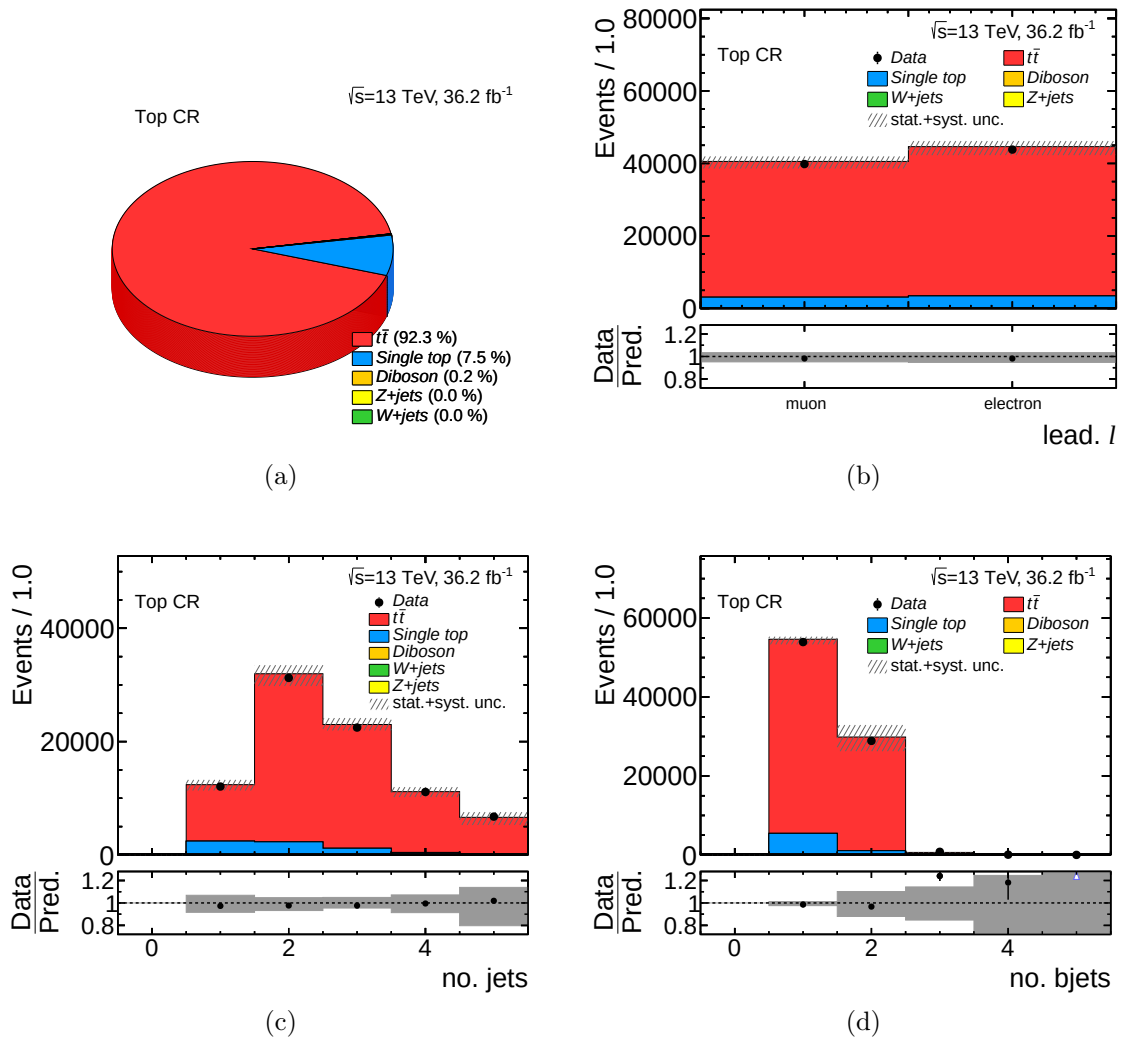


Figure 7.6.: The (a) contribution of the different processes to the total MC yield, (b) the distribution of the leading lepton among the lepton flavors, (c) the number of jets and (d) b-jets are shown in the third top control region (no m_T^W and E_T^{miss} cuts, at least 1 b-jet).

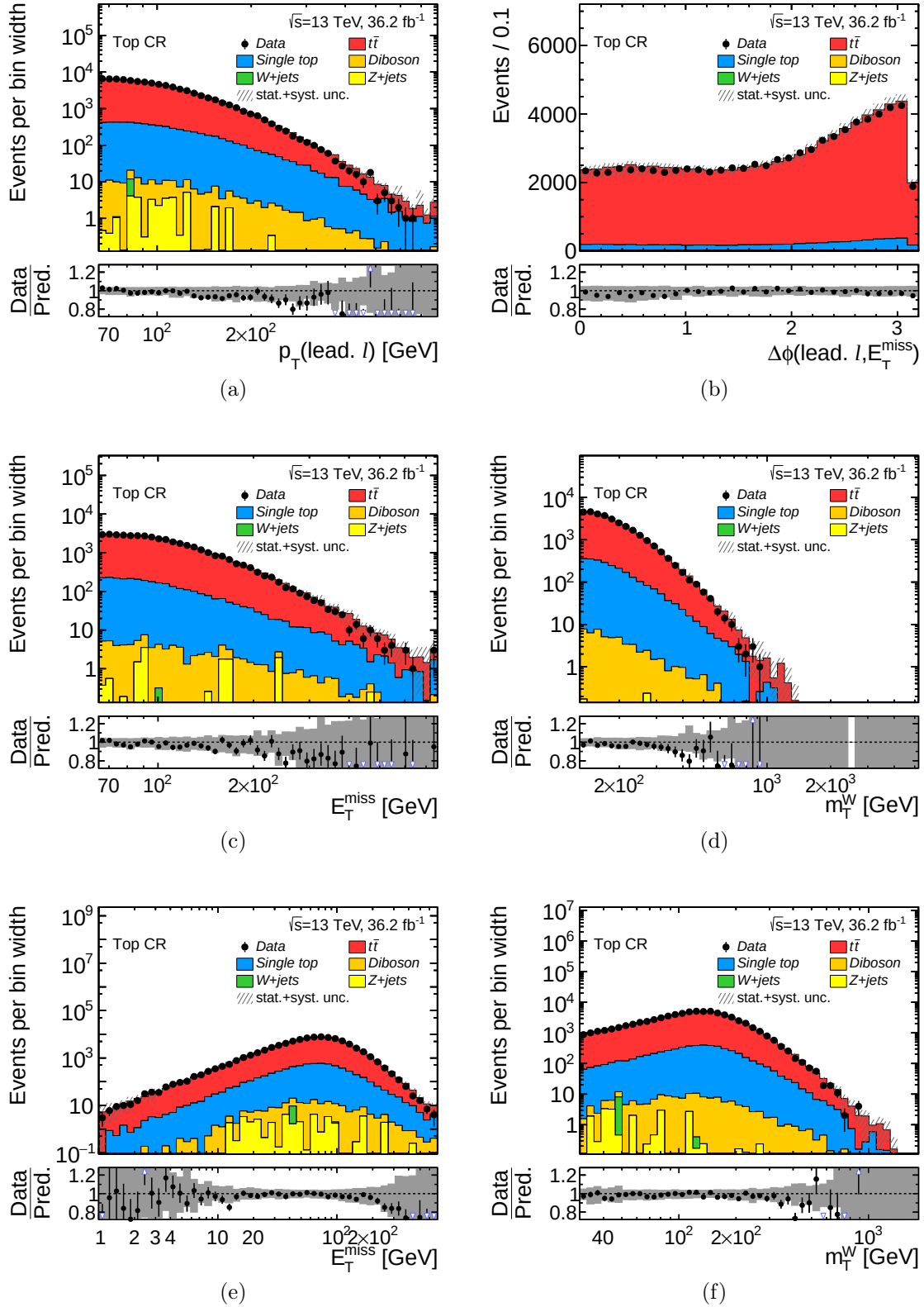


Figure 7.7.: The (a) transverse momentum of the leading lepton, (b) opening angle in the transverse plane between leading lepton and missing transverse momentum, (c)/(e) missing transverse momentum and (d)/(f) transverse mass are shown in the third top control region (no m_T^W and E_T^{miss} cuts, at least one b-jet). In (c)/(e) and (d)/(f), respectively, only the range shown on the x-axis is different.

As seen in the distribution of the number of b-jets in the second region in Fig. 7.4d a fairly large fraction of the non-top-background should be cut away by the b-jet requirement. As expected, also the diboson background gets reduced significantly, since there is not necessarily a bottom quark present in this process. The $t\bar{t}$ purity increases up to 92.3% and basically the whole remainder is covered by single top events. Also for this region, an excellent MC-data agreement can be observed. The statistical and systematic uncertainties cover the small deviations while the uncertainty band is slightly larger than in the regions shown before because of the additional systematic uncertainty due to the b-tagging.

In summary, it can be concluded that the dileptonic $t\bar{t}$ background is modeled very well. There is an excellent MC-data agreement in all three considered regions. All deviations, which are in the order of a few percent, are covered by the considered experimental and theoretical systematic as well as statistical uncertainties.

7.1.1. Theoretical systematic uncertainties on the $t\bar{t}$ process

Systematic uncertainties for the theoretical modeling of the $t\bar{t}$ process are taken into account. These are obtained by simulating this process in another generator or by varying some parameters in the simulation. As stated in Sec. 4.2, the simulation is divided into a matrix element calculation and showering/hadronization step. For both, an alternative simulation is done using the following generators and the difference in the event yield is taken as an one-sided systematic uncertainty.

- Matrix element: POWHEG-BOX $\rightarrow$ MADGRAPH 5 [39]
- Showering: PYTHIA 8 $\rightarrow$ HERWIG 7 [40]

The alternative simulations are based on an Atlfast-II [41] simulation (AF2), which has a faster and less detailed detector simulation than the full simulation (FS) in GEANT4. To compensate for the difference between FS and AF2, scale factors are calculated in each bin by calculating the ratio of FS to AF2 of the nominal POWHEG-BOX+PYTHIA 8 generators. These SFs are then applied to the systematic AF2 samples.

Further systematic uncertainties are considered for initial and final state radiation (ISR/FSR) as well as the factorization scale μ_F and the renormalization scale μ_R , which are varied independently in the calculation of the $t\bar{t}$ MC. Lastly, an uncertainty for the impact of the used parton distribution function is evaluated by taking one hundred variations of the nominal NNPDF3.0NLO PDF [6] into account. A single, symmetric uncertainty is obtained by calculating the RMS of the distribution of the one hundred variations per bin. No systematic uncertainty for the top mass is considered.

The impact of the theoretical systematic variations on the nominal $t\bar{t}$ sample in the top CR, exemplarily for the second region, is shown in Fig. 7.8 binned in the transverse mass. A larger binning than in the m_T^W distributions shown before (see e.g. Fig. 7.5f) is used in order to reduce statistical effects and focus on the systematic uncertainties only. Nevertheless, some statistical fluctuations are still visible in Fig. 7.8a and Fig. 7.8c. In general, the theoretical systematic uncertainties on the $t\bar{t}$ MC are in the order of a few percent and increase up to around 10% in the very high mass tail. The RMS of the

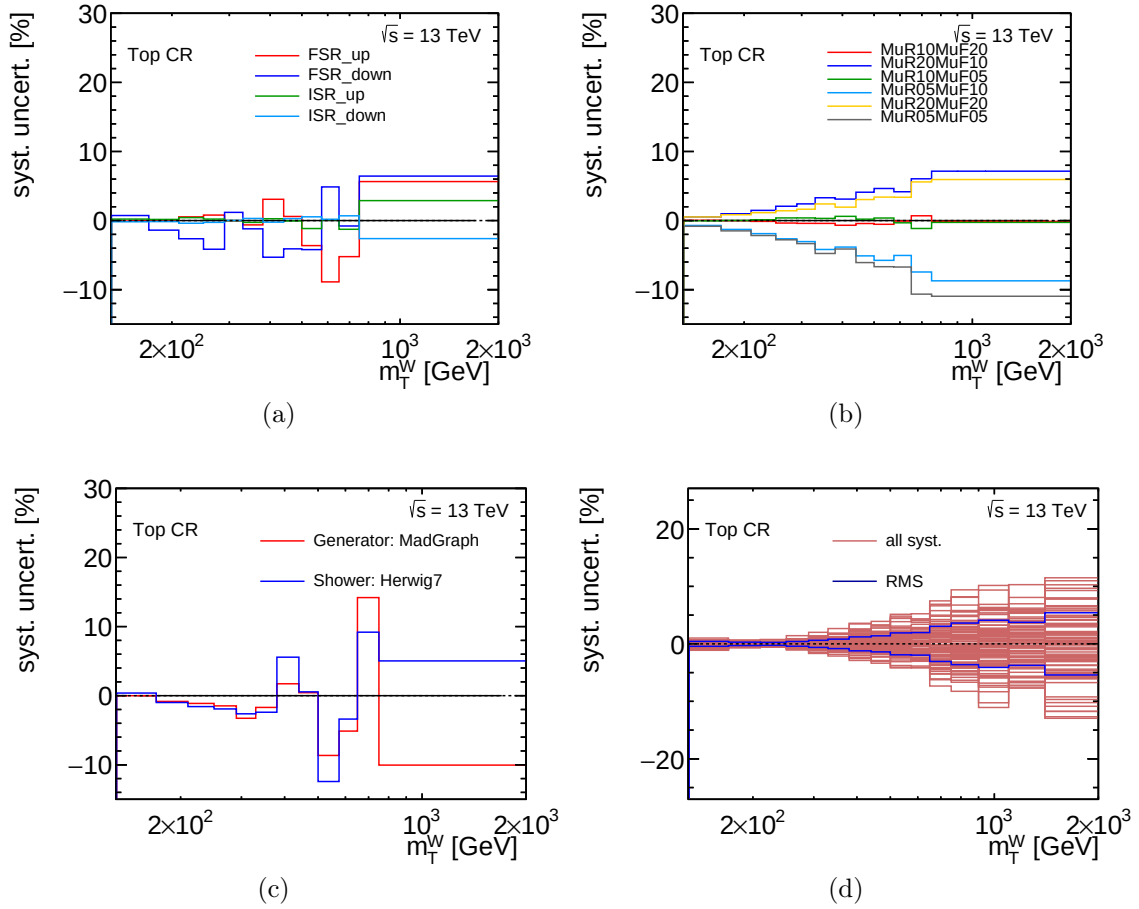


Figure 7.8.: Theoretical systematic uncertainties in the $t\bar{t}$ MC associated with (a) initial/final state radiation and (b) the renormalization and factorization scale shown in the second top control region. In (c) alternative generators for the matrix element and showering are used and in (d) 100 variations of the used PDF.

PDF variations is given by the blue line in Fig. 7.8d and shows a maximum uncertainty of around 5 %. Overall, the theoretical systematic uncertainties on the $t\bar{t}$ MC are of a size that can be expected from previous analyses.

7.2. Charge asymmetry in Z+jets background

The Z+jets background is given by the neutral-current Drell-Yan process where the Z boson decays into a lepton pair. A contribution from this two lepton final state to a single muon signature is given if the second lepton is not reconstructed, e.g. due to measurement inefficiencies in the detector. The goal of this thesis is a differential cross section measurement separated per charge, hence a distinction between a final state consisting of a μ^+ or a μ^- is made. Naively, one would expect no difference in the

Z+jets background between the two charges, since the muons are produced in pairs of opposite charge and the detector should yield the same measurement efficiency for both charges. However, in fact, a charge asymmetry in this process is visible throughout this analysis and discussed in the following.

A comparison between the event yields in the signal region for the two charges for the Z+jets process is shown in Fig. 7.9a. Substantially more events with a positively charged muon in the final state than with a negative one can be observed. The asymmetry is distributed almost over the full kinematic and detector range, exemplarily shown binned in the transverse mass of the W boson here, while more variables can be found in Fig. A.6 in the appendix. The considered Z+jets background consists, in fact, of two processes, $Z \rightarrow \mu\mu$ and $Z \rightarrow \tau\tau$, where at least one tau decays into a muon. Thus, the same comparison is made for each of these processes to see if the charge

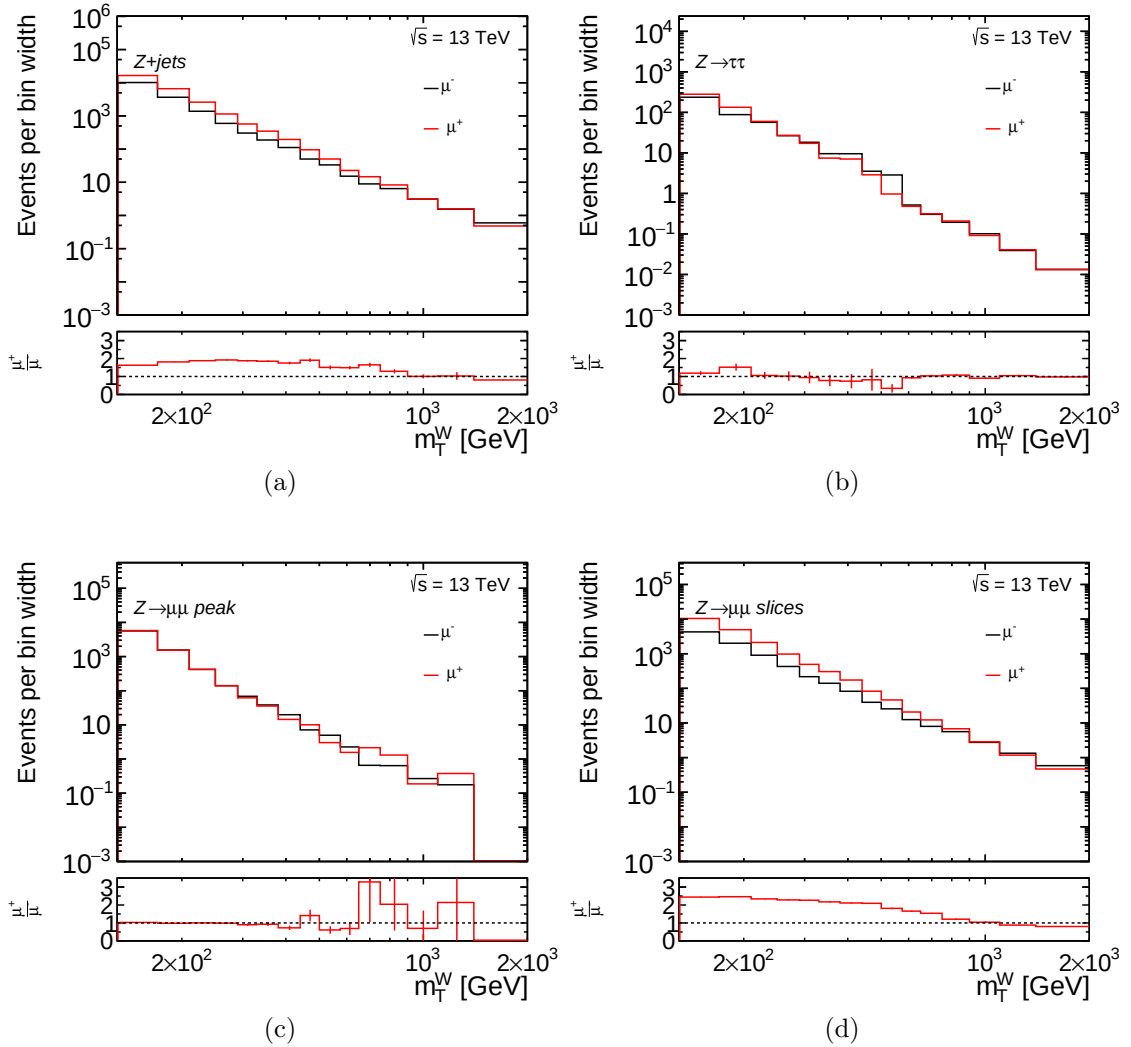


Figure 7.9.: Number of events for a μ^+ or μ^- final state as a function of the transverse mass of the W boson for different processes: (a) full Z+jets sample, (b) $Z \rightarrow \tau\tau$, (c) $Z \rightarrow \mu\mu$ inclusive sample and (d) $Z \rightarrow \mu\mu$ high mass slices.

asymmetry can be observed in both of them. As seen in Fig. 7.9b, the $Z \rightarrow \tau\tau$ process shows only a small asymmetry in the charges at low m_T^W , otherwise the μ^+/μ^- ratio is approximately at unity within statistical fluctuations. This is a clear indication that the detector yields the same measurement efficiency for both charges. Comparing the number of events shown in Fig. 7.9a with the number of events in Fig. 7.9b, it can be observed that the $Z \rightarrow \tau\tau$ background contributes only little to the full Z+jets sample. This can be explained by the two following effects. On the one hand, only a fraction of the taus decays into muons. On the other hand, the muons coming from a tau decay have a comparatively smaller energy than a muon coming from a Z decay directly and are less likely to pass e.g. the p_T cut. As discussed in Sec. 4.2, the Z+jets samples are divided into an inclusive ("peak") sample and high mass slices. The boundary between them is given at an invariant mass of 120 GeV. The charge comparison for the $Z \rightarrow \mu\mu$ process is shown for the peak sample and the high mass slices in Fig. 7.9c and Fig. 7.9d, respectively. It can be observed that the charge asymmetry does not appear in the peak sample but only in the high mass slices, where the μ^+/μ^- ratio exceeds even a factor of two.

Since the charge asymmetry can be traced back to an effect mainly in the $Z \rightarrow \mu\mu$ high mass slices, further studies in this sub-sample are made. A more general approach is followed by looking at this particular sample without the analysis-specific requirements, as presented in Sec. 6.1. Only the basic selection given in Sec. 4.1, e.g. a trigger having fired, is applied in the following. In order to minimize the effect of the trigger turn-on, the leading muon is required to have a transverse momentum above 65 GeV. Moreover, the absolute pseudorapidity is still limited to values smaller than 2.4. The following study is based exemplarily on 80000 events⁴ of the first high mass slice that covers an invariant mass range from 120 GeV to 180 GeV. No weights are used in order to see the pure number of generated MC events. A crucial difference to the main analysis' event selection is given by the fact that the additional lepton veto is not applied. Therefore, the evaluated events can be divided into three different groups.

1. Only the μ^+ is reconstructed (2717 events).
2. Only the μ^- is reconstructed (1869 events).
3. A $\mu^+\mu^-$ -pair is reconstructed (18291 events).

The cases where no muon at all or a same-sign muon pair is reconstructed are negligible. In all three defined cases, both μ^+ and μ^- coming from the Z decay can be found on the truth level. For each group, the resulting number of events on reconstruction level is given in brackets in the above enumeration. It can be seen that the largest fraction of events is given by the third case where both muons are reconstructed, as it is expected for a $Z \rightarrow \mu\mu$ sample. Moreover, already at this point, a noticeable charge asymmetry between the single muon final states is visible ($\mu^+/\mu^- = 1.46$). In order to understand this charge asymmetry in the single muon final state, it is crucial to understand at which point in the reconstruction the second muon is missed. Therefore, the distribution of

⁴Before the cuts are applied. In particular, the p_T cut has a fairly large impact.

truth level⁵ muons is evaluated in the detector coordinates ϕ and η . The distributions of the azimuthal angle of the muon show the expected behavior of an even distribution within statistical fluctuations and can be found in Fig. A.5 in the appendix. However, differences between the muon charges can be observed in the pseudorapidity of the truth level muons as shown in Fig. 7.10. All distributions are normalized to unity in order to highlight shape differences. In the two single lepton final states, depicted in Fig. 7.10a and Fig. 7.10b, an analogous behavior can be observed. It is discussed exemplarily for the case where the μ^+ is reconstructed, which corresponds to Fig. 7.10a. A substantial difference in the pseudorapidity of the truth muons is visible. The largest

⁵In general, the truth level is defined as the generator level before applying detector effects in the simulation. The truth level defined here is still limited by the acceptance of the reconstructed events, i.e. only truth events where at least one of the two muons is reconstructed are considered. A study with a "real" generator level was done analogously yielding similar results as the ones presented here.

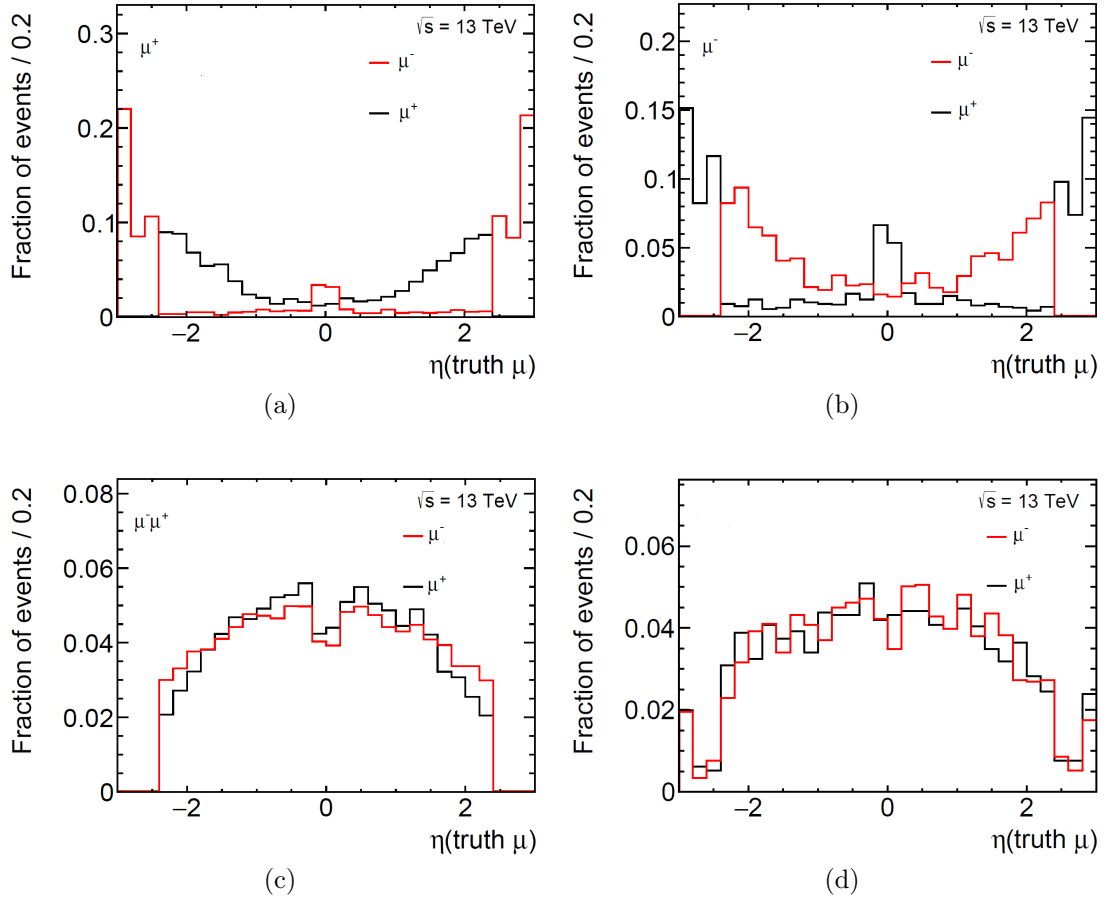


Figure 7.10.: Distribution of the pseudorapidity of the truth μ^- and μ^+ , respectively. In (a) only the μ^+ is reconstructed, in (b) only the μ^- and in (c) both muons. While (a)-(c) are based on the first $Z \rightarrow \mu\mu$ slice, (d) shows the combination of all three cases for the peak sample, in contrast.

fraction of the truth μ^- , i.e. the ones that are not reconstructed, has $|\eta| > 2.4$. As a result, these muons are not considered in this analysis, since the pseudorapidity of reconstructed muons is restricted to 2.4⁶. Thus, events with this particular signature, i.e. one muon with a pseudorapidity outside the acceptance, are the dominant source of Z+jets events considered in this analysis. The remaining single reconstructed muon has a rather large $|\eta|$, as well, because the muon pair coming from the Z decay should be approximately symmetric. Furthermore, a smaller fraction is originating from events in which the second muon is missed in other parts of the detector, for example at the very central region around $\eta = 0$, where a gap in the MS (see Sec. 3.2.4) is present. The fact that there are more μ^+ than μ^- events considered in the Z+jets background is also reflected in these distributions. Comparing the shape of the η distributions of the missed truth muon, i.e. the red line in Fig. 7.10a and the black line in Fig. 7.10b, it can be observed that the first case shows a larger fraction of events with an absolute pseudorapidity larger than 2.4. This means the μ^- is produced slightly less central than the μ^+ . In Fig. 7.10c the η distributions of the truth muons are shown in case that both are reconstructed. It can be seen even more clearly here that the μ^+ are generated slightly more central than the μ^- . The distribution of the pseudorapidity of the truth muons is shown for the peak sample in Fig. 7.10d, where a combination of all three groups is shown. Even though the test sample size is also 80000 events in the beginning, only 3265 events pass the selection applied in this study. In particular, not many events with an invariant mass below 120 GeV pass the $p_T > 65$ GeV cut. Therefore, the statistical fluctuations are substantially larger in these distributions. Nevertheless, it can be observed that the pseudorapidity is charge-symmetric for the peak sample.

Thus, in order to understand the charge asymmetry in the Z+jets sample, the origin of the difference in the η distributions per charge in the high mass slices is left to explain. It can be attributed to a physics effect happening at collider experiments, namely the forward-backward asymmetry, as discussed in detail in [42]. This asymmetry arises due to the fact that the coupling of a fermion to a Z boson has a vector and an axial-vector component. As a result, the differential cross section for the production of a forward muon, i.e. $\cos\theta > 0$, is different from the one of a backward muon, i.e. $\cos\theta < 0$. By this, also an asymmetry between left-handed particles and right-handed anti-particles is introduced. Thus, a difference between the polar angle distributions, and correspondingly pseudorapidities, of the μ^+ and μ^- can be understood. As shown in Fig. 6 in [42], the magnitude of the forward-backward asymmetry depends on the invariant mass of the lepton pair. It is shown that the asymmetry A_{FB} is around zero at the Z mass peak and increases with the mass⁷. This explains the fact that the charge asymmetry is only visible in the Z+jets high mass slices but not in the peak sample. Only at this invariant mass threshold of 120 GeV, which separates peak sample and high mass slices, the forward-backward asymmetry is sufficiently large to

⁶It can be shown that $\Delta R(\mu_{reco}, \mu_{truth}) < 0.05$ for basically all events, i.e. the pseudorapidity of the truth and reconstructed muon can be assumed to be approximately the same.

⁷This paper and figure is based on events with $\sqrt{s} = 7$ TeV. Even though a difference for $\sqrt{s} = 13$ TeV pp collision is expected, a generally similar shape can be assumed.

have a substantial effect on the η distributions per charge and, as a result, the number of events in the single muon final state.

7.3. Estimation of the multijet background

The multijet background, also called fake lepton background, consists of fake muons that originate from a heavy flavor decay inside a jet, opposed to real muons that are prompt from a W/Z boson decay. In general, fake muons are expected not to be isolated due to their jet origin and, hence, should not pass the isolation criterion of a tight signal muon. Nevertheless, there is still a fraction of fake muons fulfilling the tight level which is estimated data-driven via the Matrix Method (as presented in [43]). After a short theoretical overview of this method, the calculation of the, for this method important, real and fake efficiencies is discussed. From these, the multijet background is estimated and two control regions are presented.

An important aspect is that the particular step in the overlap removal (see 5.5) where a muon is rejected for a jet is not applied in this analysis. Otherwise, a lot of fake muons, which are obviously close to a jet, would be removed already during the overlap removal and could not be used for the fake background estimation.

7.3.1. Matrix Method

The Matrix Method is a data-driven method, i.e. the event yield of the process to be estimated is obtained from measured data. It gives an estimation of the multijet background, which consists of "fake" muons, which are among the decay products in jets and not modeled properly in the MC. Opposed to that, "real" muons originate directly from a W/Z boson and are estimated via MC simulations. The basic idea of the Matrix Method is given by lowering some identification and isolation criteria to get two levels. In this case, these are the tight and loose level as defined in Sec. 6.1. A matrix provides the connection between the number of real/fake muons (N_R/N_F) and the number of loose/tight muons (N_L/N_T), as seen in the following equation.

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_R & \epsilon_F \\ 1 - \epsilon_R & 1 - \epsilon_F \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix} \quad (7.1)$$

Since N_R and N_F are orthogonal, the left-hand vector has to fulfill this criterion as well. Thus, N_L denotes the number of events that fulfill the loose level but fail the tight level. Important measures are the two efficiencies ϵ_R and ϵ_F . The real efficiency ϵ_R corresponds to the fraction of events where a real, loose level muon fulfills the tight criteria, analogously for the fake efficiency ϵ_F .

$$\epsilon_{R/F} = \frac{N_{R/F}^T}{N_{R/F}^L} \quad (7.2)$$

In this case, $N_{R/F}^L$ is defined by the full loose level, i.e. all events that fail or pass the tight level are included, in order to get a correct definition of an efficiency, i.e. the numerator is, in fact, a subset of the denominator. With this definition, it can be seen clearly that the number of tight muons is given by the number of real muons multiplied by the real efficiency plus the number of fake muons multiplied by the fake efficiency. This is just given by the first line of the matrix defined above.

$$N_T = \epsilon_R N_R + \epsilon_F N_F \quad (7.3)$$

However, the truth quantities N_R/N_F are not accessible in the data but the numbers of tight and loose level muons are. Hence, an equation for the calculation of the number of fake muons is obtained by inverting the matrix.

$$\begin{pmatrix} N_R \\ N_F \end{pmatrix} = \frac{1}{\epsilon_R(1 - \epsilon_F) - \epsilon_F(1 - \epsilon_R)} \begin{pmatrix} 1 - \epsilon_F & -\epsilon_F \\ \epsilon_R - 1 & \epsilon_R \end{pmatrix} \begin{pmatrix} N_T \\ N_L \end{pmatrix} \quad (7.4)$$

The interesting part is the number of fake muons that pass the event selection of this analysis, i.e. in particular the tight level. This is given by the following.

$$\epsilon_F N_F = \frac{\epsilon_F}{\epsilon_R - \epsilon_F} [\epsilon_R(N_L + N_T) - N_T] \quad (7.5)$$

Summarizing, the important measures in order to get an estimation of the fake background are the number of loose/tight events in the data as well as the real and fake efficiencies. A crucial part of the Matrix Method is to get a good estimate of those two efficiencies. They are calculated from data and MC and are typically estimated binned in a certain variable in a special region that is designed to enrich real/fake muons. In practice, it is assumed that these efficiencies can be transferred to the signal region by calculating an event weight per bin, which is based on whether an event passes the tight level.

$$w_{MM}^T = \frac{\epsilon_F(\epsilon_R - 1)}{\epsilon_R - \epsilon_F} \quad (7.6)$$

$$w_{MM}^L = \frac{\epsilon_F \epsilon_R}{\epsilon_R - \epsilon_F} \quad (7.7)$$

The weight w_{MM}^T is applied to data events that pass the tight level (set $N_T = 1$, $N_L = 0$ in eq. 7.5), while w_{MM}^L is applied to events that pass the loose level but fail the tight level ($N_T = 0$, $N_L = 1$).

7.3.2. Real efficiency

The real efficiency is defined as the efficiency for a real, loose level muon to pass the tight level. Here, both levels as defined in Sec. 6.1 are used. Thus, the only difference between the levels is the additional isolation requirement in the tight level. This ensures that the tight level is indeed a subset of the loose level, which is indispensable for a correct estimation of an efficiency. A region that is dominated by real muons is defined

in order to get a good estimate of the real efficiency. For this, the $W \rightarrow \mu\nu$ MC is used, since the signal process contains mostly real, prompt muons. To ensure the muon originates, in fact, from a W decay a truth matching is applied. This means that the angular distance between the measured and generated muon must not exceed a certain threshold, here $\Delta R(\mu_{reco}, \mu_{truth}) < 0.1$. For the calculation of the real efficiency, the p_T cut is lowered to 30 GeV with respect to the selection in Sec. 6.1, the E_T^{miss} and m_T^W cuts are omitted. Moreover, only the high mass slices of the signal MC are considered (see appendix A.1 for more information on this).

The estimation of the real efficiency is done as a function of certain variables. In the following, the procedure of calculating a real efficiency is explained exemplarily for a binning in p_T . At first, two histograms are created with the cuts and requirements applied as discussed above. In one case, the muon has to fulfill the loose level, in the other case the tight level. The binning of both histograms is the same, thus they can be divided by each other by taking the quotient tight over loose per bin, yielding the real efficiency according to equation 7.2. This is shown in Fig 7.11a, binned in the transverse momentum of the muon. It can be observed that the real efficiency is overall very close to unity, i.e. above 99 % in every bin except for the first one. This very high efficiency is expected, since most real muons, which are coming from the W decay, are expected to be isolated and, hence, pass the tight criterion as well. An increase of the real efficiency for larger transverse momenta is visible. Furthermore, a dependency on the pseudorapidity of the muon is observable, as Fig. 7.11b depicts. Here, the real efficiency decreases for large absolute values of η . However, it should be noted that the dependency on both variables is on a very small scale. In order to cover both dependencies in the estimation of the multijet background, a two-dimensional binning of the real efficiency is chosen, which can be seen in Fig. 7.12. The binning in p_T and $|\eta|$ was adjusted to get, on the one hand, an appropriate representation of the dependencies and, on the other hand, retain sufficiently good statistics in each bin. Therefore, e.g. the last p_T bin is rather large, ranging from 200 GeV to 2000 GeV. Since the region with p_T below 65 GeV is not part of the signal region, it is sufficient

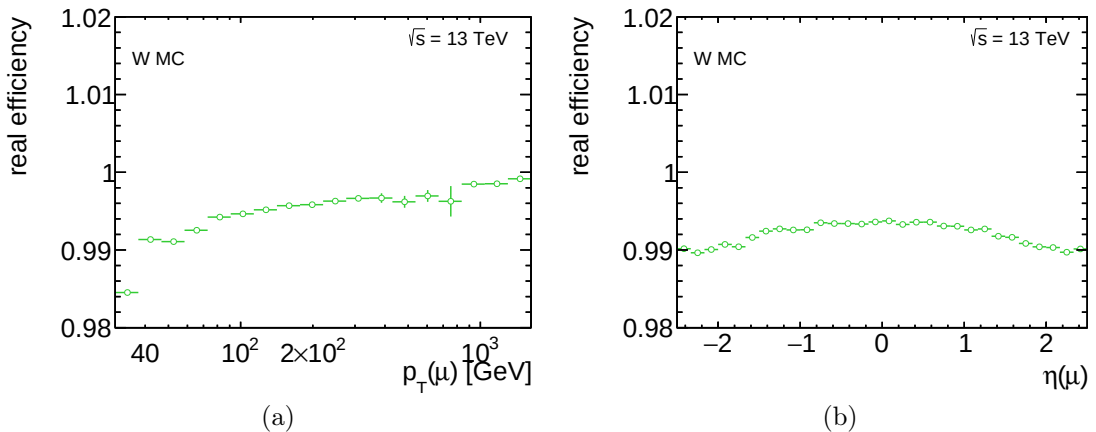


Figure 7.11.: One-dimensional real efficiency binned in the (a) transverse momentum and (b) pseudorapidity of the muon.

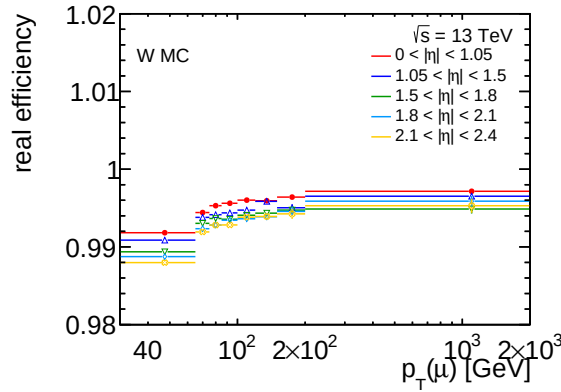


Figure 7.12.: Two-dimensional real efficiency binned in the transverse momentum and pseudorapidity of the muon.

to use only one bin there, which is shown here mainly for completeness. The binning in $|\eta|$ is partly motivated by the architecture of the MS, e.g. at $|\eta| = 1.05$, there is the transition from the barrel to the end-caps. Starting from $|\eta| = 1.5$, an equidistant binning in $|\eta|$ is chosen in order to represent the stronger dependency in this region appropriately. The same binning for the real and the fake efficiency, which is discussed below, is chosen in p_T and $|\eta|$ and an optimization of the binning is done with respect to both efficiencies.

7.3.3. Fake efficiency

The calculation of the fake efficiency, i.e. the efficiency for a fake, loose muon to fulfill the tight level, is not as straight-forward as the calculation of the real efficiency. The reason for this is that, in contrast to real muons, fake muons are not modeled properly in MC. Thus, measured data is used in order to estimate the fake efficiency, which makes it one of the data-driven parts of the Matrix Method. Analogously to the calculation of the real efficiency, a region that is enriched in fake muons is defined, at first. Since the fake muons originate from jets, in particular from heavy flavor decays within these, their production is based on QCD interactions. Hence, the following region is referred to as QCD enriched region. It is designed in order to have a substantially larger contribution of fake muons than the signal region defined in Sec. 6.1. The following changes are made with respect to it.

- Inverting the E_T^{miss} cut: $E_T^{\text{miss}} < 65 \text{ GeV}$,
- Lowering of the $p_T(\mu)$ cut to $p_T > 30 \text{ GeV}$,
- Applying no m_T^W cut,
- Requiring at least one jet with $p_T(j) > 40 \text{ GeV}$ and $\Delta R(j, \mu) > 0.2$,
- Requiring an absolute d_0 significance greater than 1.

The cut on E_T^{miss} ensures that the QCD enriched region is orthogonal to the signal region. An additional jet is required in order to enrich a dijet topology, which is a dominant source of fake muons. This jet must not overlap with the fake muon, i.e. $\Delta R(j, \mu) > 0.2$, to ensure there are in fact two jets, the one where the fake muon originates from and an additional one. Lastly, a cut on the significance of d_0 is placed in order to enrich events in which the muon is not prompt. Since the definition of this QCD enriched region is to a certain degree arbitrary, variations of the definition are performed and considered in the form of systematic uncertainties, as presented in Sec. 10.1.6.

Even though the definition of this region leads to a substantially higher fraction of fake muons in the data, there is still a non-negligible fraction of real muons present, which needs to be subtracted to get an estimate of the pure fake efficiency. All these real muons are expected to be well-modeled in the simulation, thus the elimination is covered by subtracting the MC from the data. The remaining muons in the data can then be identified as fake muons. The procedure of subtracting is depicted exemplarily in Fig. 7.13 for a tight level histogram binned in the pseudorapidity of the muon⁸. A substantial disagreement between MC and data can be observed in Fig. 7.13a, which is due to the enrichment of fake muons in the QCD region. The fraction of real muons, given by the MC, and fake muons, given by the difference between MC and data, is shown in Fig. 7.13b. This subtraction is done for a tight and a loose WP each and the histograms of the remaining fake muons are divided by each other bin-by-bin per variable to get the fake efficiency.

The fake efficiency as a function of the transverse muon momentum is shown in Fig. 7.14. It can be observed that the fake efficiency varies a lot over the whole

⁸Analogous MC data histograms of the pseudorapidity and transverse momentum of a loose/tight level muon in the QCD enriched region can be found in Fig. A.13 in the appendix.

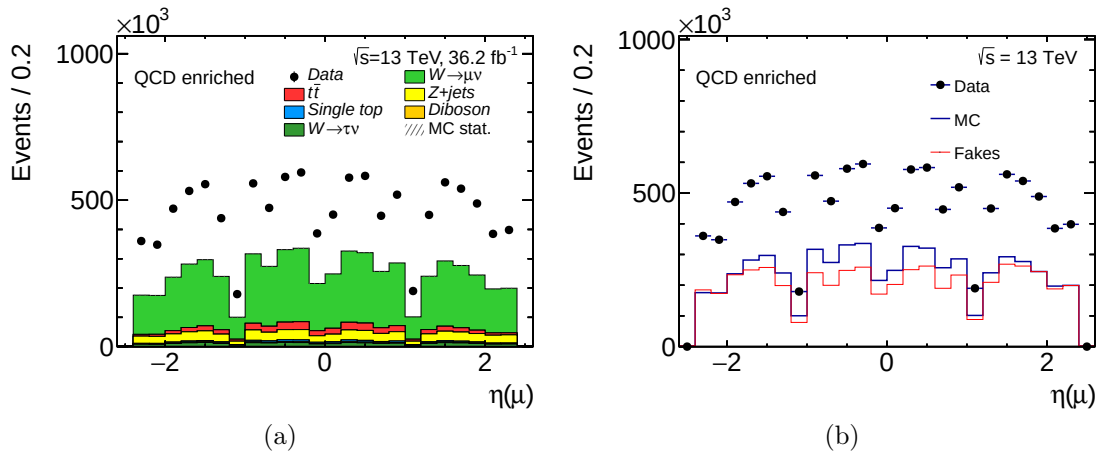


Figure 7.13.: (a) Distribution of the pseudorapidity of a tight level muon in data and MC in the QCD enriched region. (b) The number of real and fake muons in the data, where the real muons are represented by the events modeled in the MC and the fake muons by the difference between MC and data.

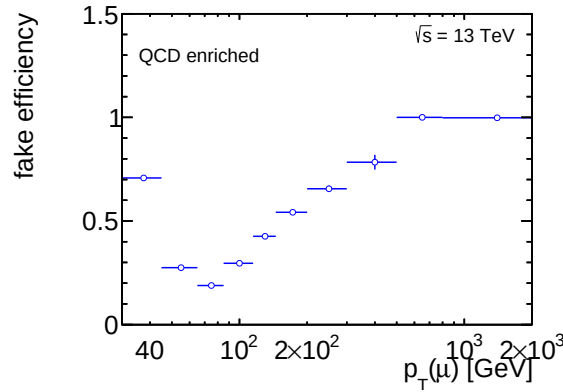


Figure 7.14.: One-dimensional fake efficiency binned in the transverse momentum of the muon.

p_T spectrum, it is e.g. at around $\epsilon_F = 0.2$ at $p_T = 65$ GeV and consecutively rises to unity. The fact that the fake efficiency remains exactly at unity in the last two bins is not due to a physical but a statistical effect. In the region of such high momenta, only a few events are left and, in particular in these two bins, only one event per bin. In this single event, the muon happens to fulfill the loose and the tight level, resulting in an efficiency of exactly one. This is, of course, not statistically significant, hence the p_T binning is adjusted in the following. Another striking aspect can be observed in the region of low p_T where a harsh decline of the efficiency at $p_T = 50$ GeV can be observed. This can be explained by the change of muon triggers at exactly this transverse momentum. As stated in Sec. 4.1, an ‘or’ between the HLT_mu50 and the HLT_mu20_loose_L1MU15 (HLT_mu26_ivarmedium) trigger is used for data taken in 2015 (2016). The former is dominating for transverse momenta larger than 50 GeV, while it does not yet trigger for lower values. The alternative two triggers are used in this region. However, they have an isolation in their definition already. As a reminder, the isolation is the discriminant criterion between the loose and tight level. Due to this requirement in the trigger, loose level muons are already isolated, which leads to a reduced difference between the two levels and, as a result, an increased fake efficiency. However, the region of low transverse momenta where this issue is visible is not part of the signal region due to the $p_T > 65$ GeV requirement.

Further dependencies of the fake efficiency are visible in the pseudorapidity of the muon as well as the angle in the transverse plane between the muon and missing transverse momentum. These are shown in Fig. 7.15 in a two-dimensional binning. The dependencies are shown for three different p_T bins each because a strong dependency of the fake efficiency on p_T is present, as discussed above. In addition, the distribution of p_T is strictly falling and one integrated bin over the full range would be dominated by events with low transverse momenta, e.g. with $p_T < 65$ GeV. This is, however, exactly the region that is not of interest in the main analysis. Therefore, the lowest p_T bin in these plots is chosen to range from 30 GeV to 65 GeV. The remaining p_T spectrum is divided into two bins, but, in principle, a similar behavior can be observed in both. The main differences are that in the last p_T bin the fake efficiency is overall larger and has less statistical significance, due to the two effects discussed

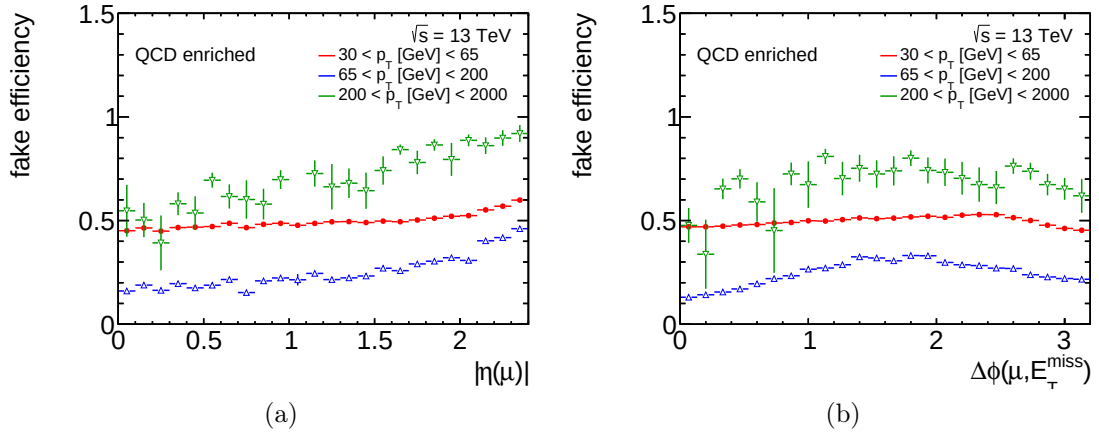


Figure 7.15.: Two-dimensional fake muon efficiency binned in the transverse momentum of the muon and (a) the pseudorapidity of the muon or (b) the azimuthal angle between muon and missing transverse momentum.

above. In general, the fake efficiency increases with a larger absolute pseudorapidity of the muon, in particular starting at around $|\eta| = 1.5$, as it can be seen in Fig. 7.15a. Moreover, it can be observed in Fig. 7.15b that the fake efficiency decreases for small and large azimuthal angles between muon and E_T^{miss} and is the largest at intermediate values around $\Delta\phi(\mu, E_T^{\text{miss}}) = \pi/2$. While the plots shown above have the purpose to present and understand all dependencies of the fake efficiency, the final binning is three-dimensional in p_T , $|\eta|$ and $\Delta\phi(\mu, E_T^{\text{miss}})$, as shown in Fig. 7.16. Just like for the real efficiency, a compromise between enough bins to describe all dependencies and sufficient statistics per bin had to be made. In the region of low p_T , the binning is finer, whereas one large bin for the high p_T region starting at 200 GeV is chosen. The dependency in $\Delta\phi$ is represented by six equidistant bins with each bin corresponding to one plot in Fig. 7.16. Each line per plot represents one $|\eta|$ bin while the binning in both, p_T and $|\eta|$, equals the one shown for the two-dimensional real efficiency.

Lastly, a crucial aspect to look at when dealing with fake muons is the overlap removal (see Sec. 5.5), which is discussed in the following. Most analyses use a standard OR where all objects measured in the ATLAS detector are compared subsequently. In particular, there is one step comparing a muon and jet. However, the particular step where a muon is rejected for a jet is removed throughout this whole analysis. This is essential because the evaluated fake muons are muons that originate from jets, thus are most likely close to a jet. Therefore, a high fraction of fake muons would normally be already eliminated by the overlap removal. In the signal region, an isolated muon is required, thus the removal of this step does not have a substantial impact. However, in the QCD enriched region, where the fake efficiency is calculated, this removal is crucial in order to enrich fake muons and get an appropriate estimation of them. In comparison, the fake muon efficiency with the full overlap removal being applied is shown in Fig. 7.17.

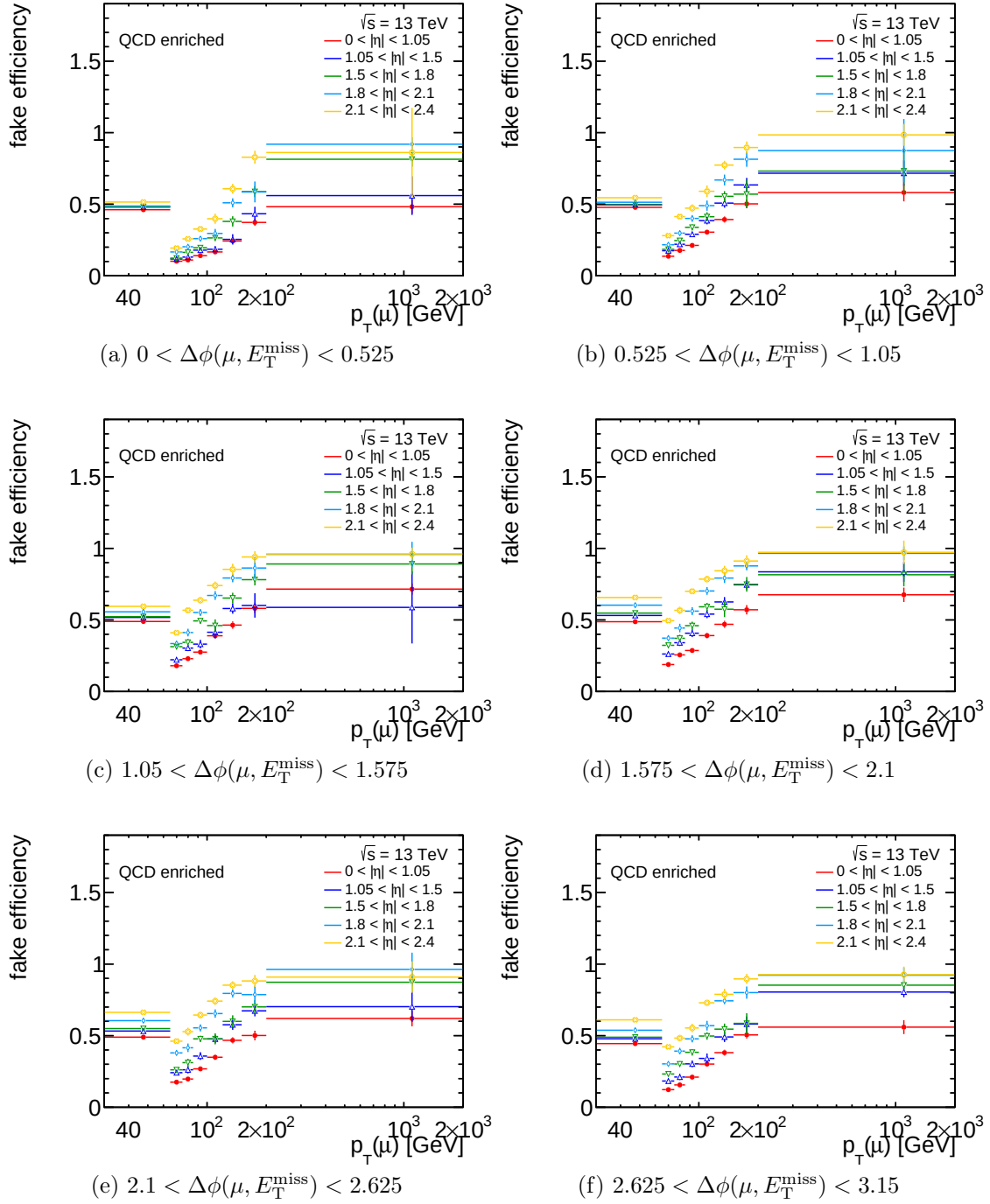


Figure 7.16.: Three-dimensional fake muon efficiency binned in the transverse momentum and pseudorapidity of the muon as well as the azimuthal angle between muon and E_T^{miss} . Each plot (a)-(f) corresponds to one $\Delta\phi$ bin where the fake efficiency as a function of p_T is shown. The $|\eta|$ bins are represented by different lines per plot.

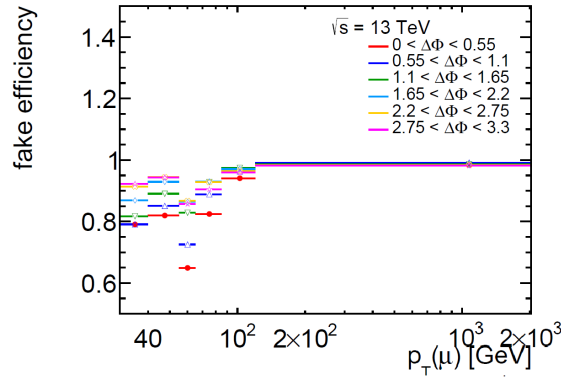


Figure 7.17.: Two-dimensional fake efficiency binned in the transverse momentum of the muon and the azimuthal angle between muon and E_T^{miss} . Here, the full overlap removal is applied, in contrast to the rest of the analysis where the step of removing a muon for a jet is omitted.

Here, different working points⁹ with respect to the final event selection, as presented in Sec. 6.1, are used. Even though the binning is two-dimensional in p_T and $\Delta\phi(E_T^{\text{miss}}, \mu)$ only, it is still very clearly noticeable that the fake efficiency is substantially higher than the one used in the analysis, as depicted in Fig. 7.16. In particular, the efficiency is already very close to unity at $p_T = 100$ GeV. The high efficiency can be explained by the fact that a high fraction of the loose, i.e. non-isolated, fake muons are already eliminated by the OR. The fake muons that pass the OR are not as close to the jet and, hence, are likely to pass the tight level as well. In the Matrix Method, there is a division by the difference of the real and fake efficiency, as seen in equation 7.5. The method possibly collapses with such high fake efficiencies, since a singularity might occur if the fake efficiency equals the real efficiency (which is also very close to unity). Thus, the removal of this particular step of the overlap removal was indispensable to achieve an appropriate estimation of the multijet background.

7.3.4. Closure region

In order to validate whether the fake muon background is well-estimated, a multijet closure region is defined. It is intended to be close to the QCD enriched region where the fake muon efficiencies are calculated. Hence, the E_T^{miss} cut is inverted and the m_T^W cut omitted with respect to the signal region. Prediction and data are compared in order to see whether the calculated multijet background, together with the MC simulation of all other processes, describes the data well. The multijet background is estimated via the Matrix Method using the multi-dimensional real and fake efficiencies as depicted in Fig. 7.12 and Fig. 7.16. Distributions of the most important variables are shown in Fig. 7.18 including a data over prediction ratio.

⁹Tight level: Medium quality and FCTightTrackOnly_VarRad isolation, loose level: Loose quality and no isolation.

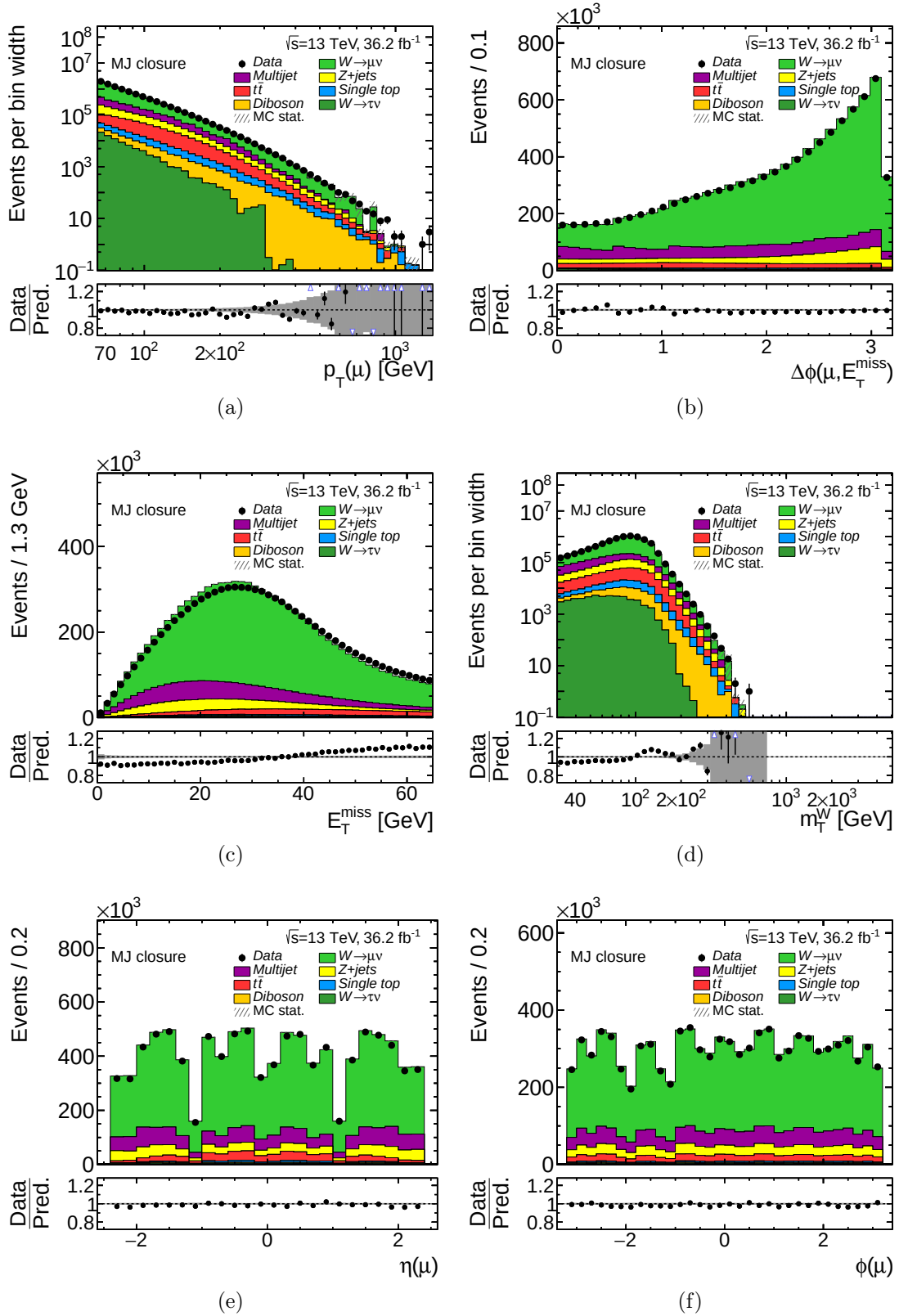


Figure 7.18.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon are shown in the closure region (inverted E_T^{miss} cut and no m_T^W cut).

The uncertainty band includes the statistical uncertainty only. In the following plots, the combination of μ^+ and μ^- final states is shown. However, analogous MC-data comparisons separated per muon charge can be found in Fig. A.14 and Fig. A.15 in the appendix. Looking at Fig. 7.18a, it can be observed that the ratio is quite close to unity over the whole range of the muon transverse momentum while the statistical uncertainty becomes predominant above a few hundred GeV. It is striking that the binning used to calculate the fake efficiency is visible in form of periodic fluctuations in the ratio. At the moment, only data taken in 2015 and 2016 is used and it is statistically not possible to choose a finer binning for the dependencies of the fake efficiency. The same effect can be seen even more clearly in the distribution of the azimuthal angle between muon and missing transverse momentum in Fig. 7.18b, in particular at $\Delta\phi(\mu, E_T^{\text{miss}}) < 1$. Another important variable is the missing transverse momentum, which is depicted in Fig. 7.18c. Here, a disagreement between the data and the prediction can be observed in the form of an overestimated prediction at low E_T^{miss} , up to around 40 GeV. For higher values, the data over prediction ratio increases up to around 1.1. A similar behavior is visible in the distribution of the transverse mass. This disagreement for E_T^{miss} values starting at around 40 GeV is known from other analyses, for example the search for a W' boson [43], but still can not be explained in detail. However, the disagreement between data and prediction in this region is expected to arise from the modeling of the missing transverse momentum, in particular the soft term. The fact that the ratio is below unity in the low E_T^{miss} region, or low m_T^W respectively, can be explained by the construction of the Matrix Method. Since real data and MC are used in the calculation, the multijet background is constructed such that in the integral over the full kinematic range the data over prediction ratio should be at unity¹⁰. Because of the known feature of too few predicted events in the higher E_T^{miss} region, there are too many events in the low E_T^{miss} region per construction. This feature is reflected in the distribution of the pseudorapidity and azimuthal angle of the muon, as well, which are shown in Fig. 7.18e and Fig. 7.18f. In these plots, the ratio is approximately at unity over the full range within some minor fluctuations. When looking at these two distributions, some sharp decreases in the number of events are visible, e.g. at $\eta = 0$ or $\phi \approx -1$. In these narrow regions, muons can not be measured with full efficiency because of the architecture of the ATLAS detector, i.e. its feet and services as well as in the transition region between barrel and end-caps at $|\eta| = 1.05$ interrupt the detecting material (see Sec. 3.2.4).

7.3.5. Validation region

In addition to the multijet closure region discussed above, a validation region is defined for the purpose of validating the estimation of the fake muon background. This region is defined by omitting the E_T^{miss} and m_T^W cuts with respect to the event selection presented in Sec. 6.1. As a result, the validation region is closer to the signal region

¹⁰The closure region and QCD enriched region, in which the fake efficiency is calculated, are slightly different (e.g. the additional jet requirement in the QCD enriched region). Hence, this argumentation holds only approximately in the closure region.

and it is important that the multijet background is also well-estimated in this case. Also in this region, the prediction is compared to the data binned in different variables, as seen in Fig. 7.19. The comparisons shown here include events with both possible muon charges, whereas charge-separated comparisons can be found in Fig. A.16 and Fig. A.17 in the appendix. In general, all distributions and data over prediction ratios appear quite similar to the ones shown in the closure region. Hence, only the plots that show a clearly different behavior are discussed at this point. Since in the closure region E_T^{miss} was cut to be lower than 65 GeV, the E_T^{miss} range shown in the validation region is substantially larger, which is shown in Fig. 7.19c. It can be observed that the MC-data agreement improves again for E_T^{miss} values above 70 GeV. This means that the increase shown in Fig. 7.18c is limited to a certain range in E_T^{miss} , in fact. This is visible even more clearly in the distribution of m_T^W , as seen in Fig. 7.19d. The disagreement is limited to a m_T^W range of around 100 GeV to 200 GeV, below and above the MC-data ratio is reasonably at unity. In the end, this high mass region is the most important for the cross section measurement and a good MC-data agreement is achieved there. The fact that the deviation of the prediction from the data is limited to a certain range is also known from other analyses and, hence, agrees with the expectation.

As a conclusion from the two multijet control regions, the MC-data agreement is reasonable in both, with the exception of one known issue, probably due to the modeling of E_T^{miss} . However, this disagreement is expected not to arise from the multijet estimation. Therefore, this background can be assumed to be well-modeled by the Matrix Method.

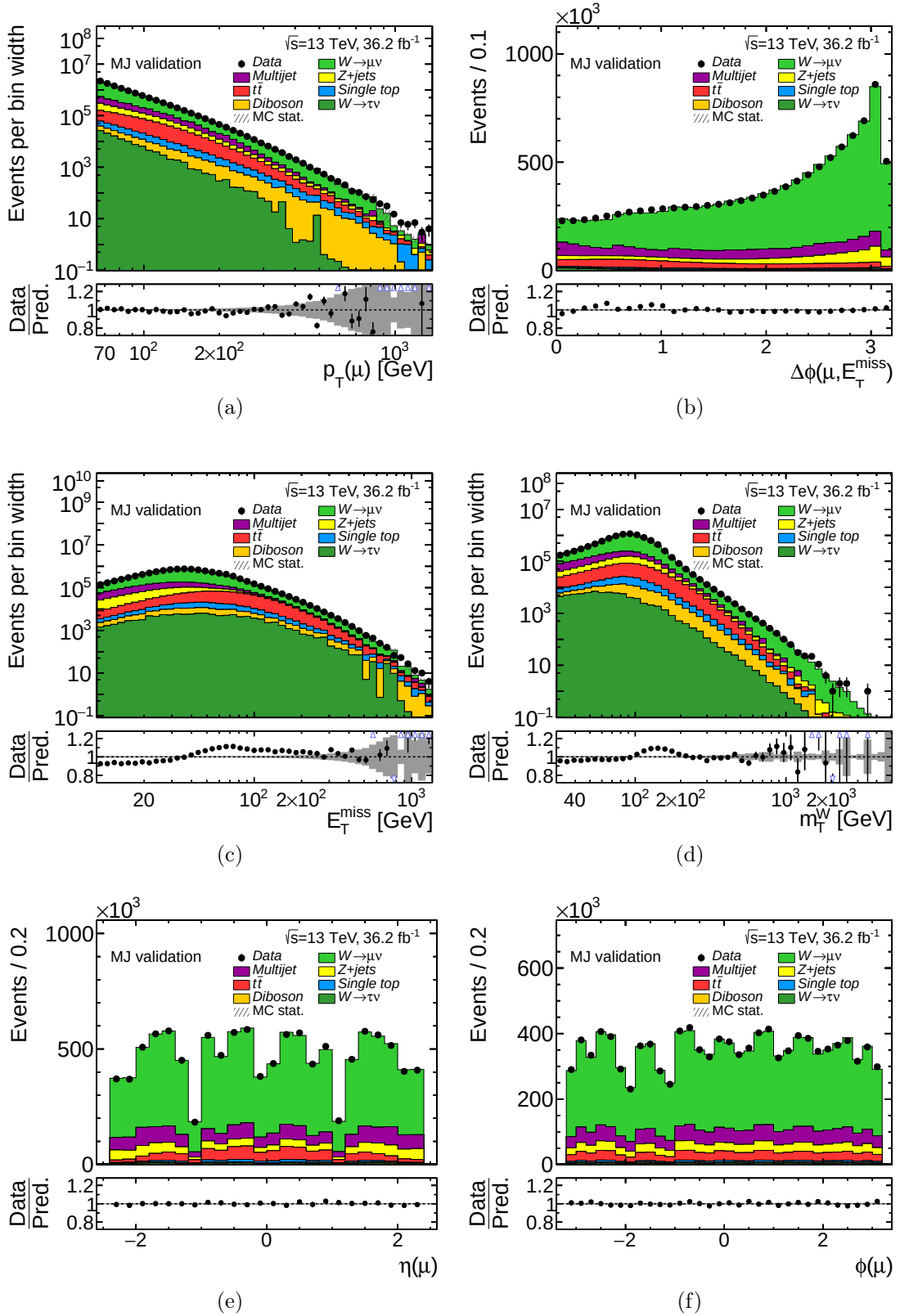


Figure 7.19.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon are shown in the validation region (no E_T^{miss} and m_T^W cuts).

8. Comparison between data and prediction in the signal region

The signal region, in which the DY cross section will be measured, is defined by the event selection presented in Sec. 6.1. It is designed in order to have sufficiently large statistics in the signal process. Other than in the control regions (see Chapter 7), a differentiation between the muon charges is made because the cross section measurement will be done separately per charge. Hence, all following plots are shown for three channels, $\mu^\pm$ combined and μ^+ or μ^- only.

Pie charts showing the contribution from all processes to the total predicted event yield are shown in Fig. 8.1. The signal process has indeed the highest fraction of events, with a contribution of approximately 70%. The largest background is given by $t\bar{t}$ events, which can be assumed to be well-modeled as presented in the top CR in Sec. 7.1. In the combination of both charges, the second largest background is given by Z+jets. The relative contribution of the Z+jets background changes slightly with charge. This can be traced back to the forward-backward-asymmetry, as discussed in Sec. 7.2. Also, the signal process is charge-dependent and more events with a positively charged muon, or

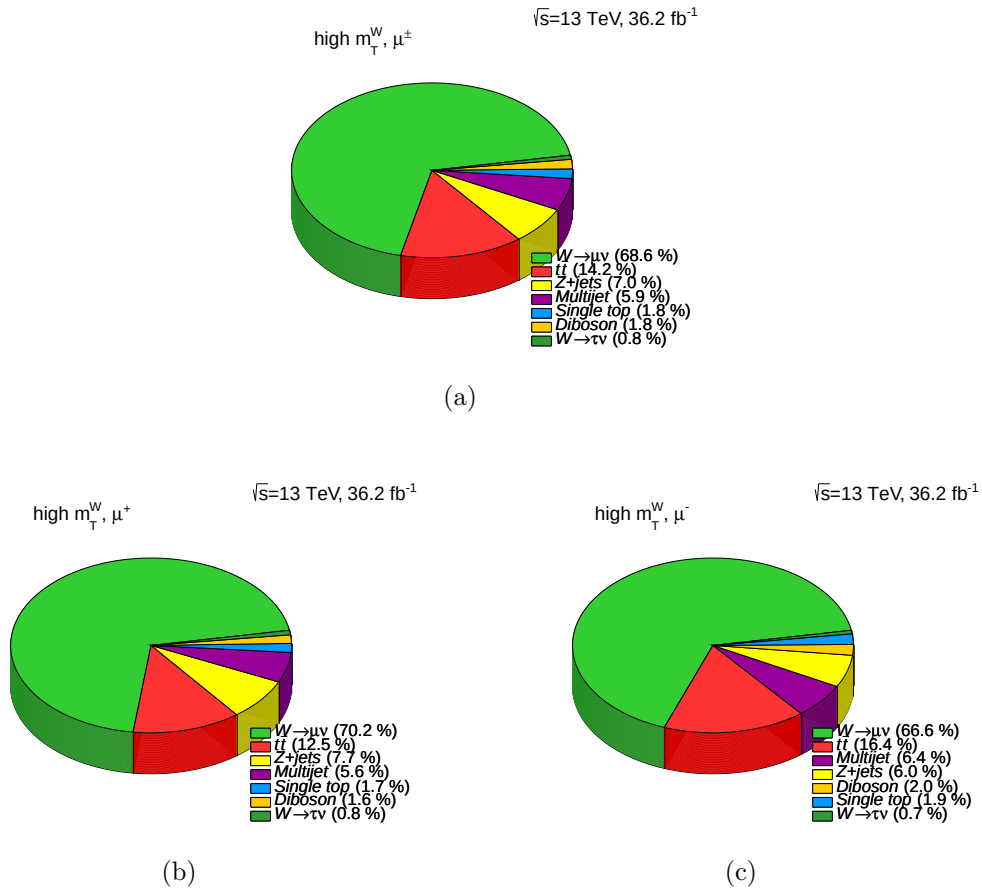


Figure 8.1.: Relative contribution of the different processes in the signal region, divided per muon charge: (a) $\mu^\pm$ combined (b) μ^+ and (c) μ^- only.

W boson respectively, are produced (this can be seen even more clearly by comparing e.g. Fig. 8.4e and Fig. 8.5e). Since other substantial backgrounds, like $t\bar{t}$, are symmetric in charge, this manifests in the relative contributions shown here. The charge asymmetry in the signal process can be understood by the production of the W boson via quark-quark interaction inside the protons: The proton contains twice as many positively charged valence quarks as negatively charged ones (up, up, down). Even though sea quarks contribute to the parton level production of the W boson as well, this asymmetry in the valence quarks propagates through to the muon final states. MC-data comparisons for the combination of both charges in the signal region are shown in Fig. 8.2 and Fig. 8.3.

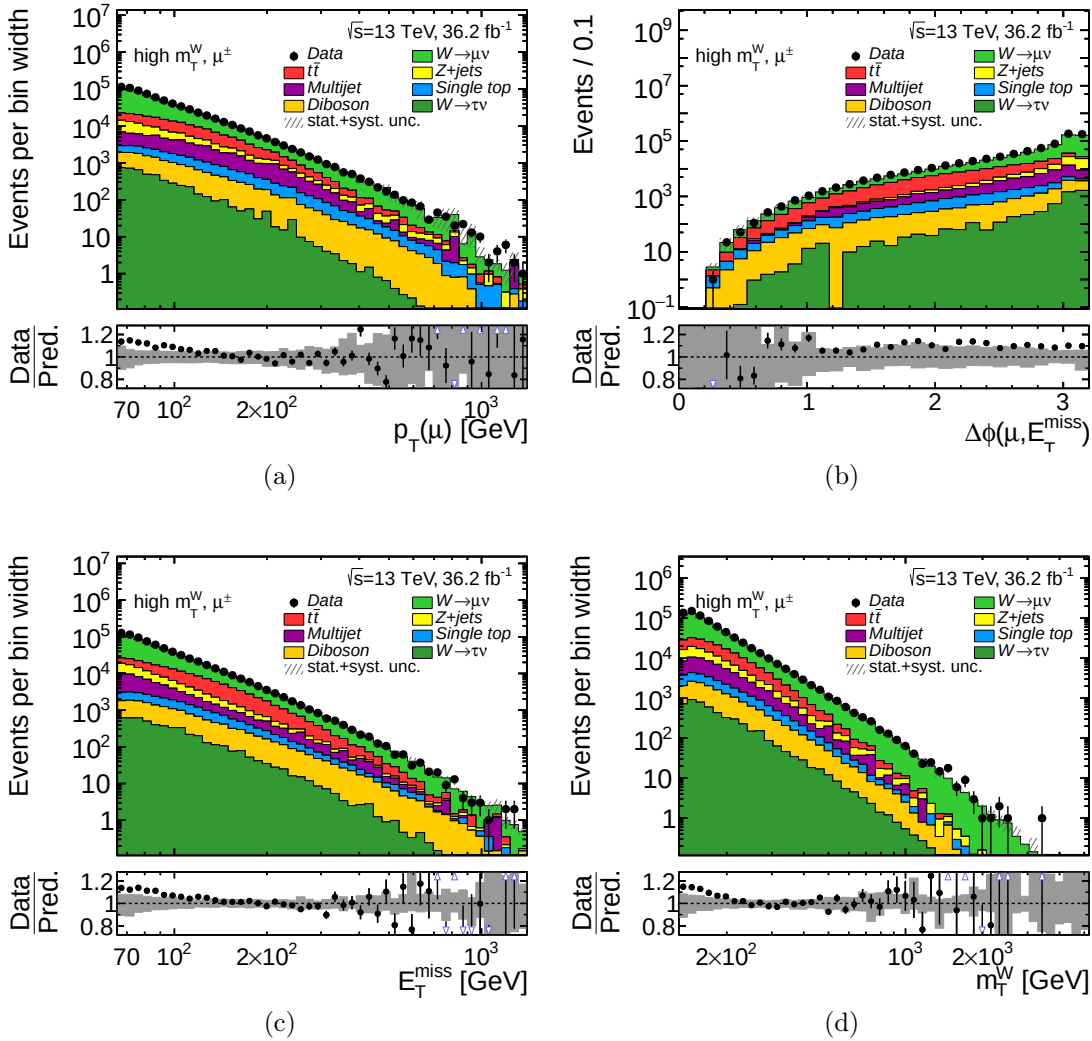


Figure 8.2.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum and (d) transverse mass of the W boson in the signal region. Statistical and systematic uncertainties are included in the uncertainty band.

Systematic and statistical uncertainties are included. Statistical uncertainties in the MC and the data are taken into account while the former are expected to be substantially smaller than the latter. Experimental systematic uncertainties are considered for the measurement of the muon, E_T^{miss} and jets in all MC processes as well as dedicated data-driven systematic uncertainties for the multijet background. Theoretical uncertainties are included for the $t\bar{t}$ background, as introduced in Sec. 7.1.1. At the moment, no systematic uncertainties for the signal process are available. A detailed breakdown of all systematic uncertainties will be given in the corresponding Chapter 10.

As depicted in Fig. 8.2, the distributions of p_T , E_T^{miss} and m_T^W are falling over many orders of magnitude, resulting in only a few events with very high energy, i.e. rather large statistical uncertainties there. Looking at the ratio between data and prediction, the agreement is reasonable for p_T and E_T^{miss} larger than around 150 GeV and m_T^W larger than 250 GeV, respectively. There is a disagreement at lower energies, which was already noticeable in the multijet closure and validation region (see Secs. 7.3.4 and 7.3.5). As a reminder, this disagreement is not fully understood but known from other analyses and expected to arise from the E_T^{miss} modeling. A larger systematic uncertainty is visible in these regions in form of the increasing uncertainty band. It will be seen in the breakdown of all systematic uncertainties in Chapter 10 that the dominant uncertainty here is due to the missing transverse momentum. Nevertheless, it can be observed in Fig. 8.2d that the systematic uncertainties do not fully cover the deviation between prediction and data at low m_T^W . However, in the region of higher energies, i.e. larger p_T , E_T^{miss} and m_T^W , the combination of statistical and systematic uncertainties covers most data points.

In Fig. 8.3, the distributions of the pseudorapidity and azimuthal angle of the muon are shown. In these, a constant offset of around 10% is visible in the ratio which is caused by the disagreement at low E_T^{miss} seen above. Since the distribution of the missing

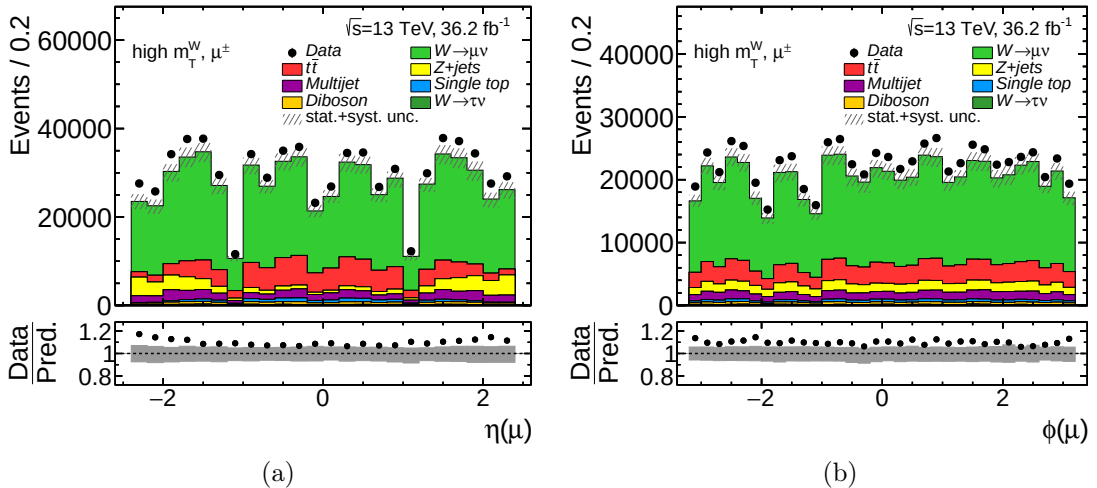


Figure 8.3.: MC-data comparisons binned in the (a) pseudorapidity and (b) azimuthal angle of the muon in the signal region. Statistical and systematic uncertainties are added in the uncertainty band.

transverse momentum is steeply falling, the events at low E_T^{miss} are dominating by far when looking at the integral. The data points in the ratio are found to be a few percent above the uncertainty band. A tendency of a worse agreement for increasing absolute pseudorapidities can be observed, in addition. All in all, the agreement between data and prediction is acceptable in the combination of both charges.

Since the cross section is measured per muon charge, the same set of MC-data comparisons can be found for the charge-separated channels in Fig. 8.4 (μ^+) and Fig. 8.5 (μ^-). In case of a positively charged muon in the final state, roughly 30% more events are observed than in case of a negatively charged one. This is expected due to the charge-dependency of the event yield of, in particular, the signal process and the Z+jets background, as discussed above. Moreover, a clear difference between the two final states is visible in the data over prediction ratio. It is noticeable that the ratio diverges overall further from unity for the μ^+ -channel, as it is shifted to higher values above unity with respect to the combination of the charges. Hence, in particular the disagreement at low E_T^{miss} is even more pronounced. It extends up to nearly 20% for transverse masses below around 150 GeV. As a result, the offset between data and prediction in the distributions of the pseudorapidity and azimuthal angle of the muon is also larger than in the combination of both charges here. When looking at the μ^- -channel, the ratio is overall closer to unity. In particular, most data points are covered by the uncertainty band. However, a trend of an overestimated prediction can be observed for increasing p_T , E_T^{miss} and m_T^W . This can be seen, for instance, quite clearly in the region of m_T^W between 300 GeV to 400 GeV in Fig. 8.5d. Overall, this difference in the MC-data agreements for the two charges can not be explained in detail at this point. Nevertheless, it should be noted that theoretical uncertainties on the signal process are not considered yet and, for example, the choice of the used PDF potentially yields a difference in the modeling of the two final states.

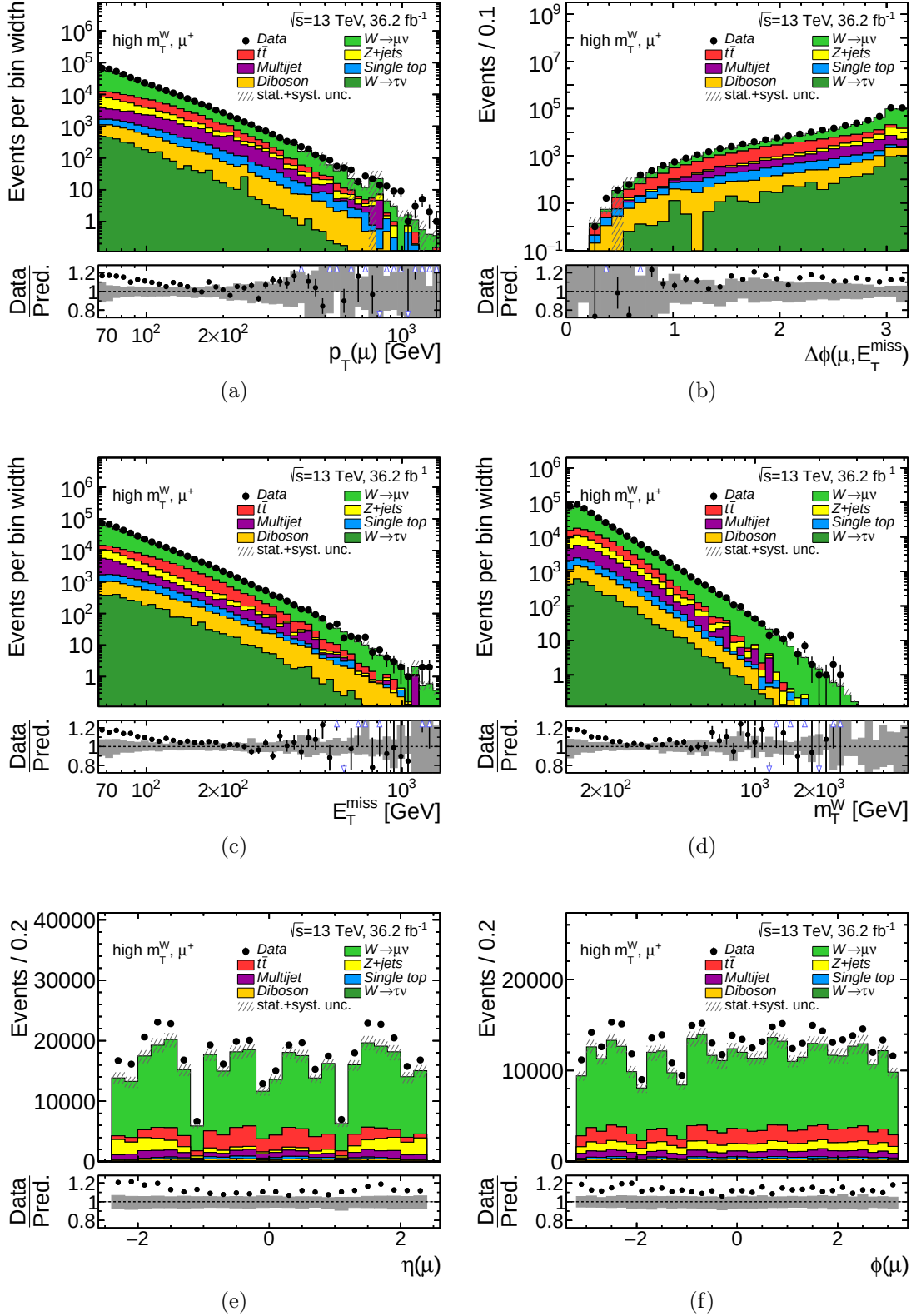


Figure 8.4.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon in the signal region for a μ^+ final state. Statistical and systematic uncertainties are included in the uncertainty band.

8. Comparison between data and prediction in the signal region

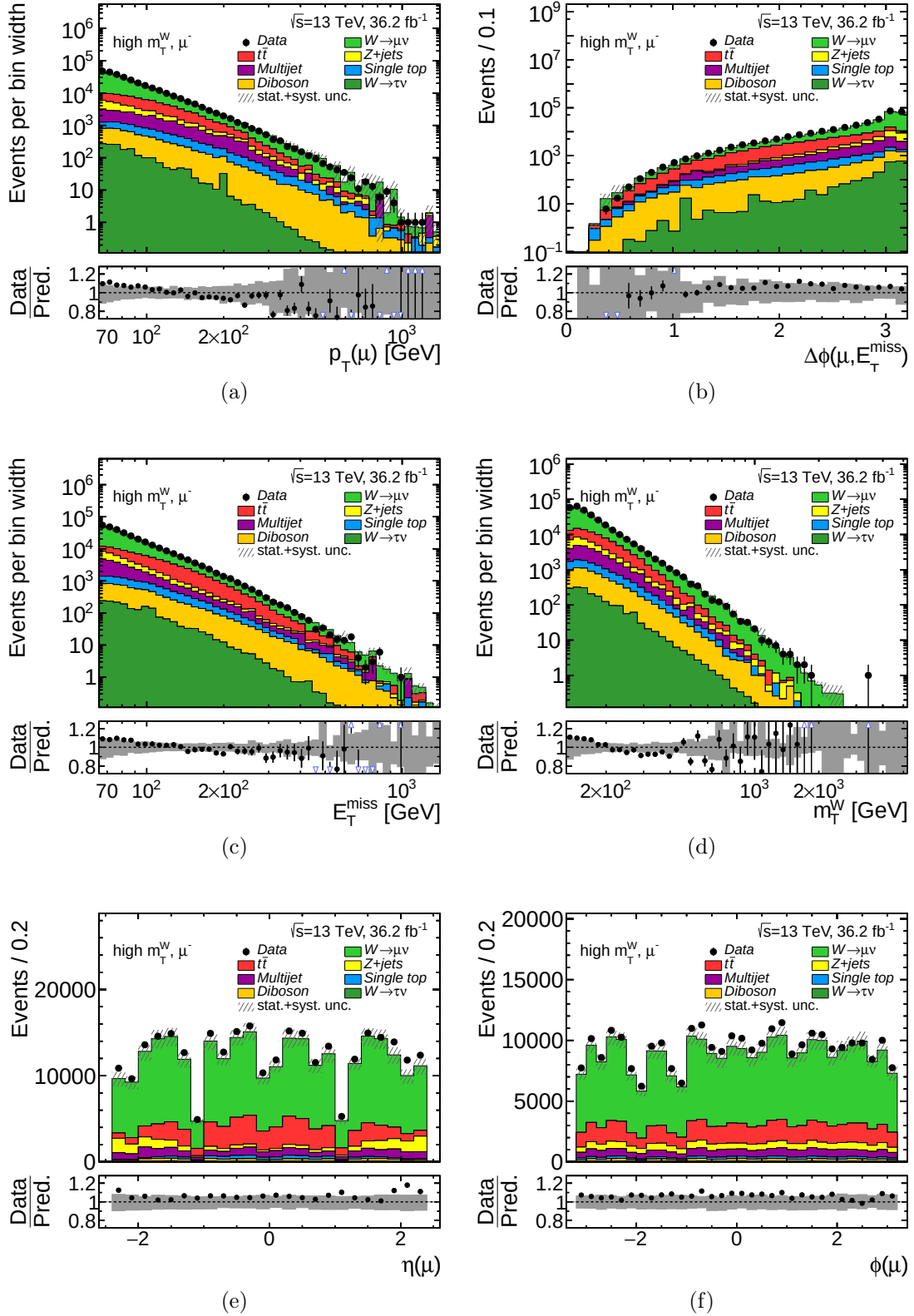


Figure 8.5.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon in the signal region for a μ^- final state. Statistical and systematic uncertainties are included in the uncertainty band.

9. Extraction of the unfolded differential cross section

The final goal of this analysis is the measurement of an unfolded differential cross section as a function of m_T^W . In this chapter, it is presented how this is extracted from the measured data. A general introduction on how a differential cross section is measured was given in Sec. 2.3. First of all, it is important to optimize the measurement binning, where effects of resolution, migration and statistical uncertainty in the data are evaluated. The number of signal events on reconstruction level per bin is then unfolded to the born lepton level. Effects of the bin-wise migration, measurement efficiency and reconstruction acceptance are taken into account while the method of Iterative Bayesian Unfolding is used.

9.1. Definition of the truth level

In order to be able to compare the measured cross section to theoretical predictions or other measurements, the effects of the detector and reconstruction need to be eliminated. For this reason, an unfolding of the measured reconstruction level to a truth level is done. In this section, the following different definitions of this truth level are discussed where the discriminant criterion is given by the definition of the lepton and final state radiation (FSR).

- Born level: before FSR,
- Bare level: after FSR,
- Dressed level: bare lepton but all photons originating from the same decay vertex in a cone of $\Delta R < 0.1$ are added in the reconstruction.

In Fig. 9.1 the distributions of the truth level invariant and transverse mass, respectively, of the W boson in the signal MC are shown where each line represents one definition of the truth level. Here, the m_T^W and E_T^{miss} cuts on reconstruction level are omitted and the p_T cut is lowered to 30 GeV with respect to the event selection in Sec. 6.1. Looking at the invariant mass in Fig. 9.1a, the distribution of the mass of the W boson is clearly visible, which has its maximum at 80 GeV. The difference between the three levels can be seen in the ratio plot where the bare and dressed level are shown with respect to the born level. It can be observed that the ratio for the bare mass with respect to the born mass is above unity for masses smaller than the mass peak and gets below unity for higher masses. This corresponds to a shift of the whole bare muon distribution to lower masses. The effect can be explained by the definition of the bare lepton level, which is after final state radiation. As a result of the radiation, the bare muon might carry less energy than a born muon and, therefore, the calculated invariant mass is lower. In order to get the dressed level, some of the radiated photons are associated with the bare muon again. Hence, the energy increases with respect to the bare mass of the W boson and the distribution of the dressed mass is shifted to higher masses. If all radiated photons were collected, the dressed level would meet the born

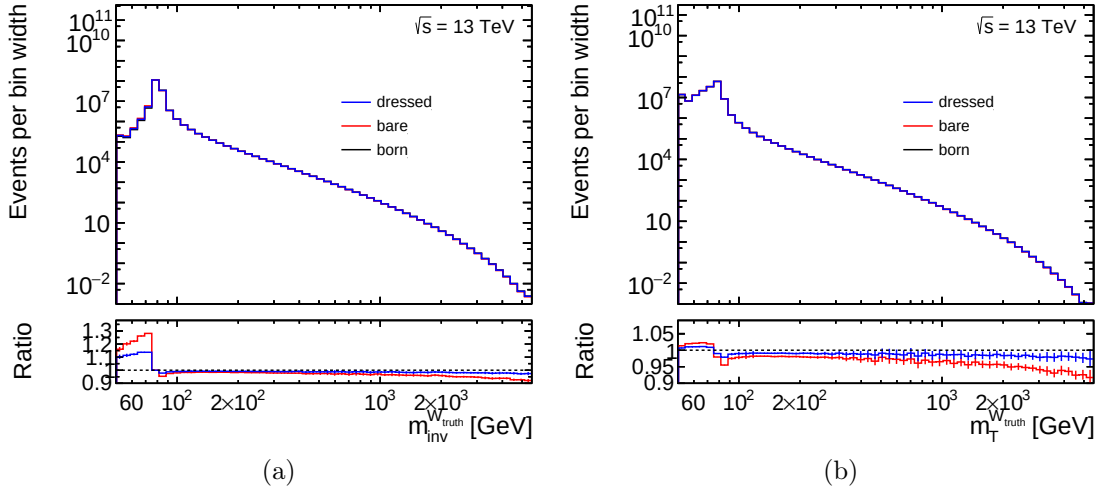


Figure 9.1.: Distribution of the truth (a) invariant and (b) transverse mass of the W boson if using bare, born or dressed level muons for the calculation.

level perfectly. In practice, this is clearly not the case, hence the dressed distribution is found between bare and born level. In Fig. 9.1b the transverse mass of the W boson is shown for all three definitions of the truth level. Even though the distribution has a slightly different shape, the behavior is analogous to the one seen in the invariant mass.

It is chosen to unfold the measured cross section to the born level. Thus, whenever the truth level is referred to it equals the born level, in fact. However, the difference between the truth levels is given purely by the signal MC. In general, a re-calculation of the final measurement results to e.g. the bare lepton level can be done at any point in the future by knowing the difference between the truth levels from the MC.

9.2. Optimization of the measurement binning

Since the cross section is measured differentially in the transverse mass of the W boson a suitable binning in this variable needs to be found. The following criteria are taken into account.

- The experimental resolution of the reconstructed events,
- The bin-wise migration caused by the reconstruction,
- The statistical uncertainty in the data.

The bin width is chosen such that it is larger than the resolution in each level bin. Furthermore, the bin-wise migration as well as the statistical uncertainty in the data are required to be reasonably small. After checking these criteria, a final binning is presented. Lastly, data and prediction are compared in this particular binning.

9.2.1. Resolution

While finding a suitable binning, it is crucial to take the resolution provided by the detector into account. This gives an insight into how precise a variable can be reconstructed as a function of its truth level value. A study is performed on the $W \rightarrow \mu\nu$ high mass slices. With respect to the signal region, the m_T^W and E_T^{miss} cuts are discarded and the p_T cut is lowered to 30 GeV. The resolution is studied as a function of the truth p_T , E_T^{miss} and m_T^W . In the end, the resolution as a function of m_T^W is of interest for choosing the binning. However, since m_T^W is composed directly of p_T and E_T^{miss} , looking at these two variables explicitly helps to understand all effects on the measurement resolution. In practice, any reconstructed variable shows a distribution around its truth value because of the limited resolution of the measurement apparatus. Here, the RMS of this distribution is taken as a measure for the resolution per truth bin, as introduced in Sec. 6.2.1. As a reminder, a large RMS corresponds to a poor resolution. The estimated RMS is shown for p_T , E_T^{miss} and m_T^W in Fig. 9.2 as a function of the corresponding truth value. It is found that the resolution essentially does not vary

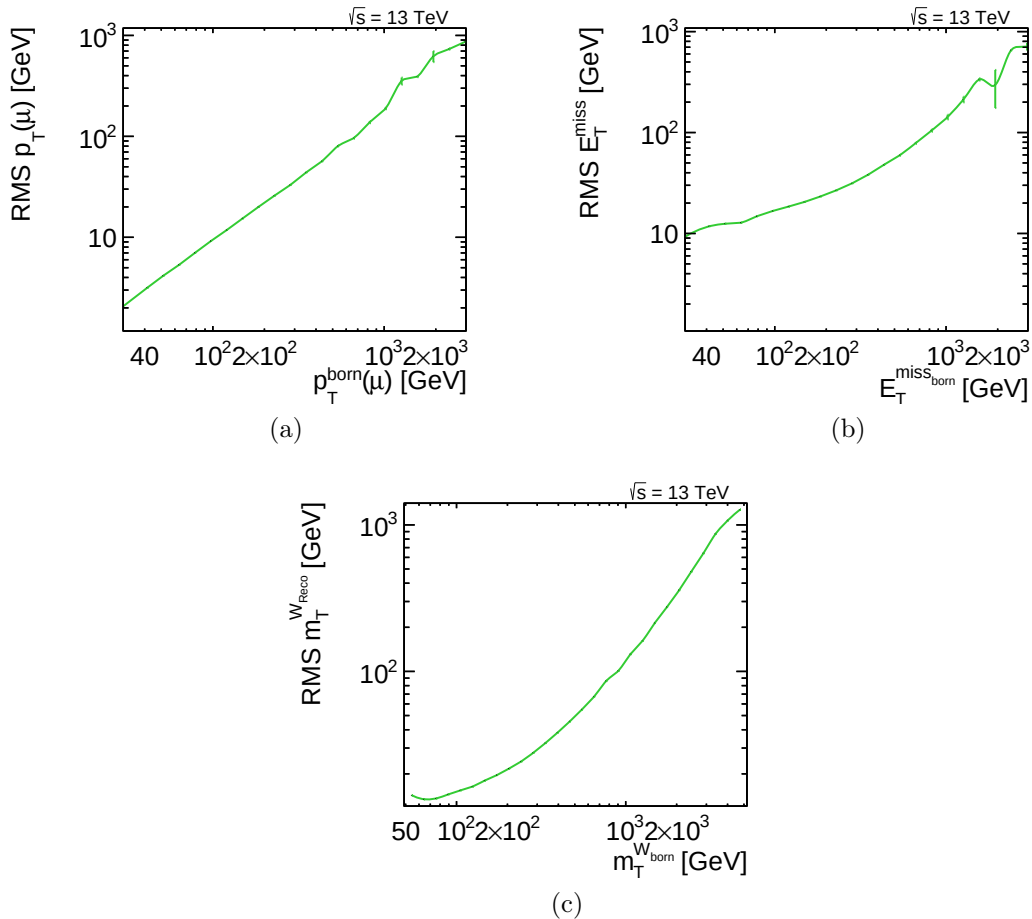


Figure 9.2.: Resolution as function of the truth level (a) transverse momentum of the muon, (b) missing transverse momentum and (c) transverse mass of the W boson.

for the two muon charges, hence only their combination is presented here. Looking at the transverse momentum of the muon in Fig. 9.2a, an increasing RMS for higher transverse momenta can be observed. While the RMS is at a few GeV at low p_T , it rises to several hundred GeV at the high energy tail. The fact that the RMS increases, or the resolution gets lower, respectively, for high p_T is expected for muons. These leptons are only measured track-based in the ID and MS and not in a calorimeter, as e.g. electrons. For higher momenta, the trajectory of a muon gets less curved by the magnetic field in the ATLAS detector and the sagitta measurement, used to calculate p_T , gets less precise. Looking at the resolution of E_T^{miss} in Fig. 9.2b, a similar behavior to the one in p_T can be observed. As a reminder, in this analysis a single lepton final state is considered, i.e. the missing transverse momentum is highly dependent on the transverse momentum of the muon. Hence, the E_T^{miss} resolution is dominated by the p_T resolution, in particular at high values. However, at low values, i.e. below 200 GeV the RMS of E_T^{miss} is observed to be higher than the RMS of p_T . In this region, the missing transverse momentum, and therefore its resolution, is not dominated by the leptons transverse momentum but by the transverse momenta of jets and the soft term (see Sec. 5.4).

Finally, the resolution of the transverse mass of the W boson is shown in Fig. 9.2c. A combination of the effects on the resolution of p_T and E_T^{miss} can be observed. While at low transverse masses E_T^{miss} is restricting the m_T^W resolution, the p_T reconstruction dominates the m_T^W resolution for higher values. Hence, the RMS of the reconstructed m_T^W distributions increase up to several hundred GeV at high values as well. While choosing a binning for the unfolding, this needs to be taken into account. The bin width should be larger than the resolution in order to reduce migration effects, i.e. events getting generated and reconstructed in different bins. Thus, the measurement binning in m_T^W is chosen the following.

$$m_T^W = [130, 170, 210, 250, 290, 330, 380, 440, 500, 575, 650, 750, 900, 1100, 1400, 2000] \text{ GeV}$$

In addition to the resolution, it is important for the choice of binning that migration effects are moderate and, in particular in the high mass tail, there should be sufficient statistics in the data left. Both criteria are justified in the following.

9.2.2. Migration

As already discussed, the value of a variable often differs on truth and reconstruction level. In a binned measurement, this results in a probability that an event is generated in a particular bin but reconstructed in a different one. It is important to understand this effect, called migration, in order to correct for the detector response. A mathematical connection between the value of a variable on truth level and after detector effects, i.e. reconstruction level, is given by the so-called migration matrix M_{ij} . Its entries give the probability for an event reconstructed in bin j that its corresponding truth level value is located in bin i . The matrix is obtained from the signal MC. A reconstructed variable is plotted against its truth value with the same binning in both axes in order to get a $N \times N$ matrix. Since, at this point, only the number of events per 2D-bin

is given, a normalization is applied to get a probability. Every row, i.e. every bin of the distribution of reconstructed events, is normalized to unity. This normalization is chosen in order to see directly where an event originates from. The migration matrix used here is denoted as $M_{reco,truth}$. In general, an inverted definition of x- and y-axis, and hence normalization, is also a valid approach for a migration matrix and it will be called $M_{truth,reco}$, in that case. This alternative definition is for example used in the unfolding procedure, as presented later.

The migration matrix $M_{reco,truth}$, using the above defined measurement binning in m_T^W , plus one additional low m_T^W bin, is shown in Fig. 9.3. The combination of both muon charges is shown and the signal region event selection is applied, with the only difference that the m_T^W cut is lowered to 60 GeV. This is done in order to see migration effects from the mass peak of the W boson explicitly. On the x-axis, the born level m_T^W is given, whereas the y-axis shows the reconstructed m_T^W . In order to understand the matrix $M_{reco,truth}$, it might be helpful to focus on one individual row. For example in the second lowest row in Fig. 9.3, the second bin of the reconstructed distribution of m_T^W is shown. All reconstructed events have a m_T^W between 130 GeV to 170 GeV in this row. For these events, the fraction of events that are generated in each truth bin (on the x-axis) are shown in percent. For instance, 39% of the events that are reconstructed in the 130 GeV to 170 GeV bin are also generated in this particular bin. On the other

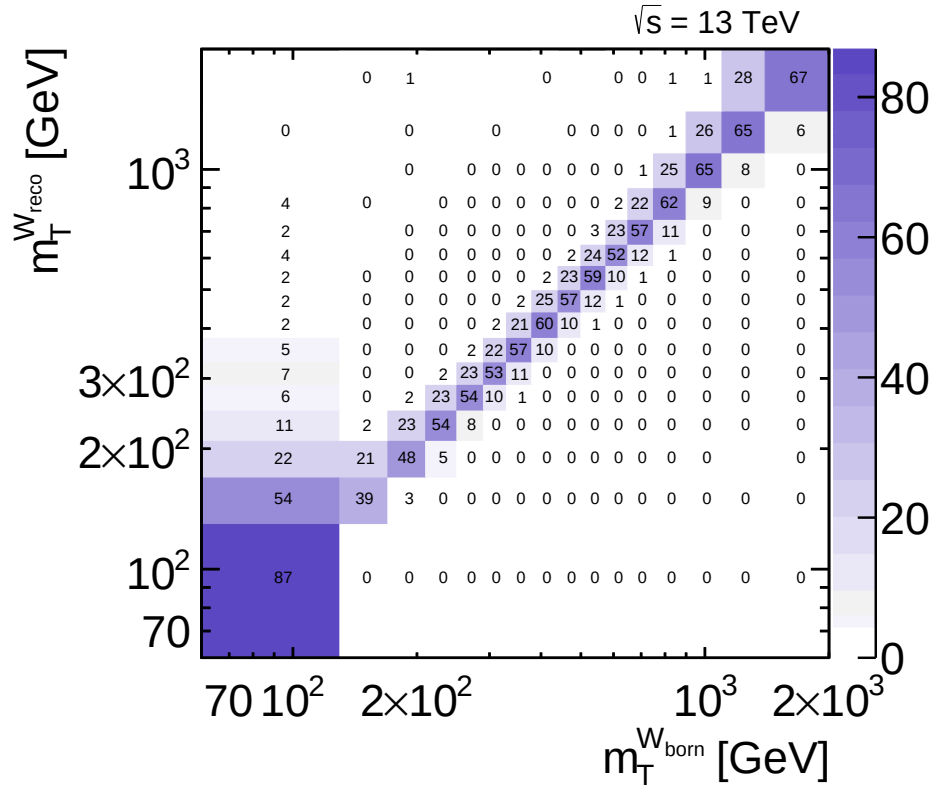


Figure 9.3.: Migration matrix $M_{reco,truth}$ for the signal process for the combination of both muon charges. The given numbers are in percent, while under- and overflow bin are considered in the normalization.

hand, 54% of the events that are reconstructed in this bin originate from the 60 GeV to 130 GeV bin, corresponding to the peak region. This rather high fraction can be explained by the fact that the distribution of m_T^W is steeply falling above the mass peak, as for example Fig. 9.1b shows. By far the most events are produced at the mass peak of the W boson at $m_W = 80$ GeV. As a result, a lot more events are produced whose transverse mass lays in the 60 GeV to 130 GeV range than in higher mass bins. Even though only a small fraction of these events happen to be reconstructed at a higher mass, their relative contribution is relatively large, since the absolute number of events that are generated in a certain bin is decreasing so drastically with increasing mass. Looking at the first column of $M_{reco,truth}$, it can be observed that, even in bins containing events reconstructed above a few hundred GeV, a few percent of these events are generated with a mass below 130 GeV. A reconstruction of a transverse mass substantially larger than the generated one can happen e.g. if the p_T of the muon is not only originating from the mass of the W boson but the boson itself already had a non-negligible transverse momentum.

The diagonal element of $M_{reco,truth}$ is called purity and indicates the fraction of events that are reconstructed and generated in the same bin. Since the effect of migration from the peak is the most pronounced in the first few bins, the purity is the lowest there. In the first two bins above 130 GeV, the purity is 39% and 48%, respectively, but for higher masses, the purity is always above 50% and increases up to 67% in the very last bin. There, the migration is the lowest, as the distribution of m_T^W is not falling as steeply as in the beginning. Even though migration effects can be corrected for in the procedure of the unfolding, it is helpful to maximize the purity. This can be done e.g. by increasing the bin width. A compromise between enough bins and sufficiently large purities needs to be made. The given binning is chosen to yield reasonable purities, in particular above 210 GeV and the binning is kept as stated in Sec. 9.2.1.

Migration matrices for the charge-separated channels are shown in Fig. 9.4. In each case, a reasonably small migration is needed for an individual unfolded cross section measurement. It is noticeable that the purity in the μ^- -channel is overall a few percent lower than in the μ^+ -channel, e.g. in the 130-170 GeV bin 37% and 41%, respectively. This discrepancy can be explained by the fact that the distribution of the truth m_T^W is steeply falling in the region above the mass peak of the W boson. However, there is a slight difference between the steepness of the mass distributions of the two charges, which can be seen in Fig. A.18 in the appendix. This effect can be traced back to the production mechanism of the W boson in pp collisions. As discussed before, more events with a positive W boson are produced because the proton consists of two up valence quarks but only one down valence quark. For very high masses a fairly large Bjorken-x is necessary to produce the W boson. As seen in the exemplary PDFs in Fig. 2.2, the valence quarks are dominant in the region of high Bjorken-x. However, at low Bjorken-x, the sea quarks become relevant, which are symmetric in charge. As a result, the difference between the production rates of the W^+ and W^- bosons is expected to be less pronounced at lower masses. Thus, the distribution of the W^- mass falls slightly steeper, resulting in higher migration effects and lower purities.

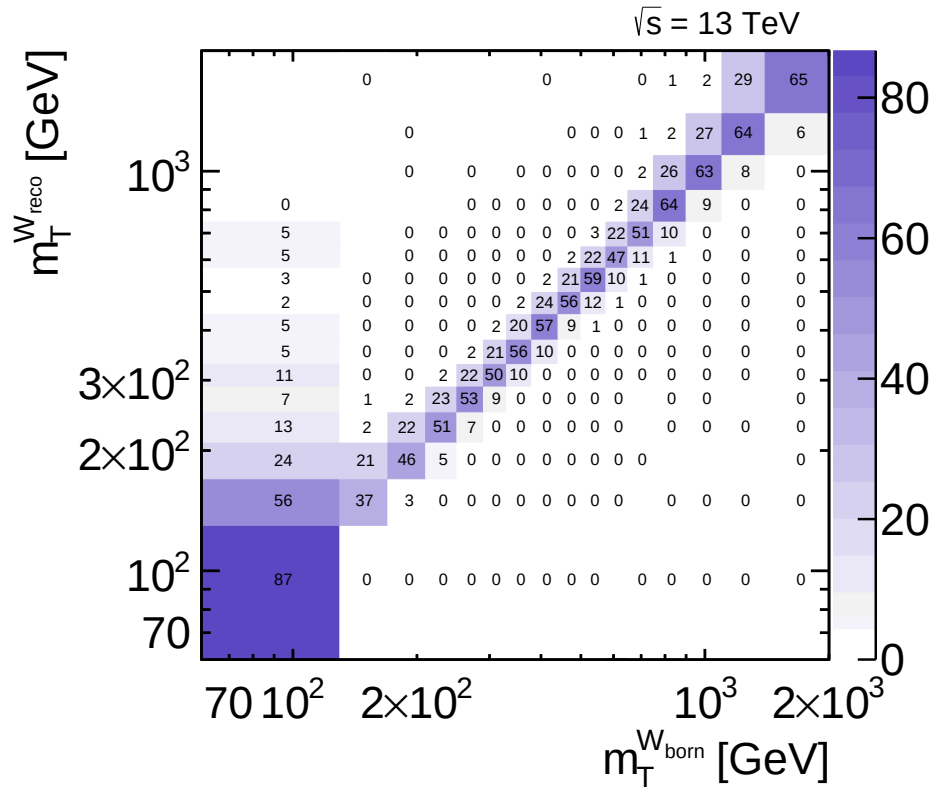
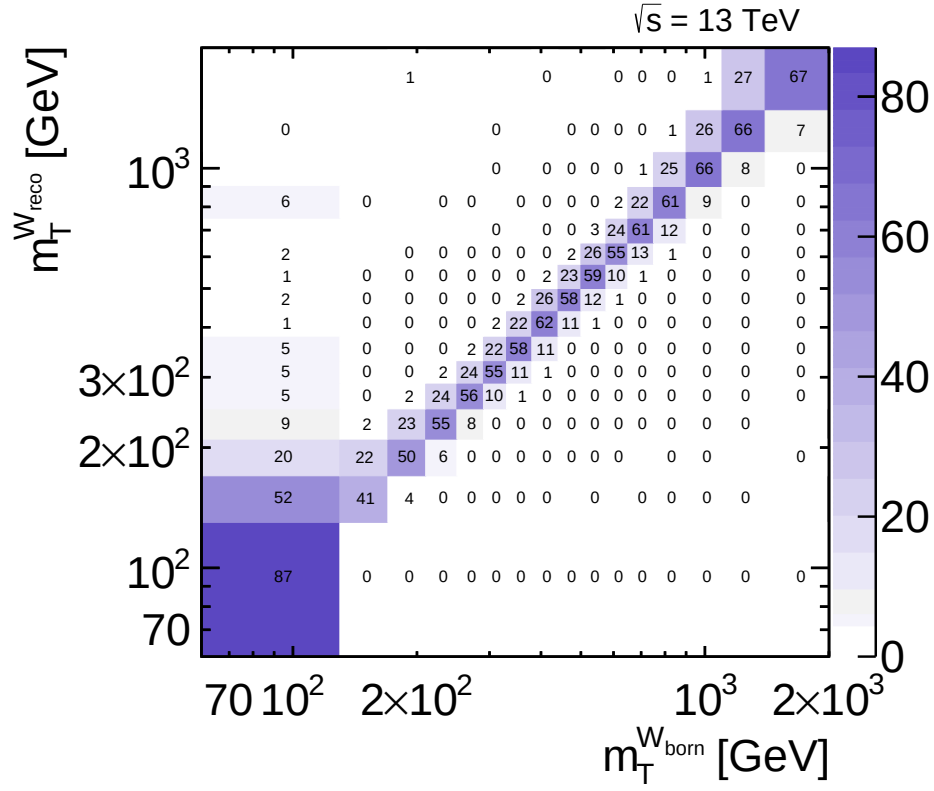


Figure 9.4.: Migration matrix $M_{reco,truth}$ for the signal process for a (a) μ^+ or (b) μ^- final state. The given numbers are in percent, while under- and overflow bin are considered in the normalization.

9.2.3. Statistical uncertainty in data

The last aspect to be taken into account for choosing a suitable binning is the statistical uncertainty in the data per bin. It is given in a counting experiment according to poisson statistics by the square root of the number of entries $\sqrt{N}$. The distribution of m_T^W is steeply falling above the mass peak, therefore only a few events are produced in the very high mass tail. To compensate for this, a binning needs to be chosen such that a reasonable number of events is still present per bin. Clearly, the larger a bin is the more events are counted in it, thus the lower its statistical uncertainty. Nevertheless, a compromise between as many bins as possible and a sufficiently large number of events per bin has to be made.

In Fig. 9.5 the relative statistical uncertainty in the data, $\frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$, is shown for the signal region in the measurement binning in m_T^W . A differentiation between the muon charges is made. Obviously, the statistical uncertainty is the lowest for the combination of both charges, as shown in Fig. 9.5a, since the sum of all events is included. It is visible that the relative statistical uncertainty increases with larger m_T^W , corresponding

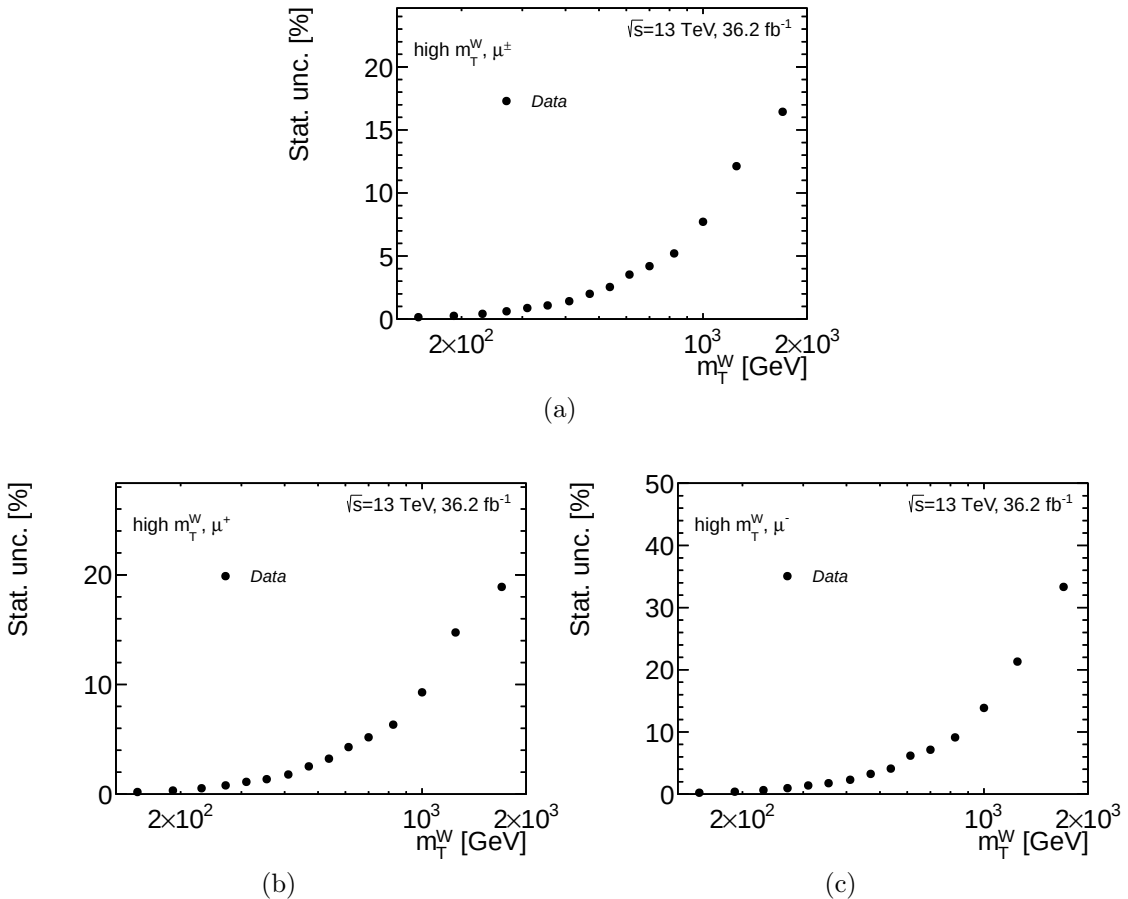


Figure 9.5.: Relative statistical uncertainty in data from 2015 and 2016 for the (a) combination of both charges, (b) positively and (c) negatively charged muon.

to a decreasing number of events. The maximal uncertainty is given in the last bin, with around 16%. Except for the last two bins, the statistical uncertainty is below 10%. Clearly, the statistical uncertainty is larger for the charge-separated channels, since only a part of the data is considered in each of them. In general, fewer events with a negatively charged W boson occur in pp collisions, thus the statistical uncertainty is the largest there. Nevertheless, even in this case the statistical uncertainty is around 20% or less, except for one bin.

It is important to mention that this cross section measurement is intended to be based on the full Run 2 dataset in the future, i.e. data taken in 2015-2018 instead of 2015-2016 only. The binning used in this thesis is chosen to be already optimized for the full dataset. An estimator for the number of collisions and, thus, the event yield is given by the integrated luminosity. Therefore, this quantity can be used to extrapolate the statistical uncertainty shown here to the full dataset. The number of events is scaled by the factor between the integrated luminosity of data taken in 2015-2016 and the full Run 2 luminosity ($\frac{139 \text{ fb}^{-1}}{36.2 \text{ fb}^{-1}} \approx 3.8$). Correspondingly, the relative statistical uncertainty $\sigma_{stat,rel}$ will be scaled by the inverse of the square root of this number as follows.

$$\sigma_{stat,rel}^{Run2} = \sqrt{1/3.8} \cdot \sigma_{stat,rel}^{Data15/16} = 0.51 \cdot \sigma_{stat,rel}^{Data15/16} \quad (9.1)$$

As a result, every relative statistical uncertainty shown here will decrease approximately by a factor of two when looking at the full dataset. This means that the relative statistical uncertainty will be below 10% in nearly every bin, even when looking at the charge-separated channels. In most bins, the statistical uncertainty is expected to be below 5%.

9.2.4. MC-data comparison in measurement binning

Data and prediction are compared in the signal region in the measurement binning in m_T^W , which was defined in Sec. 9.2.1. Since the cross section is measured in each of these bins, a reasonable agreement between data and prediction per bin is important. Again, the three channels $\mu^\pm$ combined, μ^+ and μ^- only are considered. Corresponding MC-data comparisons can be found in Fig. 9.6, where statistical and systematic uncertainties are included. In addition, the number of events per m_T^W bin in data, signal as well as each background and the total background can be found in Tab. A.1 in the appendix.

In Chapter 8, the distribution of m_T^W for data and prediction was shown in a finer binning. In general, a similar shape can be observed in the measurement binning shown here. However, by choosing a wider binning, the statistical uncertainty in the high mass tail is lowered substantially. All in all, a sensible MC-data agreement can be observed above roughly 200 GeV in the combination of both charges in Fig. 9.6a. The only bins in which data and simulation clearly do not agree within the given uncertainty are the first, extending from 130 GeV to 170 GeV, and last one, from 1400 GeV to 2000 GeV. The disagreement in the first m_T^W bin was already discussed in previous chapters and

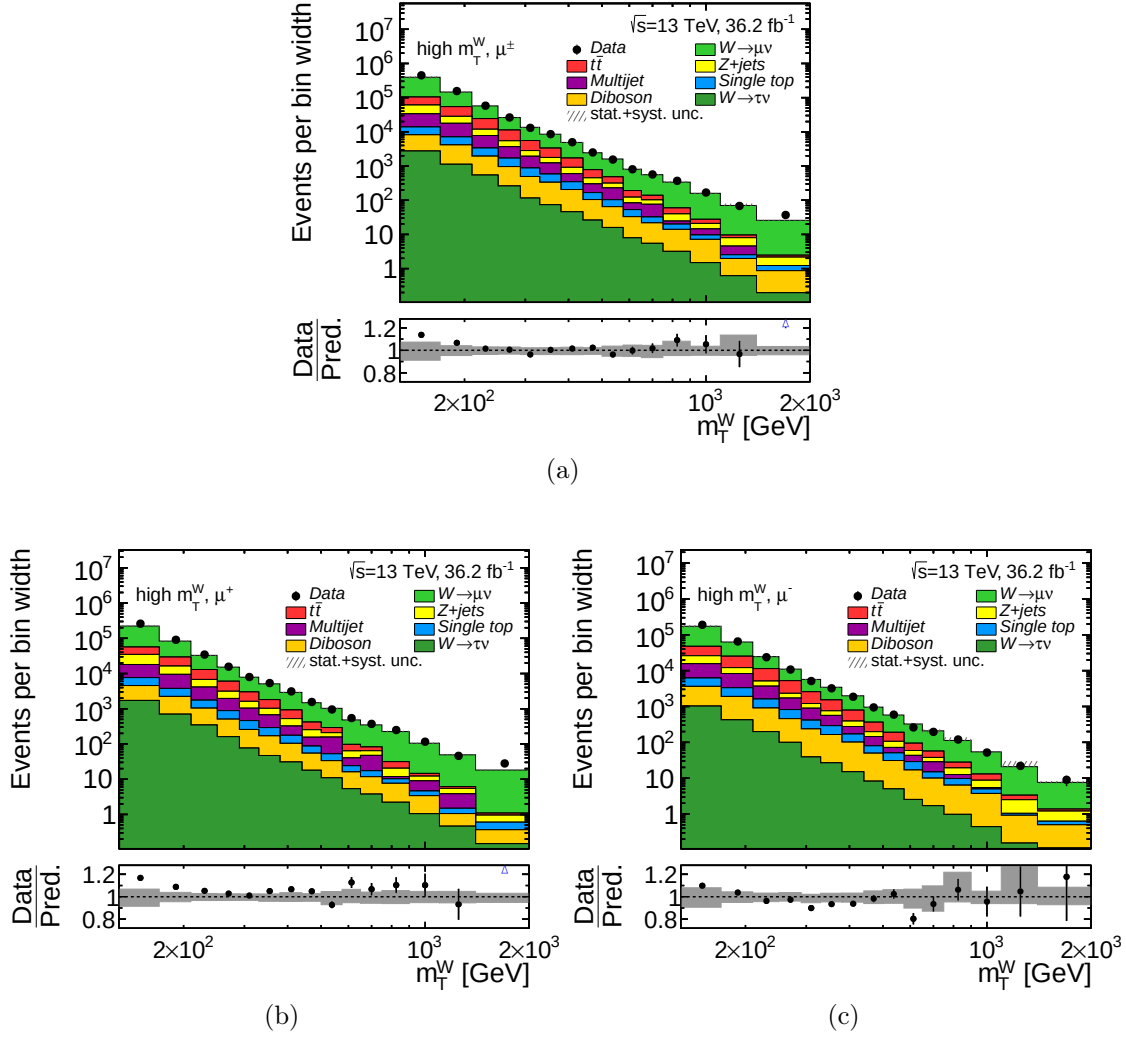


Figure 9.6.: MC-data comparisons in the signal region shown in the measurement binning of the transverse mass of the W boson, for the (a) combination of both charges, a (b) positively and (c) negatively charged muon.

is expected to be related to the modeling of E_T^{miss} . However, except for these two bins, the uncertainty band covers the deviation between data and prediction reasonably well. In the combination of both charges in Fig. 9.6a, a substantial one-sided uncertainty is noticeable in the second last m_T^W bin. Looking at the MC-data comparisons per charge in Fig. 9.6b and Fig. 9.6c, this large one-sided uncertainty is found to arise from the μ^- -channel. The origin of this uncertainty is associated with the sagitta bias correction of the muon track and is discussed in more detail in Chapter 10.

As already seen in the corresponding MC-data comparisons in Chapter 8, a clear difference between the two charges is visible in the data over prediction ratio. In the μ^+ -channel in Fig. 9.6b, a trend of an underestimated prediction is present and the ratio extends up to nearly 1.2 in the first bin. In the μ^- -channel in Fig. 9.6c, however, the ratio is shifted to lower values with respect to the combination of the charges. As

a result, the disagreement in the first bin is closely covered by the uncertainty band. Nevertheless, the agreement at intermediate transverse masses, e.g. at $m_T^W = 300$ GeV, shows a trend of an overestimated prediction. Overall, this difference in the MC-data agreements between the muon charges is not fully understood.

9.3. Unfolding procedure

In order to correct for detector efficiency and acceptance effects, a transformation from the measured reconstruction level to the truth level is necessary. This procedure is called unfolding and discussed in this section. In addition to migration effects, efficiency corrections for the event selection on reconstruction and truth level are taken into account. In this analysis, the method of Iterative Bayesian Unfolding (IBU) [44] is used. This method is adequate if non-negligible migrations between bins are present, which were seen e.g. in the migration matrices in Sec. 9.2.2.

9.3.1. Efficiency and acceptance corrections

The so far considered truth level, as e.g. in the estimation of the resolution in Sec. 9.2, is limited to events that are selected on both reconstruction and truth level. This means in particular, that only a part of the generated muons is taken into account. However, there is a non-negligible fraction of events that are generated but not reconstructed. Reasons for this are inefficiencies due to the measurement apparatus as well as the selection acceptance, induced by the analysis specific criteria given in Sec. 6.1. A correction for this effect is essential in order to get a correct, universal definition of a cross section. Moreover, the truth level is subject to certain selection criteria in the following. The method of IBU, as discussed below, requires that events considered in the response matrix lay on reconstruction and truth level within the fiducial range of $m_T^W = 130 - 2000$ GeV. As a result, there is a second correction necessary which corrects for events that are selected on reconstruction level but not on truth level. This happens, for instance, if an event with $m_T^W < 130$ GeV on truth level migrates into the accepted phase space on reconstruction level. This correction is applied to the reconstructed number of events before the inverted response matrix is multiplied.

The differential cross section is calculated according to eq. 2.3 in Sec. 2.3, where the two efficiencies ϵ_j and f_{in}^i are defined. The former corrects for the events that are generated on truth level but are not reconstructed. A bin-wise efficiency ϵ_j is obtained by taking the quotient of events that pass both the reconstruction and truth level within the measurement range with all events included in the fiducial truth level.

$$\epsilon_j = \frac{N_{reco \wedge truth[130,2000]}^j}{N_{truth[130,2000]}^j} \quad (9.2)$$

The second factor, f_{in}^i , corrects per bin on reconstruction level for events that are selected on reconstruction level but not on truth level, due to the truth level acceptance. Thus, the denominator is defined by the full number of reconstructed events per bin. This factor corrects, in particular, for events that are smearing into the measurement range on reconstruction level but were not generated in this fiducial phase space.

$$f_{in}^i = \frac{N_{reco \wedge truth[130,2000]}^i}{N_{reco}^i} \quad (9.3)$$

Both correction factors, ϵ_j and f_{in}^i , are obtained from the signal MC and shown in Fig. 9.7. The combination $\mu^\pm$ is depicted here, as no substantial difference between the muon charges is observable in these efficiencies. However, both factors are shown for the μ^+ - and μ^- -channel individually in Fig. A.19 in the appendix. It can be observed in Fig. 9.7a that the efficiency ϵ_j is around 30 % to 60 %. It increases at low m_T^W and approaches a saturation at around $m_T^W = 400$ GeV. Thus, there is a rather large fraction of events that are generated but not considered in the reconstruction. However, this is expected, on the one hand, due to the acceptance cuts on reconstruction level on e.g. p_T , E_T^{miss} and m_T^W . As a result, the efficiency is the smallest at low m_T^W . A further reconstruction acceptance restriction is given by the $|\eta(\mu)| < 2.4$ requirement. On the other hand, there is a non-negligible probability that a muon is not measured in the detector. The MS is, due to being the outermost part of the ATLAS detector, interrupted by support structures and services at multiple points, which leads to measurement inefficiencies. Also, the choice of working points introduced several efficiency losses, in particular the HighPt muon quality (see Sec. 6.2). Finally, the muon trigger is expected to induce a non-negligible measurement inefficiency.

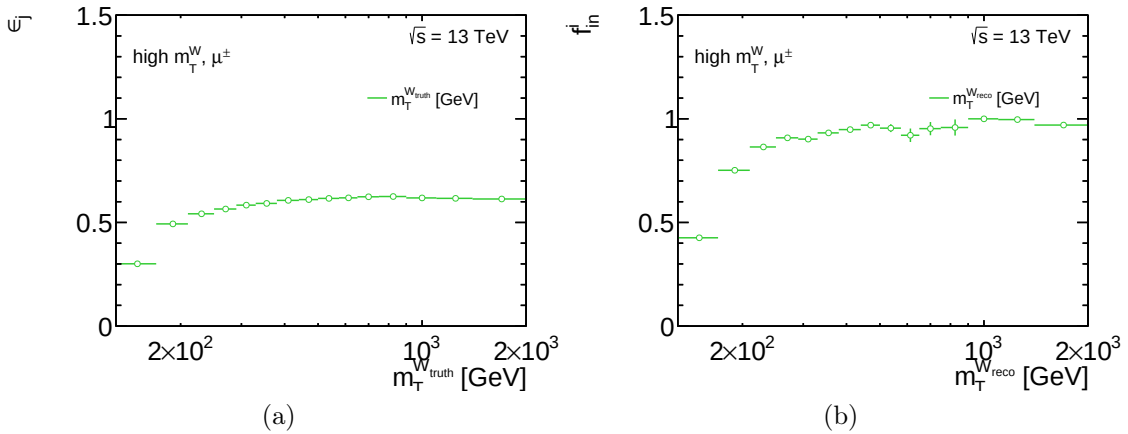


Figure 9.7.: Efficiency and acceptance factors applied in the unfolding procedure. In (a) the factor ϵ_j is shown, which corrects for events that are not reconstructed due to acceptance and efficiency effects and in (b) the correction factor f_{in}^i that corrects for events that are not generated in the fiducial measurement range.

The acceptance factor f_{in}^i , correcting for events to be selected on reconstruction level but not on truth level, is given in Fig. 9.7b, as a function of the reconstructed m_T^W . It is visible that the acceptance is the smallest at low m_T^W and consecutively increases to unity. This is as expected because the restricting factor is the $m_T^W > 130$ GeV truth level cut needed in the IBU. As seen in the migration matrix $M_{reco,truth}$ in Sec. 9.2.2, there is a large fraction of events migrating from the mass peak of the W boson into the first m_T^W bins on reconstruction level. Clearly, this effect of in-smearing from the mass peak decreases for higher m_T^W bins. In the very last m_T^W bin in Fig.9.7b, a little decline of the efficiency can be observed. However, this can be understood by the truth level restriction of $m_T^W < 2000$ GeV.

9.3.2. The method of Iterative Bayesian Unfolding

An important step in calculating a truth level cross section is the procedure of inverting the response matrix R_{ij} in eq. 2.3. The method of Iterative Bayesian Unfolding [44] implemented via `RooUnfold` [45] is used. Its mathematical framework is based on Bayes' theorem and can be expressed by effects E and causes C , which can be linked to the events on reconstruction and truth level, respectively. The number of reconstructed events N_i corresponds to the effects E_i , whereas n_E is the number of bins on reconstruction level. C_j is the number of predicted events in bin j of the truth distribution and n_C the number of causes or truth bins, respectively. Whereas the effects E_i can be measured, the causes C_j can not be measured directly in data. Using Bayes' theorem, the probability for a cause C_j to produce an effect E_i is defined the following, where $P_0(C_j)$ is an, in general arbitrary, initial distribution of the truth level.

$$P(C_j|E_i) = \frac{P(E_i|C_j) \cdot P_0(C_j)}{\sum_{k=0}^{n_C} P(E_i|C_k) \cdot P_0(C_k)} \quad (9.4)$$

Here, $P(E_i|C_j)$ indicates the probability for an effect to originate from a certain cause. This probability can be obtained in form of a migration matrix built from the signal MC. However, this is not the matrix $M_{reco,truth}$ defined in Sec. 9.2.2, more information on this is given below. In the denominator, a summation over all causes, i.e. truth level bins, is made in order to get a normalized probability.

An estimation of the number of truth level events in bin j , $\hat{N}(C_j)$, is given, as a result, by the following equation.

$$\hat{N}(C_j) = \frac{1}{\epsilon_j} \sum_{i=0}^{n_E} P(C_j|E_i) N(E_i) \quad (9.5)$$

$N(E_i)$ is the acceptance-corrected number of measured signal events per bin of the reconstructed data, i.e. it equals $f_{in}^i(N_{data}^i - N_{bkg}^i)$ in equation 2.3. It is multiplied with the probability $P(C_j|E_i)$, which can be identified with an element of the inverted matrix R_{ij}^{-1} . Hence, the multiplication of $P(C_j|E_i)$ and $N(E_i)$ denotes the number of events that migrate from a certain bin i on reconstruction level to a certain bin j on

truth level. A summation over all effects, i.e. all reconstruction level bins, is made per truth bin in order to cover migrations over the whole measurement range. In this procedure, only events that are selected on truth and, in particular, reconstruction level are considered. Therefore, the estimated number of causes, i.e. the unfolded number of events, is, at last, corrected for the events that are not reconstructed by multiplying with the inverse of the efficiency ϵ_j , as given in eq. 2.3.

The estimation of the number of events on truth level can be optimized in form of an iterative procedure. The probability for an event to be generated in bin j is obtained by dividing the estimated number of events per bin with the total estimated number of events.

$$\hat{P}(C_j) = \frac{\hat{N}(C_j)}{\sum_{j=1}^{n_C} \hat{N}(C_j)} \quad (9.6)$$

As seen in eq. 9.4, an adequate initial probability distribution, $P_0(C_j)$, is needed. As a first step in `RooUnfold`, the truth distribution of the signal MC sample is set as the initial guess $P_0(C_j)$. In a second iteration, $P_0(C_j)$ is set to the newly calculated $\hat{P}(C_j)$. This step is repeated iteratively until a certain termination criterion is fulfilled, e.g. the total uncertainty or a χ^2 distribution is minimized.

9.3.3. Response matrix in the IBU

An important aspect is that the matrix considered in the IBU is defined differently than the migration matrix $M_{reco,truth}$ in Sec. 9.2.2 which has the main purpose of understanding the migration effects per bin. In particular, migration effects from the mass peak are taken into account there. With respect to this matrix, the x- and y-axis are exchanged and a normalization per truth level bin is applied now in order to get a proper definition of the probability $P(E_i|C_j)$. Furthermore, events that are considered in the response matrix are required to be generated and reconstructed in the measurement range of $m_T^W = 130 - 2000$ GeV. To make the difference to $M_{reco,truth}$ clear, the response matrix used in the IBU is referred to as $M_{truth,reco}^{[130,2000]}$. Its components provide the probabilities $P(E_i|C_j)$, as needed in equation 9.4.

The matrix is calculated based on the signal MC and shown in Fig. 9.8, exemplarily for the combination of both charges. The matrices for the charge-separated channels can be found in Fig. A.20 in the appendix and look, in general, very similar. Since the migration from the mass peak, i.e. truth $m_T^W < 130$ GeV, is not taken into account at this point, the purities are substantially larger in $M_{truth,reco}^{[130,2000]}$ than in the migration matrix $M_{reco,truth}$. It should be highlighted again that the iterative step of the unfolding is the procedure of inverting this particular matrix $M_{truth,reco}^{[130,2000]}$. Hence, the migration effects from the mass peak are not considered iteratively but only once in the form of the correction factor f_{in}^i , as discussed in Sec. 9.3.1.

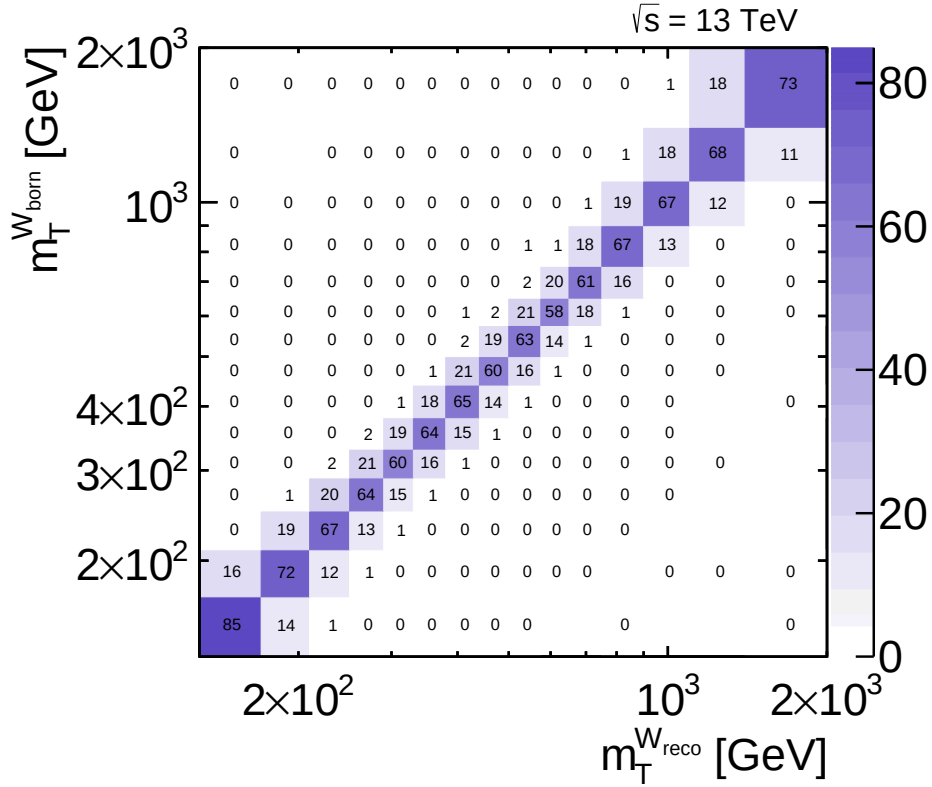


Figure 9.8.: Response matrix $M_{truth,reco}^{[130,2000]}$ as used in the Iterative Bayesian Unfolding for the combination of both charges. The numbers are given in percent, while under- or overflow bin are not considered in the normalization.

9.3.4. Technical closure test

The goal of a technical closure test is to ensure that the unfolding implemented via RooUnfold is, in fact, acting as expected and no issues are introduced by the unfolding procedure. The test is done using the signal MC only, where its reconstructed distribution is taken as the input of the unfolding instead of real measured data. A comparison between the unfolded distribution and the initial truth distribution is made. This procedure serves as a cross-check where perfect closure is expected, i.e. perfect agreement between the two distributions.

In Fig. 9.9, the unfolded, the truth level and the reconstructed distributions of the transverse mass of the W boson in the signal MC are shown. The MC statistical uncertainty is included. Here, the signal region event selection is applied on the reconstruction level, as given in Sec. 6.1. Only the closure test for the combination of both charges is shown here but the same tests were done successfully for the charge-separated channels.

A ratio between the distribution of the unfolded signal MC and the corresponding initial truth level is calculated. Indeed, the expected closure can be observed, i.e. the ratio is perfectly at unity over the whole m_T^W range. Strictly speaking, the ratio shown in Fig. 9.9 confirms this only to a certain precision, e.g. in the order of permille. How-

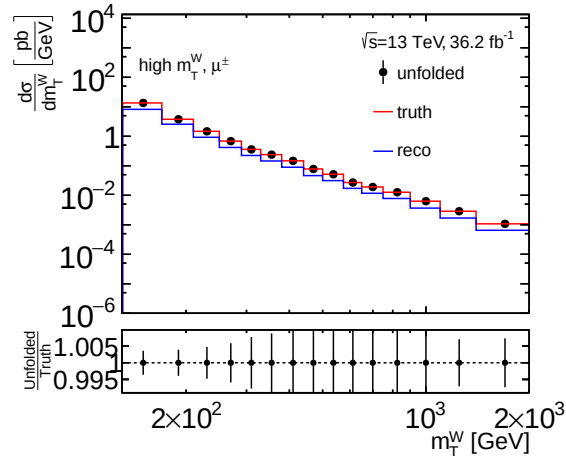


Figure 9.9.: Technical closure test of the unfolding procedure, where the signal MC is taken as the input of the unfolding.

ever, the expected closure was checked to a way higher precision, in fact, i.e. a factor of one hundred with respect to Fig. 9.9.

The truth level shown here is given by the corrected truth level, i.e. the efficiency and acceptance factors ϵ_j and f_{in}^i are applied. As a result, the rather large discrepancy between the distributions on truth and reconstruction level can be understood due to the factor ϵ_j , in particular. As discussed in Sec. 9.3.1, this factor corrects for events that are selected on truth level but not reconstructed due to the measurement efficiency and acceptance and amounts to $\epsilon_j = 0.6$, at maximum.

10. Systematic uncertainties

Statistical as well as systematic uncertainties may occur when measuring a physical quantity. The former can be reduced by repeating the measurement. However, this can not be achieved, when dealing with systematic uncertainties which depend e.g. on the detector or theoretical predictions. A repeated measurement would always yield the same bias due to these effects. This chapter gives an overview of all systematic uncertainties considered in this analysis. Their origin as well as their impact on the signal process is discussed. A differentiation between experimental and theoretical uncertainties is made. In general, experimental uncertainties are applied to MC. Furthermore, dedicated systematic uncertainties for the multijet background are defined. Lastly, theoretical uncertainties on the signal and the largest background $t\bar{t}$ are discussed. The relative systematic uncertainty with respect to the signal process is evaluated in detail for the measurement binning in m_T^W . This is, in particular, of interest because only the uncertainties with a contribution of more than 1 % in any m_T^W bin on reconstruction level are unfolded and considered in the final results. All these uncertainties will be added in quadrature to get the total uncertainty.

10.1. Experimental uncertainties

Experimental systematic uncertainties are caused by the measurement apparatus and can introduce a bias for example due to the measurement resolution or efficiency of a certain quantity. Calibrations of the ATLAS sub-detectors were made and dedicated systematic uncertainties were obtained for the luminosity and pileup as well as the measurement of the E_T^{miss} , muon, and jets. In general, a systematic uncertainty is defined as a variation by one standard deviation (1σ) and can be two-sided, i.e. an up and a down variation are defined, or one-sided.

10.1.1. Luminosity uncertainty

The luminosity at the LHC is measured with the help of a dedicated detector, called LUCID2 [46]. A calibration using the van der Meer method is used, where dedicated beam-separation scans are evaluated [47]. By comparing different sub-detectors and algorithms, an uncertainty is obtained. For the 2015-2016 dataset the total uncertainty on the luminosity is $\pm 2.1\%$.

10.1.2. Pileup uncertainty

At the LHC, bunches of protons are accelerated and brought to collisions. As a result, several inelastic collisions may take place simultaneously, which is called pileup. A pileup SF is applied to the MC to correct for the difference between the simulation and the measured data [48]. The uncertainty on this SF is considered as a systematic uncertainty in this analysis. By varying the applied SF by $\pm 1\sigma$ a new event yield of the signal

MC is obtained which is compared to the nominal one. It can be observed in Fig. 10.1 that the relative systematic uncertainty due to pileup is below 1% over the full m_T^W range, with some statistical fluctuations between 400-900 GeV.

10.1.3. E_T^{miss} uncertainties

The missing transverse momentum is calculated from all reconstructed objects as well as a track-based soft term, as discussed in Sec. 5.4. The uncertainties due to the measurement of hard tracks, i.e. the ones associated with leptons and jets, are propagated into the calculation of the E_T^{miss} . Furthermore, systematic uncertainties for the soft track term are evaluated [49]. These are divided into a symmetric scale uncertainty for the transverse momentum of the soft tracks (MET_SoftTrk_ScaleUp/Down) and two resolution uncertainties. The latter are divided into a component parallel (MET_SoftTrk_ResoPara) to the mean p_T of the hard tracks as well as a component perpendicular (MET_SoftTrk_ResoPerp) to it.

In Fig. 10.1b the relative systematic uncertainty due to the E_T^{miss} soft term is shown binned in m_T^W . A rather large uncertainty can be observed in the first m_T^W bin, ranging from 130 GeV to 170 GeV. The uncertainty extends up to 7-8% in this bin, which makes it the by far dominant uncertainty in the low m_T^W region. For higher transverse masses, the E_T^{miss} uncertainty decreases and becomes negligibly small, i.e. it is below 1% above around $m_T^W = 400$ GeV. As seen in the MC-data comparisons in the measurement binning in Sec. 9.2.4, there is a substantial deviation of the prediction from the data in the low m_T^W region, i.e. in particular in the first m_T^W bin. Even though the disagreement is expected to arise from the E_T^{miss} modeling, and in particular the soft term, it is not covered completely by the given systematic uncertainty.

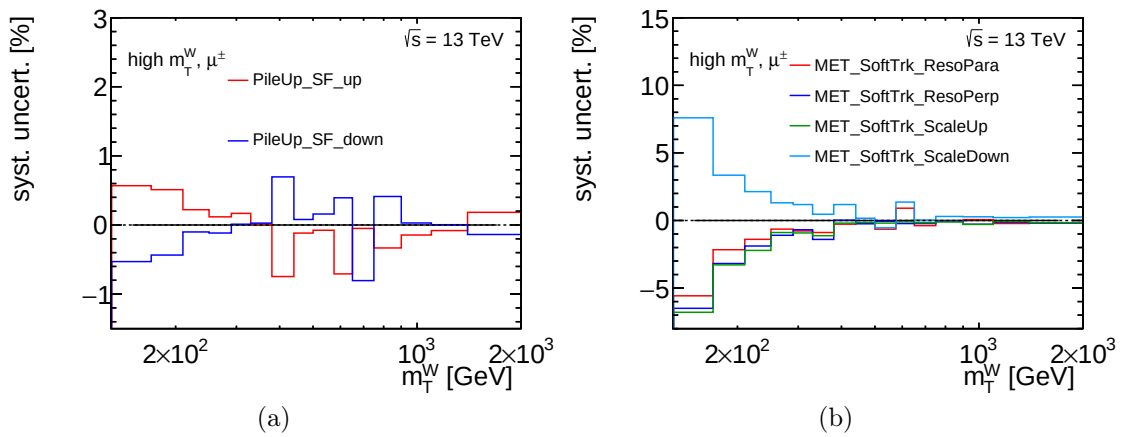


Figure 10.1.: Systematic uncertainty due to the (a) pileup re-weighting scale factor and (b) E_T^{miss} soft track term. The relative uncertainty is shown, with respect to the nominal $W \rightarrow \mu\nu$ MC, in the signal region in the measurement binning in the transverse mass of the W boson.

10.1.4. Muon uncertainties

In order to correct for small differences between MC and data, scale factors for the measurement of the muon are applied to the MC. These SFs were determined by the tag-and-probe method in $Z \rightarrow \mu\mu$ and $J/\Psi \rightarrow \mu\mu$ events [30]. The total muon SF is composed of dedicated SFs for the muon identification, isolation, trigger and track-to-vertex-association (TTVA)¹. Naturally, statistical and systematic uncertainties occur in the measurement of each of these SFs, which are propagated into this measurement in form of systematic uncertainties.

Moreover, systematic uncertainties for the resolution and scale in the measurement of the muon are evaluated. The resolution uncertainty is estimated by smearing the track of the muon, while a differentiation between the uncertainty in ID and the MS is made. One global uncertainty is defined for the muon momentum scale, which is obtained by varying the transverse momentum of the muon in the calibration. Lastly, one uncertainty accounts for a charge-dependent sagitta bias in the data [50]. At the moment no sagitta bias correction is applied, which is recommended by the MCP² group for analyses sensitive to the high p_T tail of the muon momentum distribution. The relative systematic uncertainties on the signal MC associated with the muon are shown in Fig. 10.2. At the moment, no uncertainty for the isolation SF can be obtained due to a problem in the used framework [52]. In general, the uncertainty associated with the isolation SF is expected to be in the order of 1-2 % and is, therefore, neglected for the purpose of this thesis. The problem was solved in a newer version of the framework, i.e. the isolation SF uncertainty can be easily added in a future analysis. The trigger and TTVA SF uncertainties are found to be below 1 % over the full m_T^W range. A maximum of around 2.5 % can be observed in the muon identification SF variations in Fig. 10.2c while the uncertainty is the largest at the high mass tail. Fig. 10.2d shows the muon scale, resolution and sagitta bias uncertainties. Overall, the uncertainties associated with the measurement of the muon are in the order of a few percent, with the exception of large statistical fluctuations which are, in particular, dominant for the MUON_SAGITTA_RESBIAS_up uncertainty in the high m_T^W region (see e.g. the second to last bin in Fig. 10.2d). These are caused by a known issue of a large discrepancy between the weights in the inclusive sample and the high mass slices in the signal MC, as discussed in detail in appendix A.1. Fig. A.4 shows a comparison of the sagitta bias uncertainties per muon charge if only the high mass slices and not the inclusive sample are taken into account as a part of the signal MC. It can be observed that the large fluctuations disappear if no events from the inclusive sample can migrate to the high mass region. Nevertheless, this sample is indispensable as a part of the MC in order to describe the signal process correctly. Thus, these fluctuations are kept at the moment but they need to be studied again when considering the full Run 2 dataset in the future.

¹The track-to-vertex-association includes the general cuts on the track parameters d_0 and z_0 , as introduced in Sec. 5.2.

²Muon Combined Performance. This ATLAS sub-group provides the systematic uncertainties associated with the measurement of the muon [51].

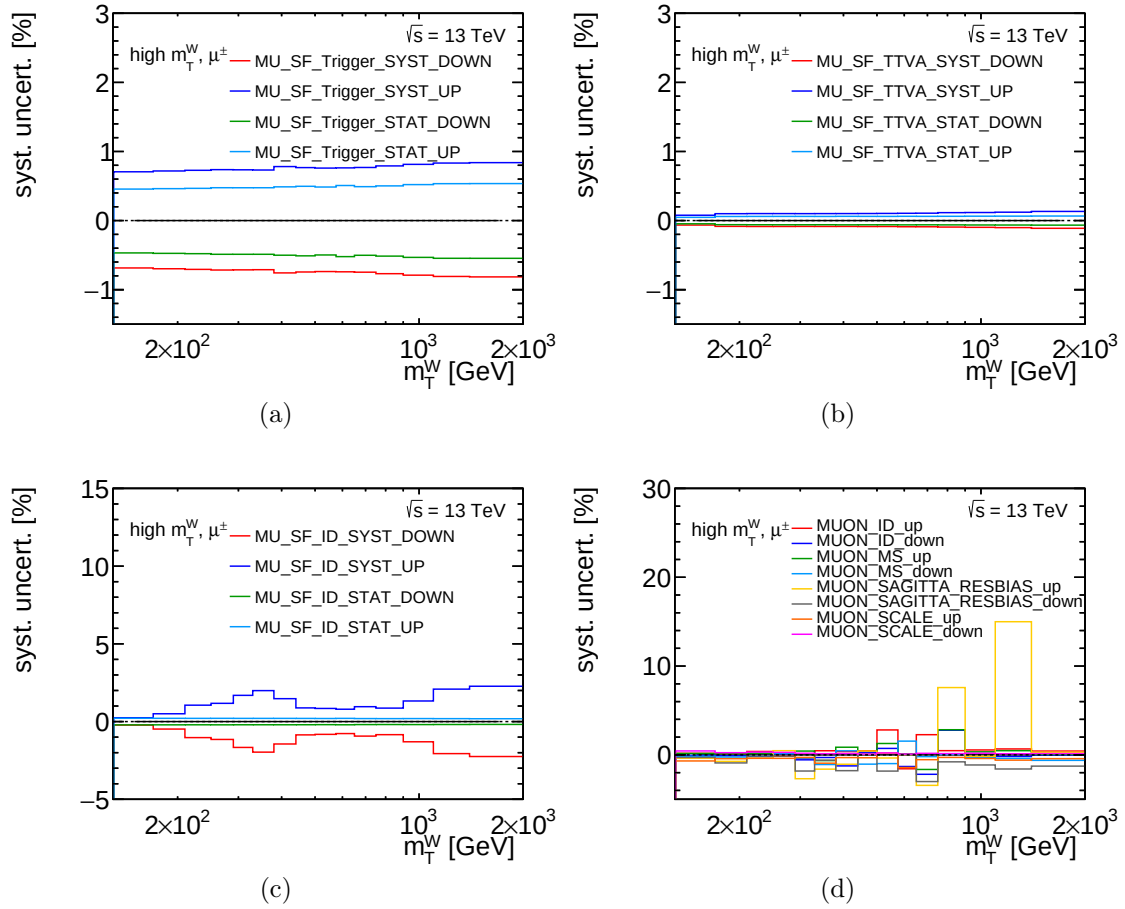


Figure 10.2.: Systematic uncertainties associated with the muon with respect to the nominal signal. In (a)-(c) uncertainties on the muon SF are shown, while in (d) the muon resolution, scale and sagitta bias correction uncertainties are shown.

10.1.5. Jet uncertainties

Also for the measurement of jets, scale and resolution systematic uncertainties are considered [53]. The detector response of jets underlays a calibration where MC is compared to data. Systematic uncertainties on this calibration are provided, which are called jet energy scale (JES) uncertainties. In this analysis, the Category Reduction scheme is used, which consists of 29 nuisance parameters (NPs). Sources of JES uncertainties are for example detector effects, the flavor composition, pileup or statistical uncertainties in the jet calibration. Furthermore, there are systematic uncertainties for the jet energy resolution (JER). These account for the limited resolution provided by the calorimeters and are derived from MC-data comparisons in dijet events. A set of eight NPs is used, which is called SimpleJER. Since this analysis is inclusive in jets, the effects of all jet uncertainties are only considered secondarily through the missing transverse momentum. Thus, the impact of the jet uncertainties is expected to be

small and it is reasonable to use these reduced models.

The relative systematic uncertainties associated with jets on the signal are shown in Fig. 10.3. Only the JES uncertainties with contributions larger than 1 % in at least one m_T^W bin are presented here, while the remaining NPs can be found in Fig. A.21 in the appendix. The largest systematic uncertainties due to JES are given by the flavor composition as well as the pileup. Nevertheless, their impact is rather small and in most bins below 1 %. The single largest uncertainty, which is `JES_Flavor_comp`, is around 2 % in the first m_T^W bin. However, this is a very conservative estimation, since the flavor composition, which is the fraction of gluon over non-b-tagged quarks initiating a jet, and its dedicated uncertainty is analysis specific, in principle [54]. At this point, the flavor composition is not yet studied and the maximal possible uncertainty is assumed. The JER uncertainties are shown in Fig. 10.3b. For each NP there is only one variation defined, here labeled as ‘up’. However, these uncertainties will be symmetrized around the central value to get a down-variation, in addition. It can be observed that the relative systematic uncertainties due to JER are always below 2.5 % and, in most bins, even below 1 %. Some statistical fluctuations at a few hundred GeV are visible, which can be traced back to the issue with the weights on the inclusive $W \rightarrow \mu\nu$ sample, as discussed in appendix A.1. Overall, the systematic uncertainties relating to jets are relatively small, as expected.

10.1.6. Multijet uncertainties

The multijet (MJ) background is obtained data-driven as opposed to the signal process as well as all other backgrounds that are simulated in MC. While for these dedicated systematic uncertainties are provided, uncertainties associated with the multijet background are obtained data-driven. As presented in Chapter 7.3, the multijet background is calculated using real and fake efficiencies. In particular, the calculation of the fake

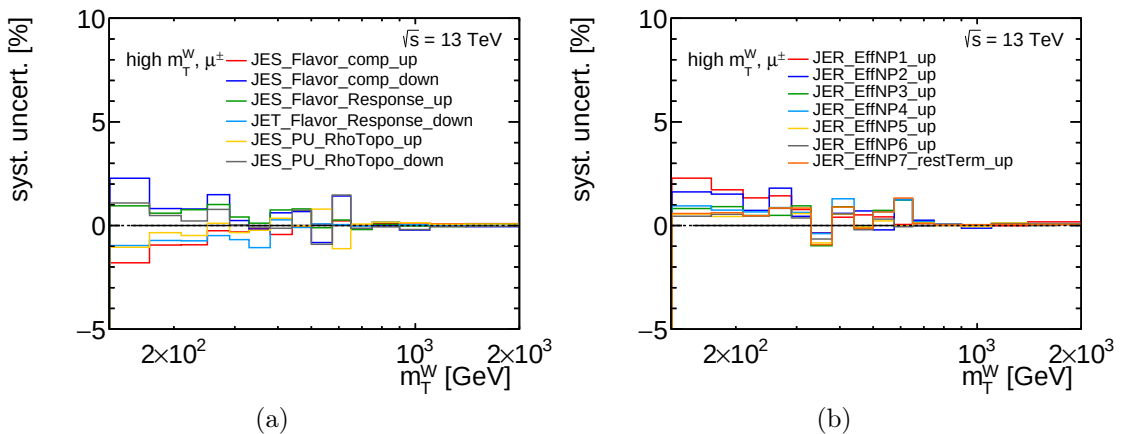


Figure 10.3.: Systematic uncertainties due to the (a) jet energy scale (only the largest ones shown here, more can be found in Fig. A.21 in the appendix) and (b) jet energy resolution.

efficiency is ambiguous and e.g. dependent on the choice of the region that it is calculated in. A QCD enriched region for the estimation of the fake efficiency was defined in Sec. 7.3.3. However, its definition is to a certain degree arbitrary. To cover this, the following changes are made individually with respect to this region and taken as systematic variations.

- Omitting the additional jet requirement,
- Changing $\Delta R(jet, \mu)$ to $\pi/2$,
- Restricting E_T^{miss} to 0 GeV to 40 GeV,
- Restricting E_T^{miss} to 40 GeV to 65 GeV,
- Omitting the d_0^{sig} cut³,
- Increasing the d_0^{sig} cut to 2.

Furthermore, an uncertainty on the cross section of the MC processes which are used for the multijet estimation is taken into account by scaling the number of MC events in the calculation of the fake efficiency.

- Scaling of the cross section of all MC processes by $\pm 6\%$.

For all these changes an alternative fake efficiency is calculated and, as a result, an alternative multijet background in the signal region. This is then taken as one-sided systematic variations.

All variations are shown with respect to the nominal multijet background in Fig. 10.4a. The relative systematic uncertainties are in the order of 30 % to 50 % over the full m_T^W range. The largest impact in the first m_T^W bin is given by restricting E_T^{miss} to 40-65 GeV

³Of course, only the $d_0^{\text{sig}} > 1$ cut used to define the QCD enriched region is omitted. The general TTVA cut on d_0^{sig} , as stated in Sec. 5.2, is kept over the full analysis.

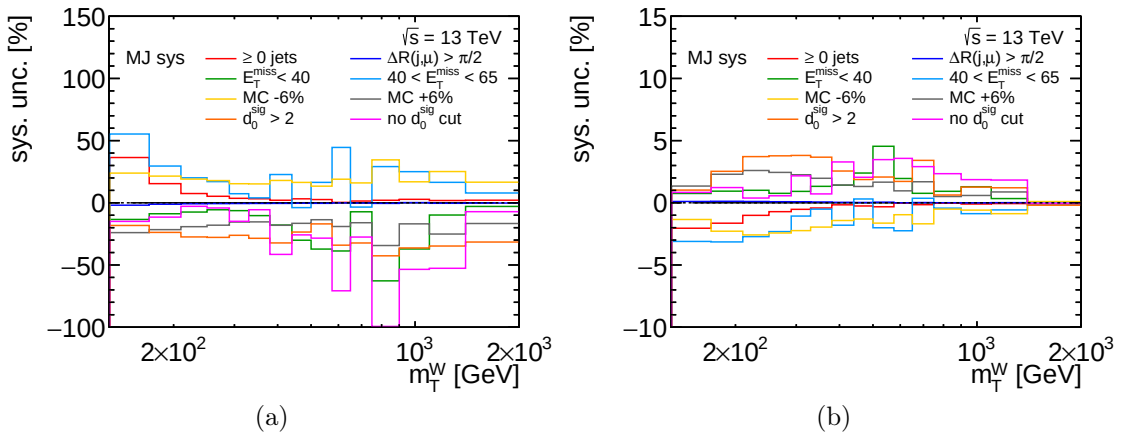


Figure 10.4.: Relative systematic uncertainty associated with the multijet background (a) normalized to the nominal multijet background, (b) normalized to the signal event yield in the data, $N_{\text{data}} - N_{\text{bkg}}$.

or omitting the additional jet requirement in the definition of the QCD enriched region. The impact of an increased angle between jet and muon, a region enriched in dijet events with back-to-back topology, is found to be negligibly small. A scaling of the MC cross sections yields a roughly constant variation of around 20 % over the full kinematic range and is approximately symmetric around the nominal value. Also for the cut value on d_0^{sig} a symmetric variation was chosen, the nominal value of one is varied to zero or two. However, it can be observed in Fig. 10.4 that both variations lead to fewer events than in the nominal multijet process. This behavior can not be explained in detail at this point but might be due to poor modeling of d_0 . The d_0^{sig} variations are among the largest multijet systematic uncertainties in the high m_T^W region with around 50 % in the second last bin. Overall, some statistical fluctuations are visible in the multijet uncertainties, in particular the ones associated with E_T^{miss} and d_0^{sig} .

Finally, the impact of the MJ uncertainties on the cross section measurement is important. So far, systematic uncertainties were shown with respect to the nominal signal process. In the case of background uncertainties, as shown here, the relative systematic uncertainty can be scaled to the cross section as follows. As given in eq. 2.3, the cross section is proportional to the number of data events subtracted by the sum of all background events. Hence, the absolute uncertainty is propagated linearly⁴ via $\Delta(N_{data} - N_{bkg}) = -\Delta N_{bkg}$, where ΔN_{bkg} is the absolute difference between the nominal multijet background and a systematically varied multijet background. As a result, the relative uncertainty on the number of signal events, and hence also cross section, is given by $-\Delta N_{bkg}/(N_{data} - N_{bkg})$. Exactly this is shown in Fig. 10.4b for all systematic uncertainties on the multijet background. As presented in Chapter 8, the MJ background contributes overall less than 10 % to the total data. Therefore, the relative systematic uncertainty on $N_{data} - N_{bkg}$, i.e. the cross section, is in the order of max. 4 %. The relative uncertainty decreases with the transverse mass m_T^W because the contribution of fake muon events is small at very high masses (see Tab. A.1 in the appendix).

10.2. Theoretical uncertainties

In addition to the experimental uncertainties that were discussed above, theoretical uncertainties are considered in form of systematic uncertainties. These were already discussed for the largest background, which is the $t\bar{t}$ process, in Sec. 7.1. Similarly, it is important to consider these theoretical uncertainties for the signal $W \rightarrow \mu\nu$ process. Unfortunately, the weights needed for this were not available in the course of this thesis. In a future analysis, systematic uncertainties for the factorization and renormalization scale, final and initial state radiation will be taken into account, as well as different PDF models. The signal PDF used in this analysis is CT10 [55]. This measurement is expected to show a high sensitivity to the PDF modeling (see Sec. 2.3), therefore in particular the PDF variations will be essential to understand and interpret the

⁴Under the assumption that this one background uncertainty is, in this case, the only uncertainty.

measurement results in detail. Lastly, alternative MC for the showering and matrix element need to be considered, as soon as they are available.

All theoretical systematic uncertainties on the $t\bar{t}$ process were introduced and discussed for the top CR in Chapter 7.1. Nevertheless, their impact in the signal region is of interest. Their expected impact on the cross section can be extrapolated as presented in Sec. 10.1.6. In Fig. 10.5 systematic uncertainties on the $t\bar{t}$ background for the scale, ISR/FSR, PDF and alternative generators are shown. A re-binning is applied by merging the last four m_T^W bins and then the relative uncertainty is normalized to signal yield in the data, $N_{data} - N_{bkg}$. It can be observed over all theoretical uncertainties that their impact on the cross section to be measured is rather small and at maximum in the order of 1% to 2%. The impact is, in particular, very small in the region of low and very high m_T^W . At low transverse masses, the systematic uncertainty itself is rather small, as it was seen in the top CR (see Fig. 7.8). In the very high mass tail, however, only a few $t\bar{t}$ events are present (see Tab. A.1), thus the impact of their uncertainty on the cross section is negligible in this region.

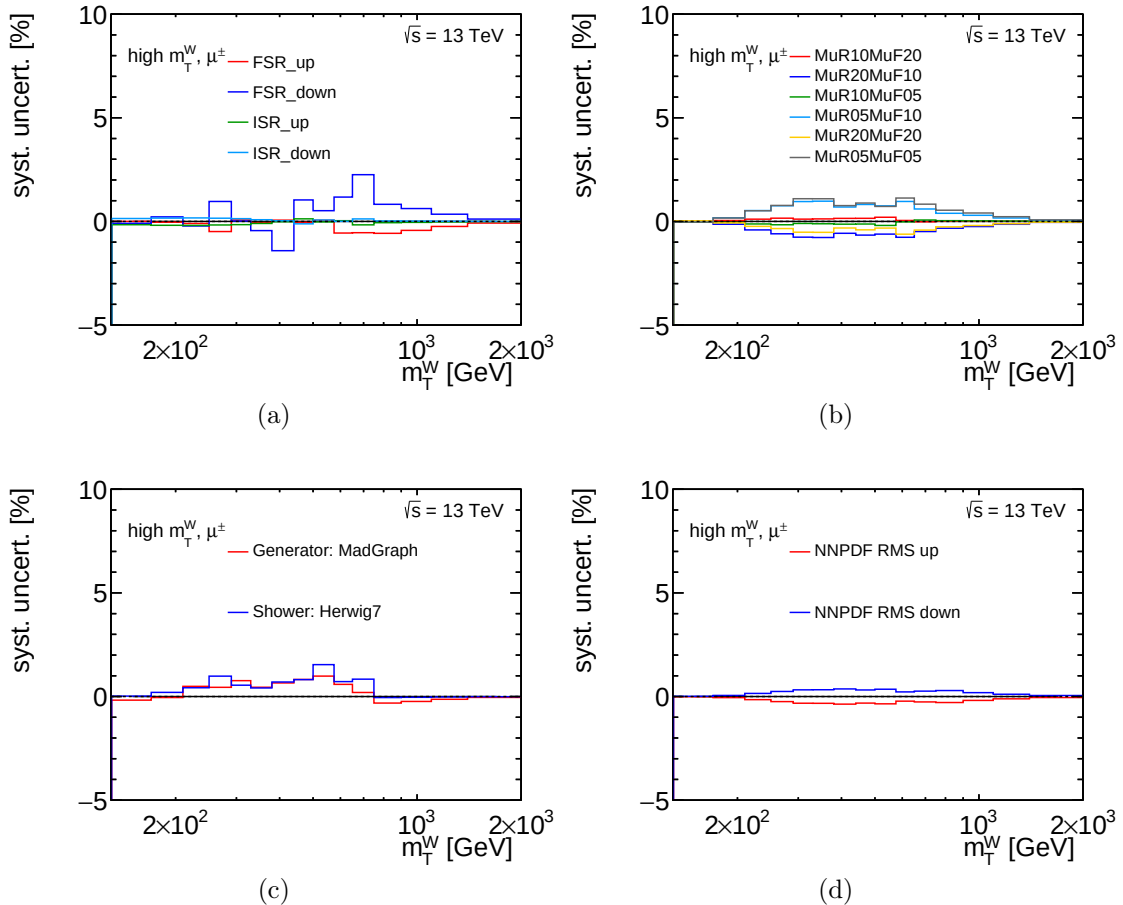


Figure 10.5.: Theoretical systematic uncertainties on the $t\bar{t}$ MC, as defined in Sec. 7.1.1. They are normalized to $N_{data} - N_{bkg}$, which gives the relative impact on the measured cross section.

11. Measurement results

In this chapter, the final unfolded differential cross section for the charged-current Drell-Yan process is presented. Results for the combination of both muon charges, as well as for μ^+ and μ^- separately, are given. The number of iterations in the IBU is set to one, while no final optimization of this number was done. Nevertheless, two, three and four iterations were tested and a consecutively increasing total uncertainty was observed. These alternative results can be found in Fig. A.22, Fig. A.23 and Fig. A.24 in the appendix.

The final cross sections as a function of the transverse mass of the W boson are shown in Fig. 11.1 for the combination of both charges and in Fig. 11.2 for the charge separated processes, respectively. It can be observed that the cross section is decreasing by four orders of magnitude over the investigated m_T^W range of 130 GeV to 2000 GeV. The cross section for the production of a positively charged W boson is larger than for a negatively charged W boson, as expected in pp collisions. Statistical and systematic uncertainties are included in the measurement results. In general, the statistical uncertainty on the cross section is given by the combination of the statistical uncertainty in the data and simulated background processes. However, the statistical uncertainty in the MC is found to be negligible compared to the data uncertainty, as seen in Tab. A.1 in the appendix. Only systematic uncertainties that have a contribution larger than 1% in any m_T^W bin are taken into account in these final results. In addition to the plots, the measured cross section as well as the total relative systematic and statisti-

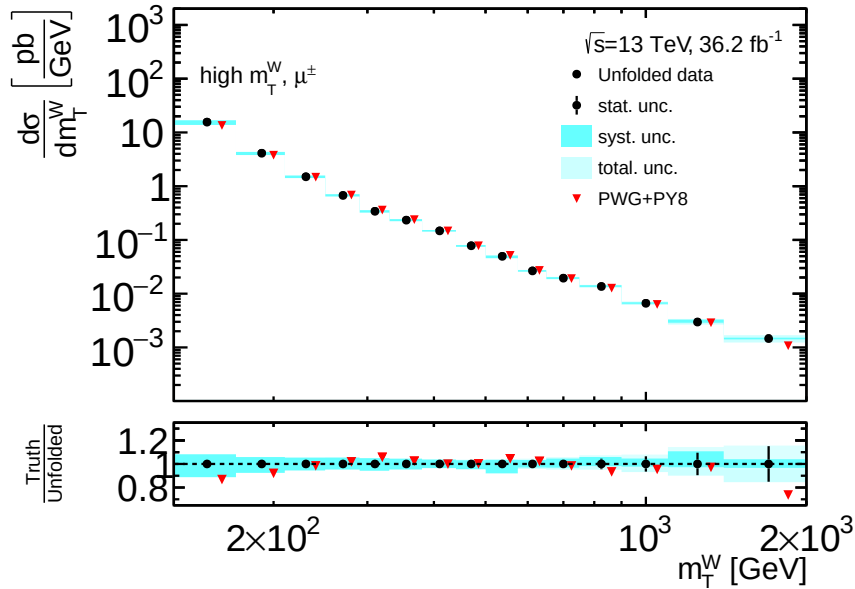
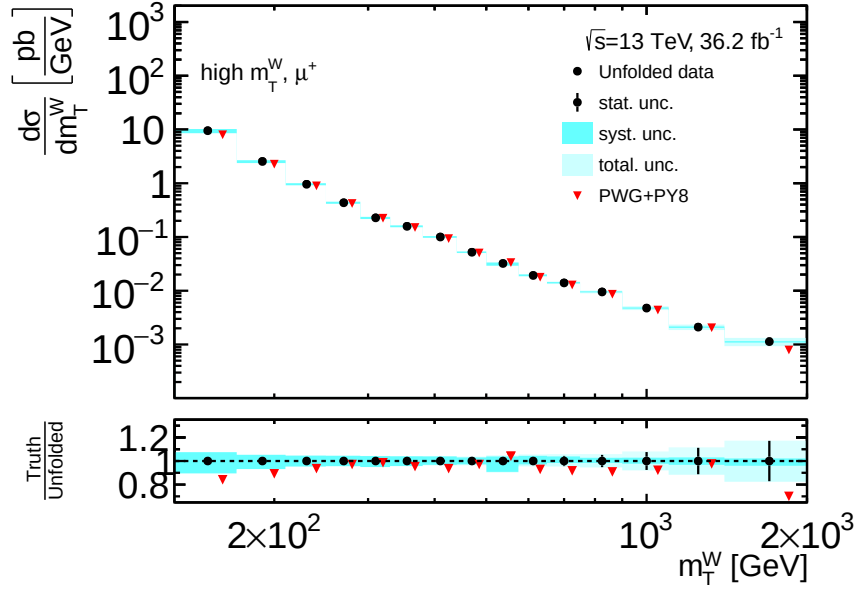
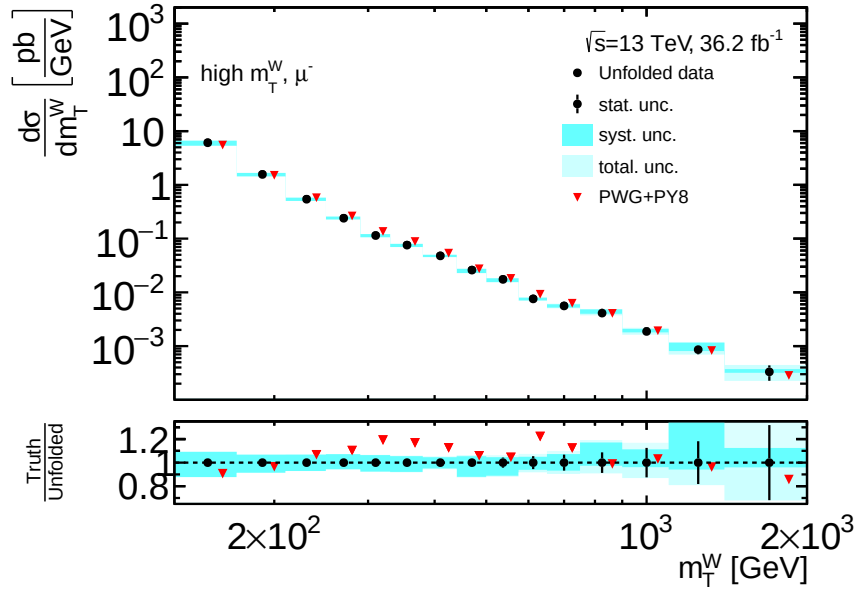


Figure 11.1.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range 130 GeV to 2000 GeV for the combined process $W^\pm \rightarrow \mu^\pm \nu$. Statistical and systematic (larger than 1% in at least one m_T^W bin) uncertainties are included. The luminosity uncertainty is excluded. A comparison to the POWHEG+PYTHIA 8 fiducial born level is made.



(a)



(b)

Figure 11.2.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range 130 GeV to 2000 GeV for the charge-separated processes (a) $W^+ \rightarrow \mu^+ \nu$ and (b) $W^- \rightarrow \mu^- \bar{\nu}$. Statistical and systematic (larger than 1% in at least one m_T^W bin) uncertainties are included. The luminosity uncertainty is excluded. A comparison to the POWHEG-BOX+PYTHIA 8 fiducial born level is made.

cal uncertainty per bin are summarized in Tab. 11.1 ($\mu^\pm$ comb.), Tab. 11.2 (μ^+) and Tab. 11.3 (μ^-). A list of all considered systematic uncertainties and their individual

contribution in percent per m_T^W bin is included in these tables. Lastly, the uncertainty associated with the luminosity is written in the tables but not considered in the plots. The most dominant sources of systematic uncertainties are E_T^{miss} and the multijet estimation. The E_T^{miss} systematic uncertainties make up most of the total uncertainty in the first m_T^W bin and extend up to around 5 % to 7 % each. In the region of intermediate transverse masses, the multijet uncertainties contribute with several percent (2 % to 4 %). Above around $m_T^W = 900$ GeV, the statistical uncertainty becomes predominant and exceeds the systematic ones. The statistical uncertainty increases up to 15 % in the combination of both charges and 17 %/32 % in μ^+/μ^- -channels, respectively. However, the statistical uncertainty is expected to decrease by half when this measurement will be done on the full Run 2 dataset in the future, as discussed in Sec. 9.2.3. Overall, the systematic uncertainty band is slightly more pronounced in the μ^- -channel. It is remarkable in Fig. 11.2b that out of the last four m_T^W bins two bins show a rather large one-sided systematic uncertainty. This behavior also propagates to the charge-combined channel in Fig. ???. The issue can be traced back to the uncertainty associated with the muon sagitta bias. It could be shown that these fluctuations are induced by a few events with very large weights that migrate from the peak sample to the high m_T^W region (see appendix A.1 for more on this). However, the effect is slightly less pronounced after the unfolding if compared with Fig. 10.2, which shows this particular uncertainty before the unfolding. In general, it can be observed that all systematic and statistical uncertainties have slightly different magnitudes per bin before and after the unfolding procedure.

In Fig. 11.1 and Fig. 11.2, a ratio comparing the unfolded data to the truth level of the POWHEG-BOX+PYTHIA 8 signal MC is included. No theoretical systematic uncertainties or alternative MC of the signal process could be taken into account, so only a comparison with the particular MC that is also the basis of the modeling and unfolding could be made. The deviation of the theoretically predicted MC truth level from the unfolded measured data is shown. In the combination of both charges in Fig. 11.1, it can be observed that the deviation between MC truth and unfolded data is covered by the systematic and statistical uncertainties reasonably well in most bins. The small deviation in the first m_T^W bin that was already seen in the MC-data comparison plots on reconstruction level shown in Sec. 9.2.4 is also reflected here. It can be linked to a known issue in the estimation of the E_T^{miss} , which was seen in other analyses as well. Looking at the results separated per muon charge, clear differences can be observed. Overall, the results in the μ^+ -channel show a slightly better agreement between the theoretical prediction and the measurement. Substantial deviations between MC truth and unfolded data are only observable in the first and last bin. In general, a trend of an underestimated cross section in the truth MC is noticeable. An opposite trend can be observed in the results of the μ^- -channel, where the ratio is in many bins substantially above unity. In particular around 250 GeV to 450 GeV, the difference between POWHEG-BOX+PYTHIA 8 and the unfolded data extends up to 20 % and is distinctly not covered by the estimated uncertainties. It is not exactly clear why there is such a noticeable difference in the agreements between data and prediction for the two muon charges. However, this tendency was already seen in the MC-data comparison plots on reconstruction level in Sec. 9.2.4.

Table 11.1.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range of 130 GeV to 2000 GeV for the combined $W^\pm \rightarrow \mu^\pm \nu$ process, including statistical and systematic uncertainties. Only systematic uncertainties with a contribution larger than 1% in any m_T^W bin are taken into account. All uncertainties are given in percent with respect to the nominal cross section.

m_T^W [GeV]	130 - 170	170 - 210	210 - 250	250 - 290	290 - 330	330 - 380	380 - 440	440 - 500	500 - 575	575 - 650	650 - 750	750 - 900	900 - 1100	1100 - 1400	1400 - 2000
σ [pb/GeV]	1.55e+01	4.10e+00	1.49e+00	6.72e-01	3.40e-01	2.33e-01	1.47e-01	7.78e-02	4.94e-02	2.65e-02	1.94e-02	1.36e-02	6.61e-03	2.96e-03	1.46e-03
stat. unc. [%]	0.18	0.29	0.50	0.74	0.98	1.23	1.51	1.93	2.45	2.98	3.66	4.49	6.50	9.54	15.10
tot. sys. unc. [%]	8.18 -11.36	5.85 -7.61	5.37 -5.65	5.40 -4.85	4.88 -5.80	4.43 -4.77	3.72 -3.41	3.16 -4.41	3.45 -7.91	3.37 -3.00	4.62 -3.16	5.94 -1.88	4.44 -2.13	10.69 -2.68	3.95 -2.70
lumi. unc. [%]	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
MET SoftTrk Scale	-6.26 6.94	-3.69 3.86	-2.25 2.27	-1.19 1.47	-0.96 1.10	-0.95 0.72	-0.37 0.89	-0.18 0.28	-0.18 -0.09	-0.14 0.69	-0.15 0.32	-0.15 0.26	-0.23 0.27	-0.13 0.24	-0.15 0.25
MET SoftTrk ResoPara	-5.06	-2.60	-1.45	-0.82	-0.78	-0.77	-0.39	-0.29	-0.33	0.30	-0.08	-0.06	0.01	-0.16	-0.19
MET SoftTrk ResoPerp	-5.99	-3.54	-2.04	-1.22	-0.90	-1.05	-0.30	-0.18	-0.12	-0.19	-0.20	-0.10	-0.22	-0.17	-0.17
MU ID	0.17 -0.05	0.17 -0.10	0.27 -0.13	-0.06 -0.05	-0.20 -0.37	0.27 -0.46	0.40 -0.83	0.80 0.01	1.67 0.27	0.10 -0.97	1.22 -1.15	0.79 1.41	0.58 0.30	0.62 0.15	0.48 -0.06
MU MS	0.15 -0.17	0.13 -0.21	0.19 -0.09	0.21 0.02	0.20 -0.36	-0.20 -0.70	0.47 -0.06	0.43 -0.70	0.84 -0.61	0.07 0.63	-0.51 0.16	-0.51 1.65	0.81 -0.35	0.43 -0.41	-0.15 0.56
MU SAGITTA RESBIAS	-0.44 -0.39	-0.63 -0.72	-0.35 -0.29	-0.35 -0.39	-1.79 -1.23	-1.68 -0.99	-0.95 -1.30	-0.06 -0.68	-0.22 -1.22	-0.63 -0.90	-0.91 -2.00	4.45 -1.22	10.28 -1.13	3.19 -1.46	-3.19 -1.34
MU SCALE	-0.64 0.42	-0.46 0.29	-0.39 0.30	-0.38 0.23	-0.41 0.20	-0.70 0.15	-0.42 0.14	-0.25 0.13	-0.16 0.17	-0.88 0.13	-0.66 0.15	-0.37 0.16	-0.41 0.17	-0.54 0.15	-0.46 0.15
MU SF ID SYST	0.29 -0.27	0.53 -0.51	0.97 -0.95	1.23 -1.20	1.62 -1.59	1.83 -1.81	1.48 -1.45	1.02 -0.99	0.87 -0.84	0.85 -0.82	0.92 -0.89	0.95 -0.93	1.33 -1.31	1.95 -1.93	2.23 -2.20
JES Flavor Composition	-1.67 2.07	-1.07 1.05	-0.85 0.89	-0.40 1.15	-0.29 0.44	-0.23 0.06	-0.32 0.47	-0.10 0.41	0.06 -0.18	0.14 0.63	0.11 0.16	-0.06 0.16	0.01 -0.05	-0.03 -0.15	0.04 -0.05
JES Flavor Response	0.90 -0.93	0.67 -0.76	0.76 -0.70	0.86 -0.57	0.49 -0.69	0.28 -0.78	0.63 -0.04	0.62 -0.00	0.14 0.04	0.11 0.03	-0.06 0.02	0.01 0.12	-0.00 0.06	-0.03 -0.00	0.04 0.03
JES Pileup RhoTopology	-0.94 0.99	-0.47 0.55	-0.38 0.34	-0.08 0.55	-0.22 0.17	-0.16 0.04	0.18 0.00	0.18 0.27	0.34 -0.22	-0.46 0.64	-0.13 0.18	0.13 -0.07	0.13 -0.14	0.08 -0.08	0.07 -0.04
JER EffectiveNP 1	2.19 -2.19	1.76 -1.76	1.42 -1.42	1.30 -1.30	0.73 -0.73	0.01 -0.01	0.29 -0.29	0.46 -0.46	0.39 -0.39	0.15 -0.15	0.09 -0.09	0.07 -0.07	0.02 -0.02	0.02 -0.02	0.14 -0.14
JER EffectiveNP 2	1.60 -1.60	1.43 -1.43	1.02 -1.02	1.37 -1.37	0.60 -0.60	0.02 0.02	0.43 -0.43	0.52 -0.52	0.21 -0.21	0.74 -0.74	0.40 -0.40	0.06 -0.06	-0.06 0.06	0.06 -0.06	0.09 -0.09
MU: 40 < E_{T}^{miss} [GeV] < 65	-3.03 -0.79	-3.02 -0.82	-2.79 0.35	-2.31 -0.21	-1.91 -1.31	-1.70 -1.48	-1.46 -0.21	-0.53 -3.81	-1.49 -5.86	-1.62 -0.51	-0.33 0.80	-0.39 0.88	-0.74 1.07	-0.52 0.46	-0.05 0.04
MU: $d_0^{s19} > 2$	1.26	2.40	3.40	3.65	3.65	3.42	2.62	2.04	1.96	2.05	2.50	1.18	1.14	0.99	0.92
MU: no d_0^{s19} cut	0.71	0.92	0.33	-1.59	-3.42	-1.48	-0.36	-0.25	-4.57	0.82	2.62	2.30	1.92	1.53	0.24
MU: $N_{jets} > 0$	-2.02	-1.63	-1.08	-0.73	-1.08	-0.39	-0.23	-0.24	-0.25	-0.11	-0.11	-0.06	-0.08	-0.06	0.00
MU: MC scaling by $\pm 6\%$	1.50	2.16	2.46	2.37	2.18	1.89	1.50	1.37	1.45	1.21	1.31	0.72	0.61	0.66	0.04
$t\bar{t}$ theory: PSR	-0.00 -0.05	-0.04 0.13	-0.14 0.02	-0.33 0.58	-0.08 0.13	-0.03 0.48	0.02 -0.86	-0.01 0.43	-0.07 0.71	-0.43 1.23	-0.54 1.76	-0.55 1.04	-0.44 0.65	-0.26 0.38	-0.11 0.16
$t\bar{t}$ theory: showering	-0.16	-0.01	0.38	0.49	0.64	0.55	0.66	0.82	0.89	0.60	0.20	-0.19	-0.22	-0.13	-0.06

Table 11.2.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range of 130 GeV to 2000 GeV for the $W^+ \rightarrow \mu^+ \nu$ process, including statistical and systematic uncertainties. Only systematic uncertainties with a contribution larger than 1 % in any m_T^W bin are taken into account. All uncertainties are given in percent with respect to the nominal cross section.

m_T^W [GeV]	130 - 170	170 - 210	210 - 250	250 - 290	290 - 330	330 - 380	380 - 440	440 - 500	500 - 575	575 - 650	650 - 750	750 - 900	900 - 1100	1100 - 1400	1400 - 2000
σ [pb/GeV]	9.49e+00	2.54e+00	9.56e-01	4.33e-01	2.27e-01	1.58e-01	9.98e-02	5.19e-02	3.21e-02	1.92e-02	1.40e-02	9.48e-03	4.75e-03	2.10e-03	1.13e-03
stat. unc. [%]	0.23	0.37	0.61	0.89	1.16	1.43	1.78	2.29	2.97	3.54	4.34	5.21	7.60	11.21	17.13
tot. sys. unc. [%]	7.47 -10.66	5.25 -6.93	4.56 -4.80	4.44 -4.47	4.19 -5.07	3.98 -4.22	3.87 -3.21	3.03 -2.75	3.86 -9.20	4.40 -2.85	3.94 -1.70	2.85 -1.64	2.66 -2.30	2.79 -3.21	2.08 -4.01
lumi. unc. [%]	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
MET SoftTrk Scale	-5.77	-3.36	-1.89	-1.08	-0.69	-0.48	-0.20	-0.15	-0.19	-0.13	-0.18	-0.18	-0.25	-0.07	-0.15
MET SoftTrk ResoPara	6.32	3.51	2.03	1.18	1.10	0.63	0.94	0.27	-0.23	1.07	0.49	0.25	0.23	0.17	0.21
MET SoftTrk ResoPerp	-5.10	-2.66	-1.18	-0.70	-0.13	-0.49	-0.01	-0.10	-0.39	0.59	-0.04	-0.11	-0.01	-0.12	-0.18
MU ID	-5.63	-3.16	-1.78	-1.19	-0.66	-0.53	-0.16	-0.11	-0.15	-0.18	-0.25	-0.12	-0.25	-0.14	-0.18
MU MS	0.29	0.28	0.40	-0.13	-0.14	0.04	-0.10	0.38	1.16	0.63	-0.19	0.30	0.55	0.60	0.33
MU SAGITTA RESBIAS	-0.11	-0.13	-0.08	-0.06	0.02	0.07	-0.97	-0.48	-0.02	-0.21	-0.16	-0.12	-0.25	-0.11	0.02
MU SCALE	0.17	0.18	0.09	0.21	0.22	-0.28	1.37	0.14	0.61	1.41	0.48	-0.05	0.23	0.30	-0.10
MU SF ID SYST	-0.13	-0.13	-0.09	-0.07	-0.30	-0.45	0.08	-1.05	-0.91	1.28	0.36	-0.01	-0.28	-0.35	-0.63
JES Flavor Composition	-0.24	-0.36	-0.15	-0.05	-0.80	-1.57	-0.94	0.01	-0.95	-0.75	-0.08	-0.01	0.29	0.36	0.11
JES Flavor Response	-0.31	-0.71	-0.35	-0.61	-0.99	-1.92	-0.92	-0.70	-1.95	-0.08	-0.51	-1.13	-1.48	-2.32	-3.38
JES Pileup RhoTopology	-0.58	-0.45	-0.38	-0.37	-0.30	-0.53	-0.36	-0.34	-0.43	-0.25	-0.46	-0.37	-0.47	-0.46	-0.44
JER EffectiveNP 1	0.36	0.30	0.23	0.31	0.22	0.15	0.11	0.12	0.17	0.12	0.16	0.17	0.15	0.12	0.12
JER EffectiveNP 2	0.29	0.52	0.95	1.22	1.63	1.84	1.45	1.00	0.82	0.79	0.79	0.88	1.23	1.77	2.00
MJ: $40 < E_T^{\text{miss}}$ [GeV] < 65	-0.26	-0.50	-0.93	-1.19	-1.60	-1.82	-1.43	-0.98	-0.80	-0.76	-0.77	-0.86	-1.20	-1.74	-1.98
MJ: $0 < E_T^{\text{miss}}$ [GeV] < 40s	-1.73	-0.90	-0.50	-0.13	-0.32	-0.10	0.03	0.06	0.11	0.08	-0.02	0.14	0.12	0.19	0.13
JES Flavor Composition	2.25	0.95	0.74	0.69	0.40	0.21	0.98	0.10	-0.48	1.08	0.26	-0.07	-0.19	-0.06	-0.08
JES Flavor Response	0.82	0.63	0.53	0.55	0.53	0.25	0.93	0.19	-0.41	1.07	0.26	0.04	0.00	-0.01	0.05
JES Pileup RhoTopology	-0.85	-0.50	-0.47	-0.45	-0.67	-0.37	-0.03	-0.03	0.05	-0.00	-0.02	0.15	0.04	0.08	0.06
JER EffectiveNP 1	-0.98	-0.24	-0.12	0.19	-0.17	0.07	0.09	0.05	0.12	0.07	0.07	0.16	0.10	0.17	0.10
JER EffectiveNP 2	1.04	0.39	0.15	0.26	0.26	0.08	0.26	-0.10	-0.53	1.05	0.32	-0.05	-0.16	-0.08	-0.05
MJ: $40 < E_T^{\text{miss}}$ [GeV] < 65	1.76	1.52	1.18	1.01	0.74	0.14	0.08	-0.43	0.98	0.51	0.01	0.02	0.03	0.11	0.18
MJ: $d_0^{\text{sig}} > 2$	-1.76	-1.52	-1.18	-1.01	-0.74	-0.14	-0.08	0.43	-0.98	-0.51	-0.01	-0.02	-0.03	-0.11	-0.18
MJ: no d_0^{sig} cut	1.31	1.35	0.87	1.22	0.64	-0.02	0.29	-0.34	0.69	1.45	0.50	0.08	-0.08	0.09	0.10
MJ: $N_{jets} > 0$	-1.31	-1.35	-0.87	-1.22	-0.64	0.02	-0.29	0.34	-0.69	-1.45	-0.50	-0.08	0.08	-0.09	-0.10
MJ: MC scaling by $\pm 6\%$	-2.72	-2.77	-2.42	-1.99	-1.41	-1.76	-1.55	-1.24	-2.65	-1.91	0.25	-0.18	-0.82	-0.74	-0.10
$t\bar{t}$ theory: FSR	MJ: $0 < E_T^{\text{miss}}$ [GeV] < 40s	0.69	0.17	-0.30	-1.75	-0.77	0.80	0.02	-3.14	-0.13	-0.12	0.46	0.85	0.51	0.07
$t\bar{t}$ theory: showering	MJ: $d_0^{\text{sig}} > 2$	1.13	2.09	2.84	3.01	2.94	3.02	2.39	2.61	1.88	2.29	1.04	1.30	1.48	0.10
	MJ: no d_0^{sig} cut	0.62	0.87	0.09	-1.92	-3.19	0.04	-0.83	-1.05	-0.31	2.00	1.99	1.34	0.67	0.06
	MJ: $N_{jets} > 0$	-1.80	-1.41	-0.90	-0.61	-0.47	-0.30	-0.15	-0.17	-0.03	-0.08	-0.06	-0.11	-0.09	-0.00
	MJ: MC scaling by $\pm 6\%$	1.34	1.90	2.09	2.03	1.86	1.63	1.29	1.58	1.02	1.03	0.55	0.63	0.94	0.09
	$t\bar{t}$ theory: FSR	-1.33	-1.89	-2.08	-2.02	-1.85	-1.62	-1.28	-1.56	-1.01	-1.03	-0.55	-0.63	-0.94	-0.09
	$t\bar{t}$ theory: showering	-0.01	-0.03	-0.04	-0.06	0.17	0.06	0.16	-0.06	-0.46	-0.37	-0.34	-0.17	-0.10	-0.04
		0.03	0.02	-0.32	0.13	-0.17	-0.70	0.66	1.25	1.48	1.81	1.13	0.57	0.35	0.14
		-0.12	0.00	0.24	0.32	0.17	0.24	0.25	0.38	0.24	0.16	0.46	0.34	0.21	0.09

Table 11.3.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range of 130 GeV to 2000 GeV for the $W^- \rightarrow \mu^- \bar{\nu}$ process, including statistical and systematic uncertainties. Only systematic uncertainties with a contribution larger than 1% in any m_T^W bin are taken into account. All uncertainties are given in percent with respect to the nominal cross section.

m_T^W [GeV]	130	170	210	250	290	330	380	440	500	575	650	750	900	1100	1400
	- 170	- 210	- 250	- 290	- 330	- 380	- 440	- 500	- 575	- 650	- 750	- 900	- 1100	- 1400	- 2000
σ [pb/GeV]	6.07e+00	1.56e+00	5.40e-01	2.39e-01	1.14e-01	7.56e-02	4.77e-02	2.59e-02	1.74e-02	7.55e-03	5.59e-03	4.11e-03	1.87e-03	8.59e-04	3.32e-04
stat. unc. [%]	0.28	0.49	0.87	1.32	1.78	2.32	2.80	3.54	4.30	5.49	6.79	8.72	12.51	18.16	31.87
tot. sys. unc. [%]	9.18	6.77	6.79	7.18	6.40	5.50	4.61	5.43	4.63	4.99	7.31	17.13	11.09	34.35	12.41
	-12.36	-8.66	-7.09	-5.74	-7.64	-7.86	-4.92	-12.04	-11.08	-6.11	-6.79	-3.08	-3.30	-3.06	-3.01
MET SoftTtk Scale	-6.91	-4.17	-2.79	-1.35	-1.40	-1.73	-0.67	-0.23	-0.15	-0.15	-0.10	-0.07	-0.19	-0.28	-0.12
	7.77	4.34	2.62	1.93	1.10	0.88	0.81	0.32	0.22	0.08	0.03	0.29	0.38	0.40	0.36
MET SoftTtk ResoPara	-5.00	-2.51	-1.86	-1.01	-1.80	-1.23	-1.04	-0.62	-0.19	-0.16	-0.13	-0.04	0.04	-0.27	-0.21
MET SoftTtk ResoPerp	-6.48	-4.07	-2.42	-1.27	-1.30	-1.94	-0.53	-0.29	-0.08	-0.20	-0.09	-0.07	-0.14	-0.24	-0.15
	0.01	0.02	0.06	0.04	0.27	0.66	1.24	1.52	2.71	-0.66	3.67	1.67	0.63	0.68	0.87
MU ID	0.02	-0.06	-0.21	-0.04	-0.99	-1.37	-0.58	0.88	0.85	-2.21	-2.63	4.97	1.61	-0.24	-0.28
MU MS	0.13	0.06	0.30	0.19	0.17	-0.02	-1.02	1.03	1.35	-2.10	-1.94	5.60	2.18	0.74	0.80
	-0.23	-0.33	-0.07	0.16	-0.46	-1.11	-0.28	-0.06	0.01	-0.41	-0.17	-0.06	-0.18	-0.53	-0.39
MU SAGITTA RESBIAS	-0.70	-1.03	-0.66	-0.40	-3.35	-1.83	-0.95	-0.20	0.30	-2.85	-2.41	14.72	9.87	34.05	11.27
	-0.49	-0.73	-0.19	-0.04	-1.58	0.65	-1.92	-0.60	0.18	-2.20	-4.52	-1.25	-0.32	0.68	4.11
MU SCALE	-0.73	-0.47	-0.40	-0.38	-0.60	-1.00	-0.52	-0.10	0.40	-1.88	-0.98	-0.37	-0.29	-0.71	-0.52
	0.48	0.27	0.41	0.23	0.18	0.15	0.19	0.14	0.18	0.15	0.15	0.14	0.22	0.22	0.23
MU SF ID SYST	0.30	0.55	1.00	1.24	1.60	1.82	1.53	1.05	0.95	0.95	1.14	1.09	1.56	2.41	2.82
	-0.27	-0.53	-0.98	-1.22	-1.58	-0.23	-0.44	-0.37	-0.04	0.24	0.20	-0.04	0.10	-0.16	-0.02
JES Flavor Composition	-1.60	-1.33	-1.37	-0.84	-0.23	-0.44	-0.90	-0.37	-0.04	0.24	0.20	-0.04	0.10	-0.16	-0.02
	1.83	1.20	1.12	1.87	0.51	-0.19	-0.39	1.01	0.42	-0.08	-0.01	-0.01	-0.06	-0.05	0.04
JES Flavor Response	0.99	0.74	1.11	1.36	0.44	0.35	0.14	1.43	1.24	-1.41	-0.58	-0.05	-0.02	-0.06	0.02
	-1.04	-1.14	-1.04	-0.76	-0.74	-1.49	-0.07	0.03	0.00	-0.09	0.10	-0.05	0.08	-0.20	-0.04
JES Pileup RhoTopology	-0.91	-0.80	-0.77	-0.52	-0.31	-0.56	0.34	0.39	0.80	-1.31	-0.47	0.06	0.18	-0.14	-0.02
	0.94	0.78	0.64	1.00	0.02	-0.23	-0.42	0.99	0.37	-0.01	-0.06	-0.13	-0.11	-0.08	-0.02
JER EffectiveNP 1	2.77	2.11	1.78	1.76	0.71	-0.20	0.64	2.12	-0.72	-0.51	0.23	0.15	0.00	-0.20	0.04
	-2.77	-2.11	-1.78	-1.76	-0.71	0.20	-0.64	-2.12	0.72	0.51	-0.23	-0.15	-0.00	0.20	-0.04
JER EffectiveNP 2	1.98	1.55	1.24	1.59	0.53	-0.01	0.65	2.12	-0.66	-0.46	0.24	0.03	-0.02	-0.01	0.07
	-1.98	-1.55	-1.24	-1.59	-0.53	0.01	-0.65	-2.12	0.66	0.46	-0.24	-0.03	0.02	0.01	-0.07
MU 40<E _T ^{miss} [GeV]<65	-3.47	-3.39	-3.43	-2.87	-2.84	-1.54	-1.25	0.89	0.66	-0.93	-1.55	-0.80	-0.52	-0.02	0.12
	0.92	1.04	0.66	-0.04	-0.49	-3.01	-2.29	-11.46	-10.92	-1.50	2.76	1.80	1.61	0.34	-0.05
MU 0<E _T ^{miss} [GeV]<40	1.45	2.89	4.37	4.77	5.03	4.22	3.09	1.44	0.72	2.36	2.95	1.54	0.75	-0.16	-0.26
MU d ^{stg} >2	0.85	1.01	0.76	-1.00	-3.93	-4.73	0.58	1.18	1.07	3.59	3.96	2.99	3.37	3.54	0.78
MU no d ^{stg} cut	-2.34	-1.97	-1.38	-0.96	-0.67	-0.58	-0.38	-0.48	-0.40	-0.27	-0.16	-0.07	-0.01	0.02	0.02
MU N _{jets} >0t	1.75	2.57	3.09	2.98	2.79	2.43	1.92	1.54	1.18	1.61	1.90	1.11	0.56	-0.01	-0.11
MU MC scaling by $\pm 6\%$	-1.74	-2.56	-3.07	-2.96	-2.77	-2.41	-1.91	-1.52	-1.17	-1.61	-1.91	-1.11	-0.57	0.00	0.11
t theory: PSR	0.01	-0.06	-0.32	-0.81	-0.55	-0.19	-0.25	0.10	-0.34	-0.34	-0.48	-1.02	-1.20	-0.68	-0.34
	-0.16	0.30	0.61	1.37	0.71	-0.02	-1.11	-0.02	0.10	0.63	1.69	0.88	0.63	0.35	0.17
# theory: showering	-0.20	-0.02	0.62	0.81	1.51	1.16	1.47	2.06	1.83	1.39	0.20	-1.91	-2.49	-1.41	-0.70

12. Conclusion and outlook

The goal of this thesis was the measurement of the differential cross section of the charged-current Drell-Yan process in the muonic decay channel at high transverse masses. A precise measurement of this cross section allows, in particular, insight into the structure of the proton, which is essential for further measurements and searches at hadron colliders. Direct constraints on the parton distribution functions of the proton can be concluded with the help of these results in the future. Furthermore, sensitivity to electroweak and effective field theory parameters is expected.

An unfolded differential cross section is obtained successfully for both charges of the W boson, as well as their combination, as a function of its transverse mass m_T^W in the range from 130 GeV to 2000 GeV. The measurement is based on pp collisions at the LHC at CERN at a center-of-mass-energy of $\sqrt{s} = 13$ TeV. The data used was taken with the ATLAS detector in 2015 and 2016, corresponding to an integrated luminosity of 36.2 fb^{-1} .

After several studies concerning the choice of optimal working points for this analysis, the number of events predicted by SM processes is estimated via MC simulations as well as a data-driven method. The largest background process is given by $t\bar{t}$ events, which is evaluated in a dedicated control region and found to be modeled very well. A crucial aspect in the background modeling is the calculation of the multijet background, which is based on fake muons. These originate from jet activities, as opposed to real muons that are coming directly from a decay of a W or Z boson. The event yield of this particular process is estimated data-driven via the Matrix Method. Overall, a reasonable agreement between data and prediction can be observed in dedicated control plots. Nevertheless, an underestimated prediction is remarkable in the low m_T^W region, i.e. below 200 GeV, where around 15% more data than prediction is present. However, this issue is expected to originate from the E_T^{miss} modeling and was already seen in other analyses where the missing transverse momentum plays a key role. An unfolding to the born lepton level is done. The method of Iterative Bayesian Unfolding is used, which corrects for the detector smearing, measurement efficiency and acceptance induced by the analysis specific selection criteria. This method is adequate if non-negligible migration effects between bins are present, as they were seen in this analysis. The unfolded differential cross sections are calculated in a binning in m_T^W that is optimized by taking the effects of the bin-wise resolution, migration and statistical significance in the data into account.

In the final results, statistical as well as systematic uncertainties are included. Experimental systematic uncertainties arise from the measurement of the missing transverse momentum, muons and jets as well as the estimation of the multijet background. In the course of this thesis, no theoretical systematic uncertainties on the signal process are available. However, theoretical uncertainties on the biggest background, $t\bar{t}$, are taken into account. All uncertainties are evaluated before the unfolding procedure and only the ones with a contribution larger than 1 % in any m_T^W bin are considered in the unfolded results. In the end, the largest contributions to the total uncertainty are given by the E_T^{miss} uncertainties as well as the data-driven multijet variations. The former extend up to 5-7 % each in the first m_T^W bin, ranging from 130 GeV to 170 GeV. In the region of intermediate m_T^W , the multijet uncertainties are among the largest with

an impact of 3-4% per bin. Starting at around 900 GeV, the statistical uncertainty becomes predominant and increases up to 32%, at maximum, in the μ^- -channel in the last m_T^W bin ranging from 1400 GeV to 2000 GeV.

Lastly, the final results are compared to the born level of the used POWHEG-BOX and PYTHIA 8 signal MC. Overall, the measured cross sections are in reasonable agreement with the MC prediction within the considered uncertainties. However, a discrepancy at low m_T^W is noticeable, which was already observed in the control plots on reconstruction level, as discussed above. A slight difference between the agreement in the μ^+ - and μ^- -channel is visible. Whereas in the μ^+ -channel a trend of an underestimated theoretical cross section is noticeable, an opposite tendency can be observed in the μ^- -channel.

There are multiple aspects to further improve this analysis. First of all, the full Run 2 dataset should be taken into account, which will cut the statistical uncertainty approximately in half and improve the measurement precision substantially. Moreover, theoretical systematic uncertainties on the signal process need to be considered in the future in order to classify and interpret the results entirely. These are variations of initial and final state radiation, the factorization and renormalization scale as well as alternative PDF models and MC generators. As a further extension of this analysis, the differential cross section measurement presented here can be enlarged to a double-differential measurement in the transverse mass of the W boson as well as the pseudorapidity of the muon. Lastly, the results in the muonic decay channel are intended to be combined with a parallel electron channel analysis.

A. Appendix

A.1. Issues due to large weights in the signal MC

In the simulation of the signal process, a large discrepancy between the MC weights on the inclusive sample and the high mass slices (as defined in section 4.1) is present. In the used POWHEG-BOX MC, this weight equals the truth level cross section in picobarn per sub-sample. This leads to some issues as this section will present. In Fig. A.1 the distribution of the MC weight for the inclusive sample and the high mass slices, respectively, are shown. With respect to the event selection defined in section 6.1, the E_T^{miss} and m_T^W cuts are omitted and the p_T cut is lowered to 30 GeV. In these plots, the under- and overflow bins are included, hence, all events must necessarily lay within the shown bins. It can be observed that the MC weight of the inclusive sample is in the order of 10^4 , while the slices always have a MC weight of less than 40. Furthermore, the W^+ process always has a higher weight. Clearly, this behavior agrees with the expectation on the cross section.

However, this large discrepancy in the weights between peak sample and high mass slices induces some issues in calculations based on the signal MC only, e.g. the calculation of the resolution (see Sec. 6.2.1) or the real efficiency (see Sec. 7.3.2). In the estimation of the resolution, the distribution of the reconstructed transverse momentum of the muon around its corresponding truth value is evaluated. In this course, sharp peaks could be observed when the inclusive sample is considered as a part of the signal MC, as shown exemplarily in Fig. A.2a. In comparison, the same distribution is found to be smooth in Fig. A.2b where only the high mass slices are used. Thus, the fluctuations are clearly induced by events originating from the inclusive sample. In general, events originating from the peak sample, i.e. with an invariant mass below 120 GeV, are not expected to have such a large transverse muon momentum (e.g. around 800 GeV in Fig. A.2). However, this can happen if the W boson itself already has a very large transverse momentum. Only very few events from the peak sample

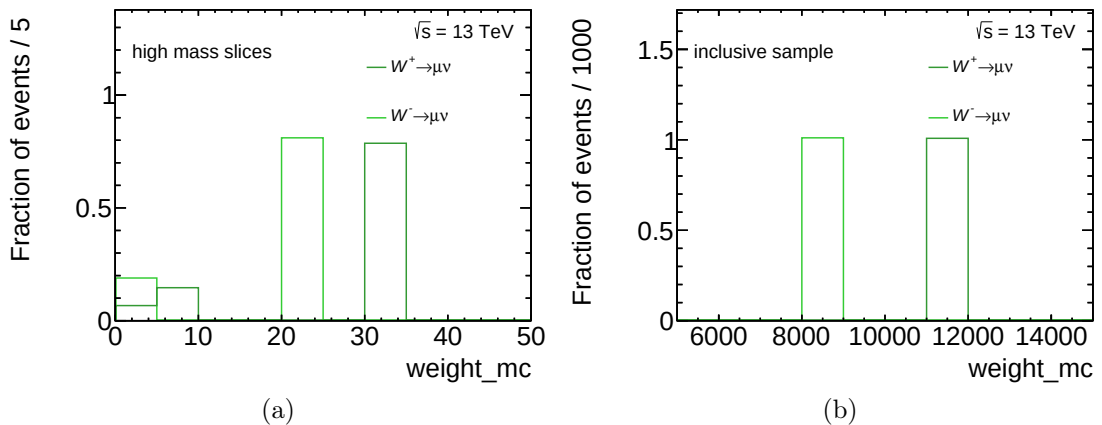


Figure A.1.: MC weight for the signal $W \rightarrow \mu\nu$ process, divided in (a) high mass slices ($m_{\text{inv}} > 120$ GeV) and (b) inclusive sample ($m_{\text{inv}} < 120$ GeV).

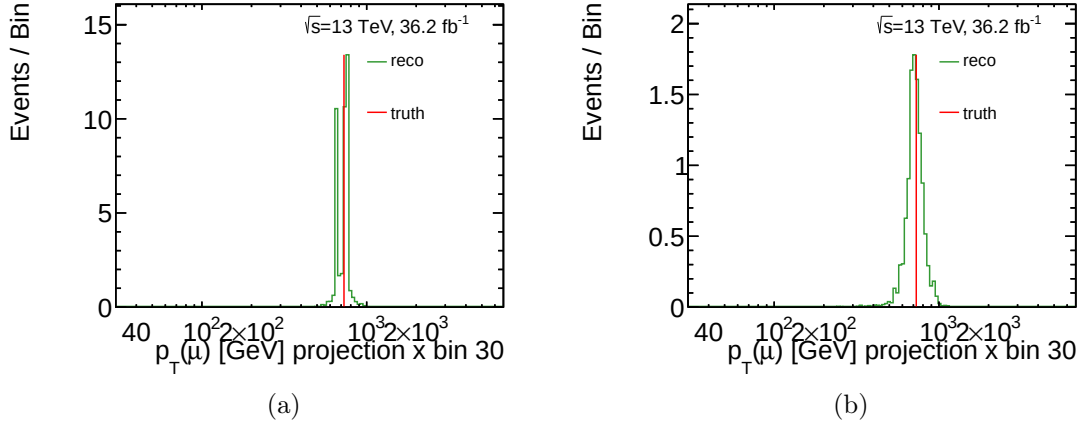


Figure A.2.: Distribution of the reconstructed $p_T(\mu)$ for one truth bin. In (a) the full W MC is used for the calculation while in (b) only the high mass slices are considered.

are boosted to such high muon momenta, but these have a substantially larger weight than events that originate from high masses. As a result, few events can have a significant impact, which is not a physical but more of a statistical and technical effect. This issue propagates to the calculated resolution in the form of fluctuations in a p_T range of around 300 GeV to 900 GeV, as Fig. A.3a illustrates. Moreover, the same behavior appears in the estimation of the real efficiency, which is based on the signal simulation as well. This can be seen in Fig. A.3b. In order to avoid this non-physical

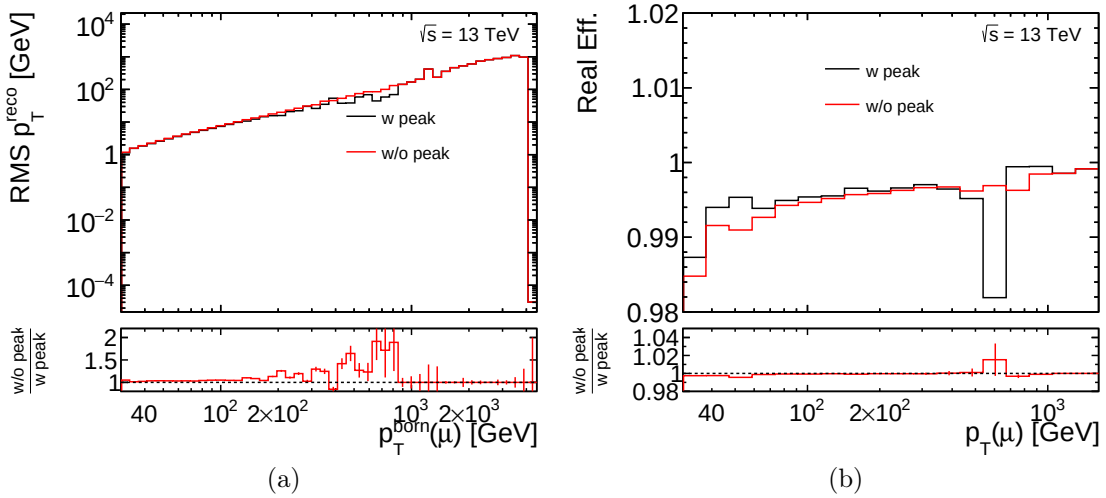


Figure A.3.: (a) Resolution and (b) real efficiency as defined in the corresponding chapters 7.3.2 and 9.2.1. While in the main analysis only the high mass slices were considered in the calculation, the inclusive sample is used as well in this study shown here.

problem caused by the large weights, the calculation of the resolution as well as the real efficiency can be done using the high mass slices only. This is legitimate because the boosted events from the peak sample induce, in these cases, mainly fluctuations but change the general shape of the resolution or real efficiency only very little, in particular above 65 GeV, as the ratio in Fig. A.3 highlights.

Lastly, these fluctuations are visible as well when evaluating experimental systematic uncertainties on the signal sample. In particular, the uncertainties associated with the muon sagitta bias, as presented in Sec. 10.1.4, are affected. In Fig. A.4 a comparison between this uncertainty with and without considering the inclusive sample as part of the signal MC is shown. Since this uncertainty is, in general, expected to be charge-dependent, a separation per muon charge is shown and it can be observed that, in the μ^- -channel, the uncertainty increases substantially when using the peak sample, in particular in the high m_T^W region above 800 GeV. This is expected to be caused by very

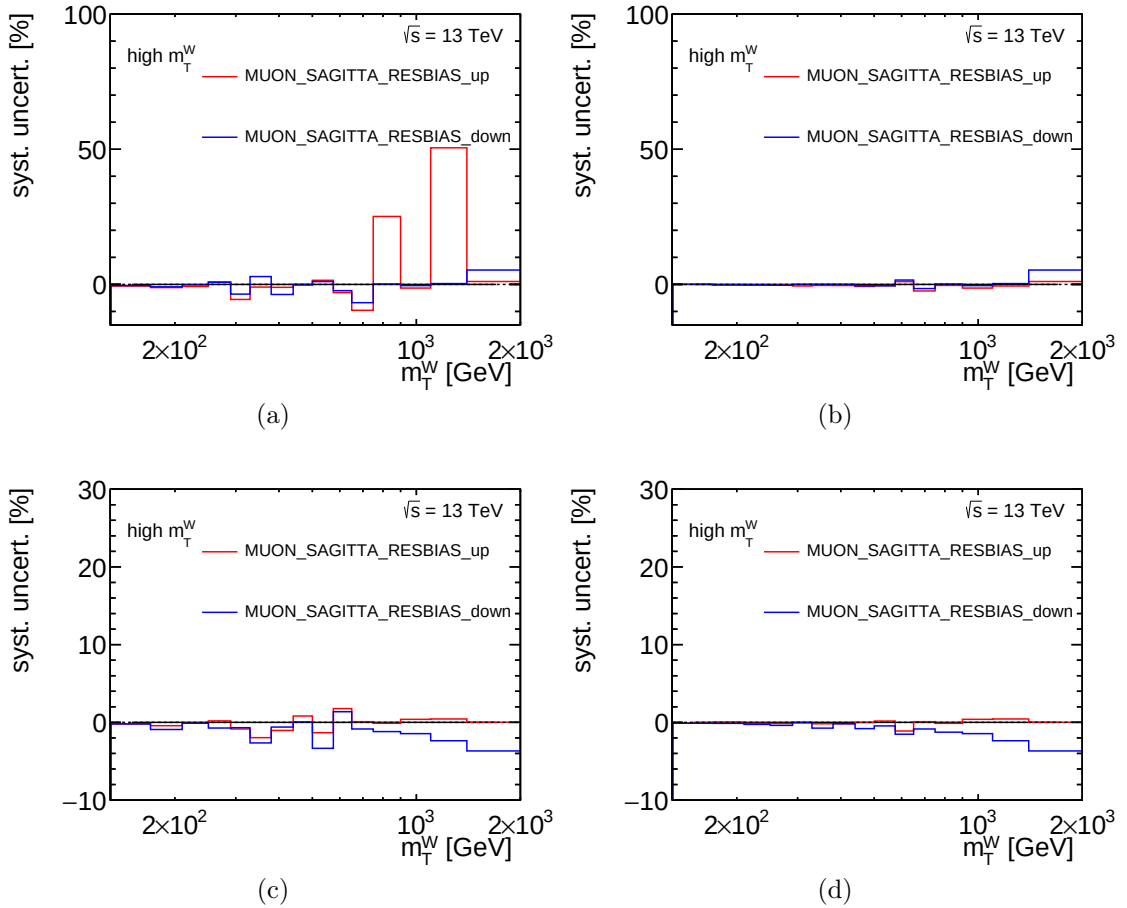


Figure A.4.: Systematic uncertainty associated with the muon sagitta correction shown in percent with respect to the nominal signal MC. In the upper row, the μ^- -channel is shown. On the left, the full signal MC is considered and, on the right, only the high mass slices. In the lower row, the same is shown for the μ^+ -channel.

few events migrating from the mass peak to the very high m_T^W region, in an extreme case even one event is sufficient. Nevertheless, the peak sample cannot be omitted in the estimation of systematic uncertainties as it was done e.g. in the estimation of the real efficiency. It is e.g. crucial to reflect the systematic uncertainties which have a non-negligible impact at low m_T^W correctly. Moreover, other smaller fluctuations that are visible in the systematic uncertainties presented in chapter 10 can be traced back to this particular issue in the signal sample.

A.2. Supplemental material

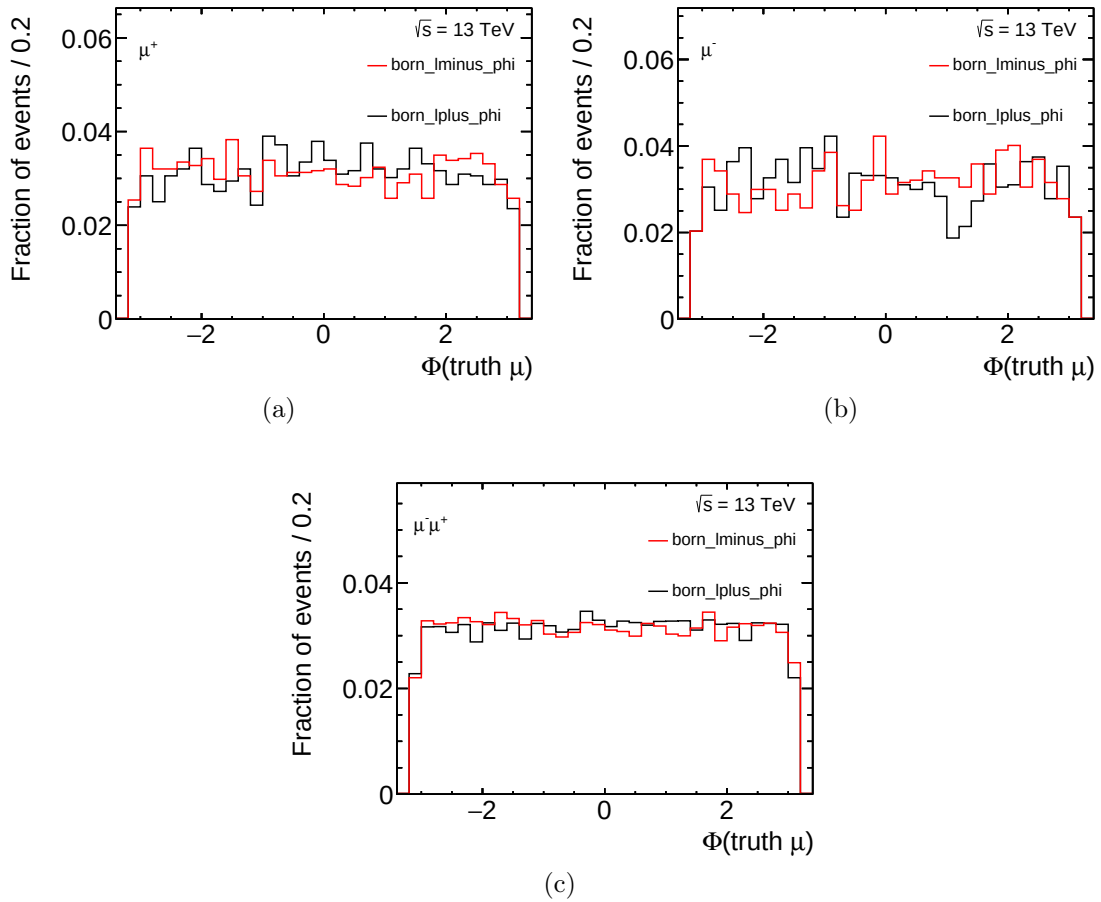


Figure A.5.: Distribution of the azimuthal angle of the truth muons based on a test sample of the first $Z \rightarrow \mu\mu$ slice. In (a) only the μ^+ , in (b) only the μ^- and in (c) both muons are reconstructed.

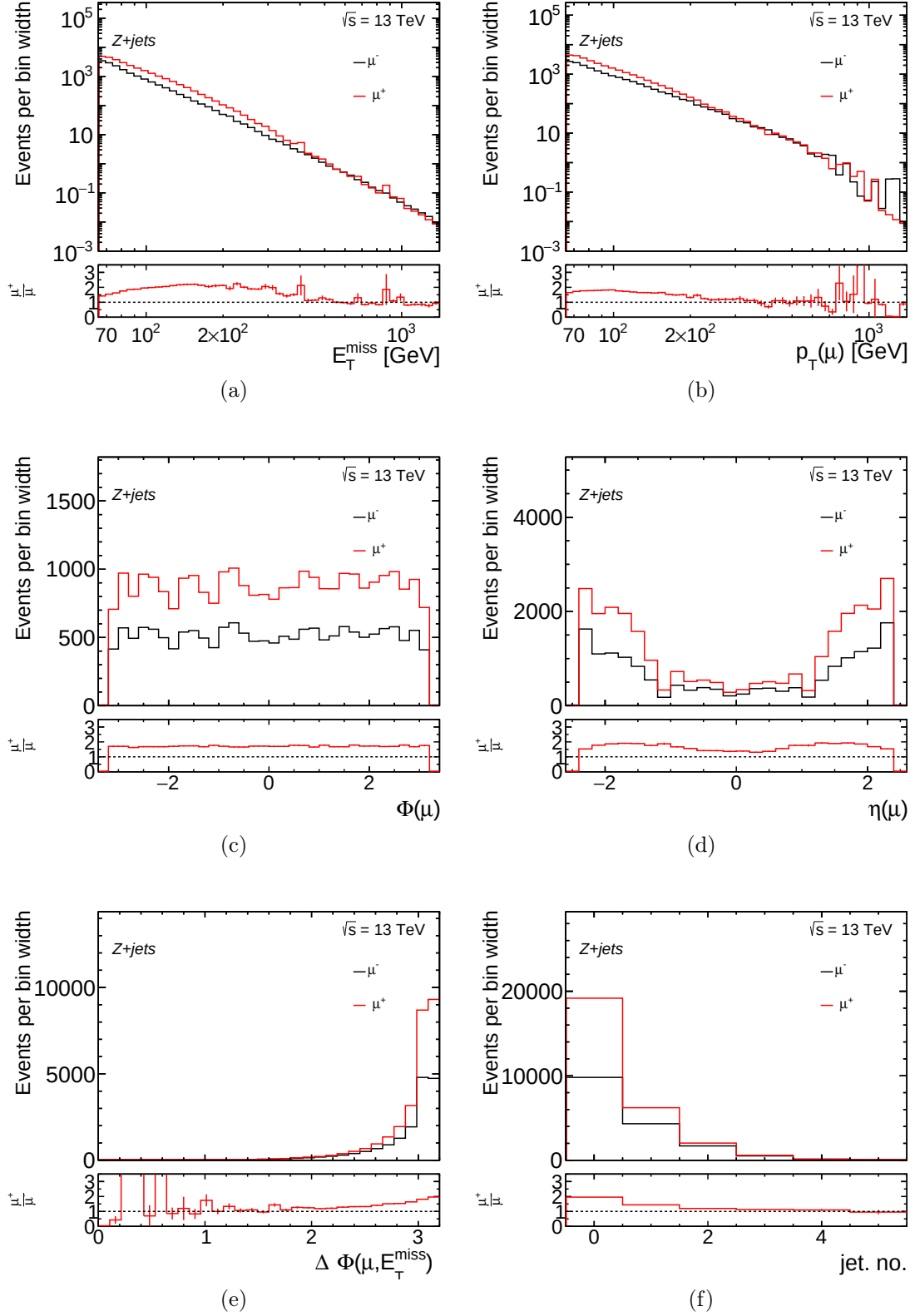


Figure A.6.: Supplemental plots for a μ^+ or μ^- final state in the Z +jets ($Z \rightarrow \tau\tau$ and $Z \rightarrow \mu\mu$ combined) background.

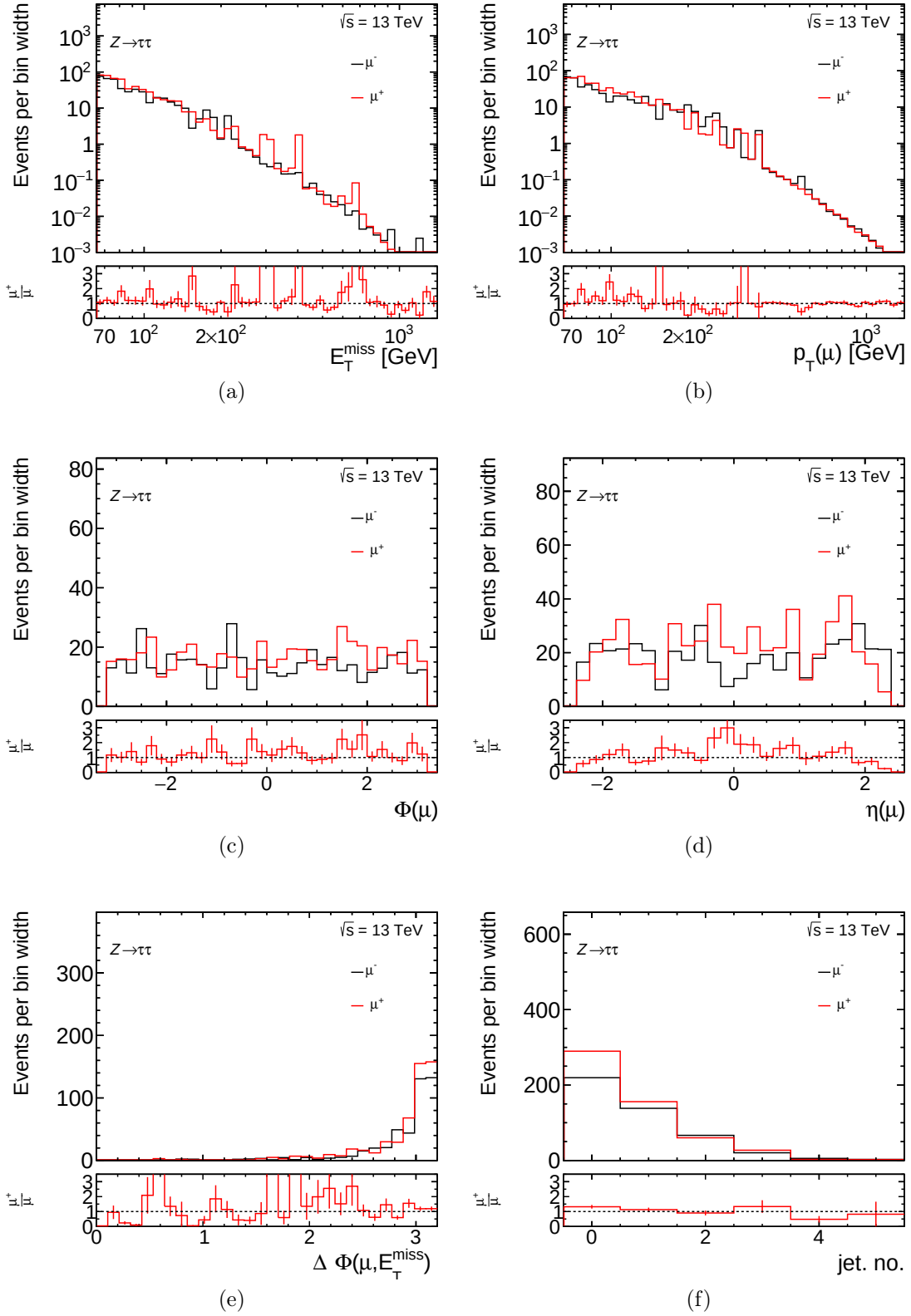


Figure A.7.: Supplemental plots for a μ^+ or μ^- final state in the $Z \rightarrow \tau\tau$ background.

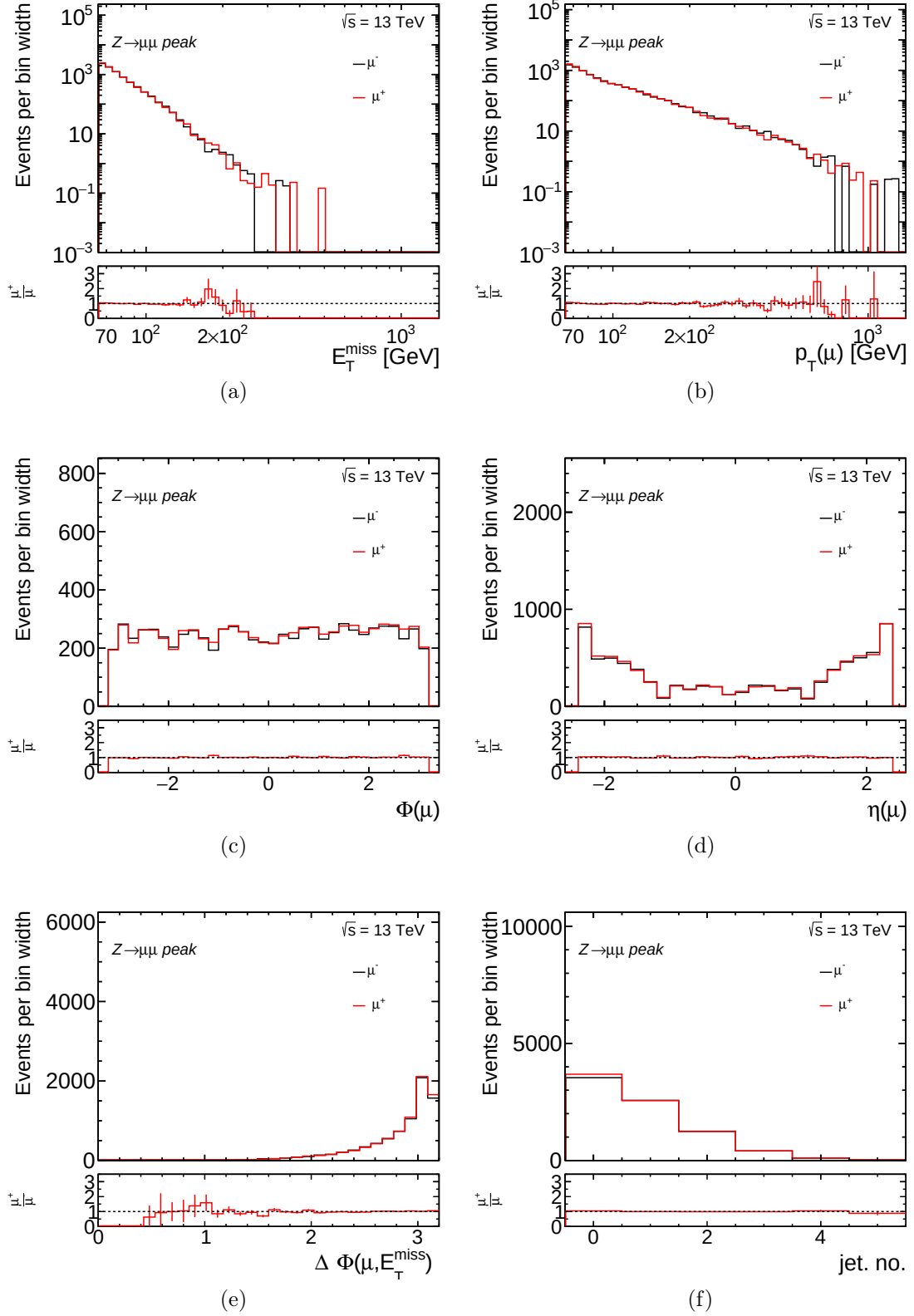


Figure A.8.: Supplemental plots for a μ^+ or μ^- final state in the $Z \rightarrow \mu\mu$ background (peak only, i.e. $m_{inv} < 120$ GeV).

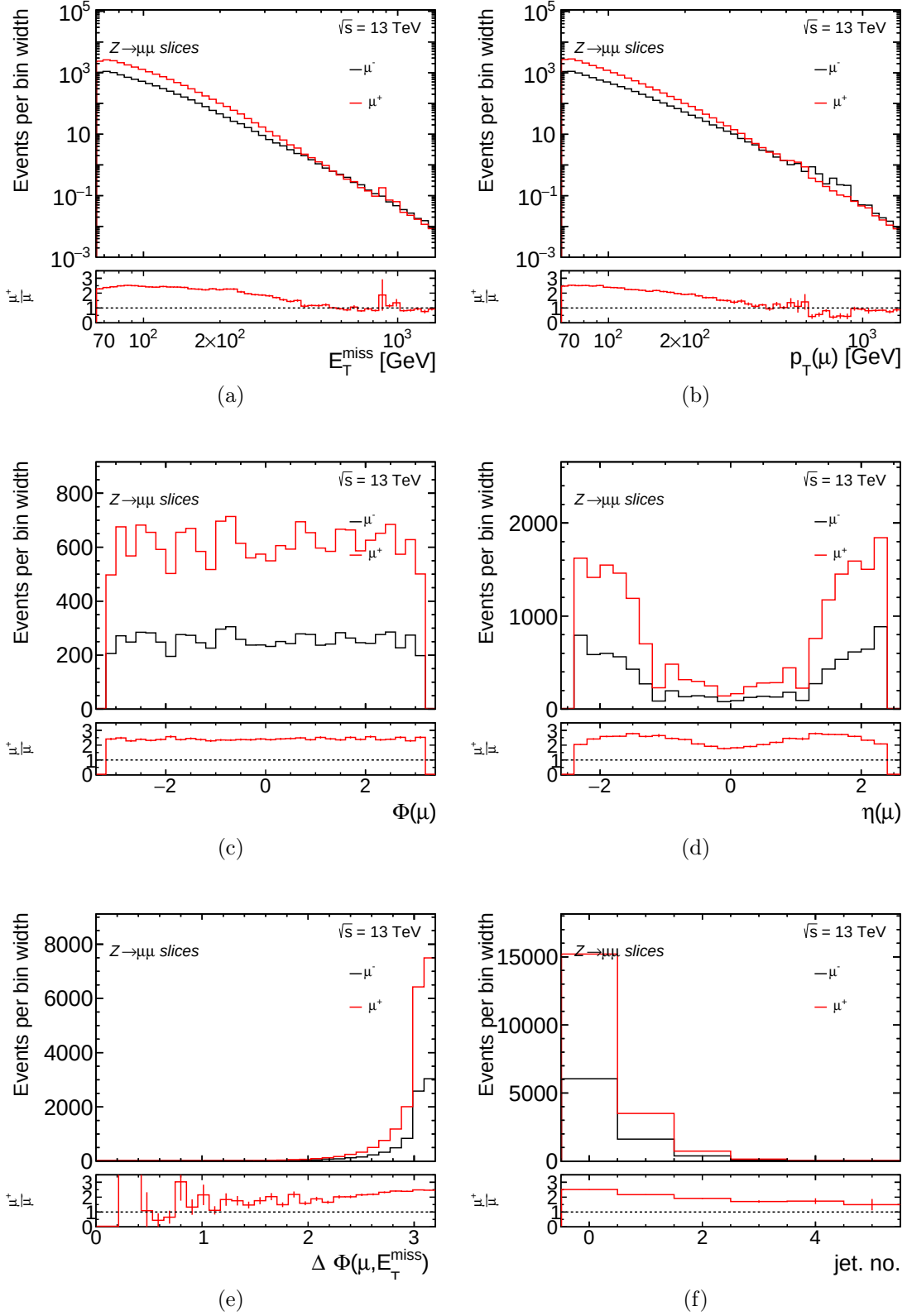


Figure A.9.: Supplemental plots for a μ^+ or μ^- final state in the $Z \rightarrow \mu\mu$ background (slices only, i.e. $m_{inv} > 120$ GeV).

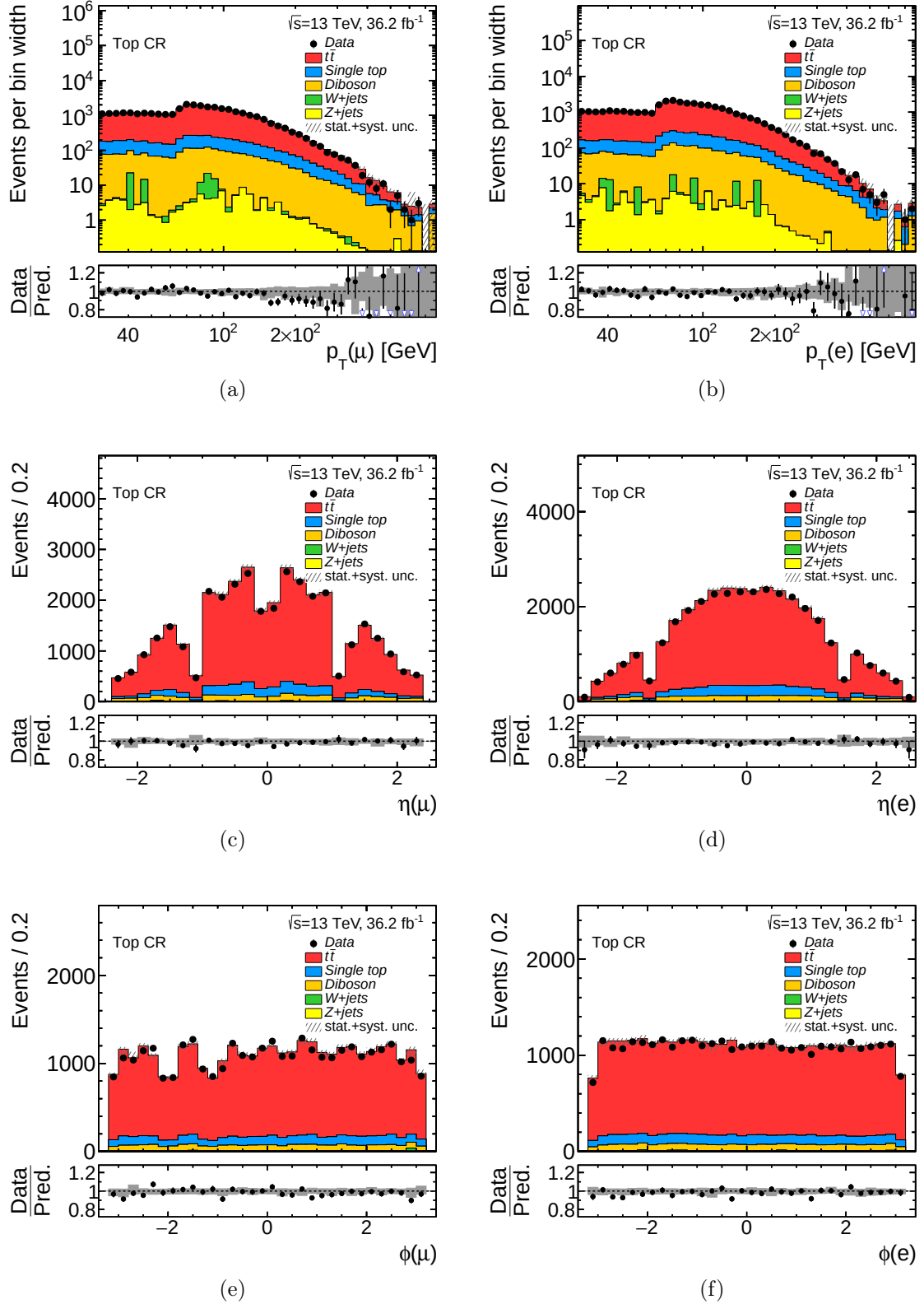


Figure A.10.: MC-data comparisons in the first top control region ($m_T^W > 130$ GeV and $E_T^{miss} > 65$ GeV). The transverse momentum, pseudorapidity and azimuthal angle of the muon (left) and electron (right), respectively, are shown.

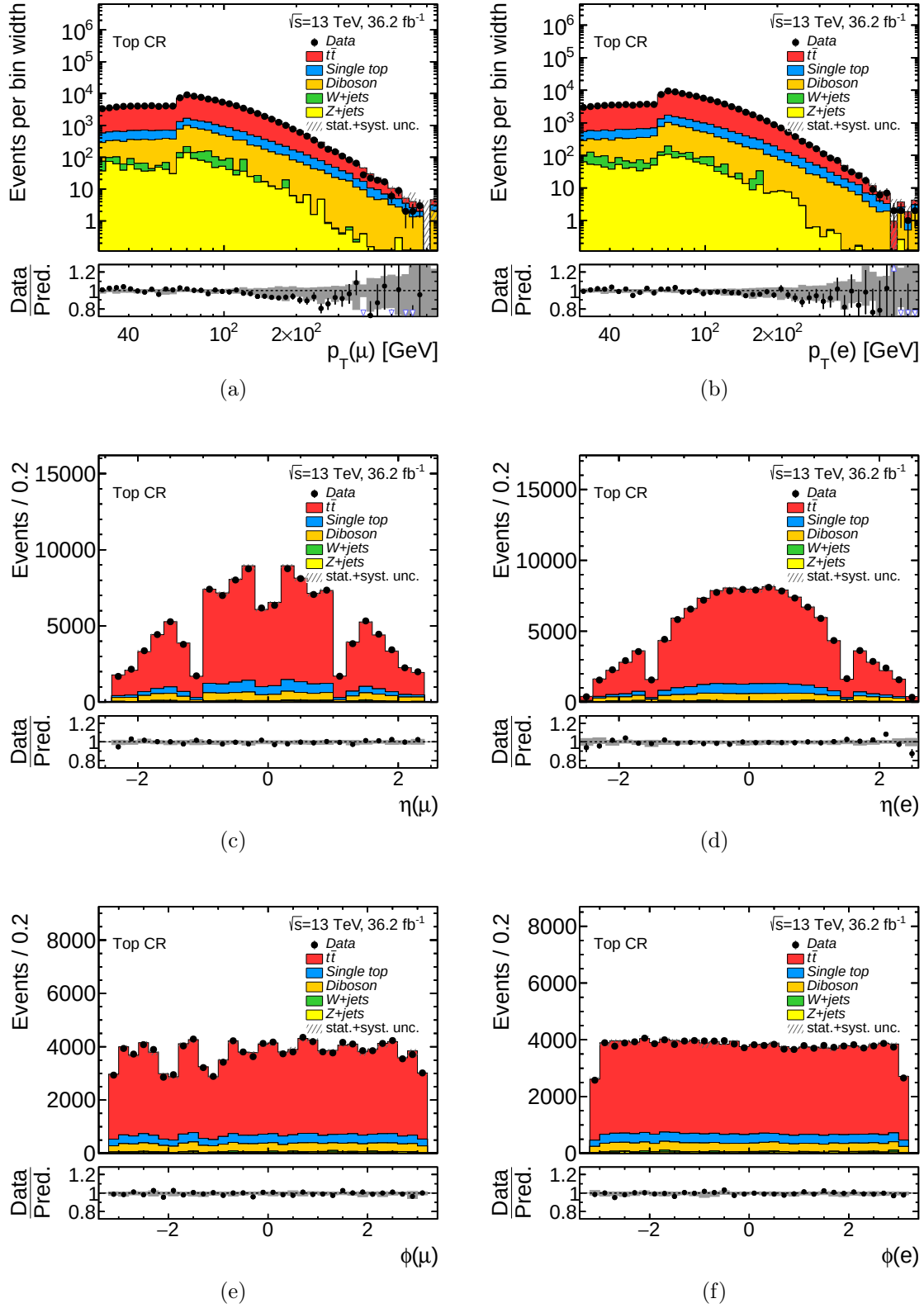


Figure A.11.: MC-data comparisons in the second top control region (no m_T^W and E_T^{miss} cuts). The transverse momentum, pseudorapidity and azimuthal angle of the muon (left) and electron (right), respectively, are shown.

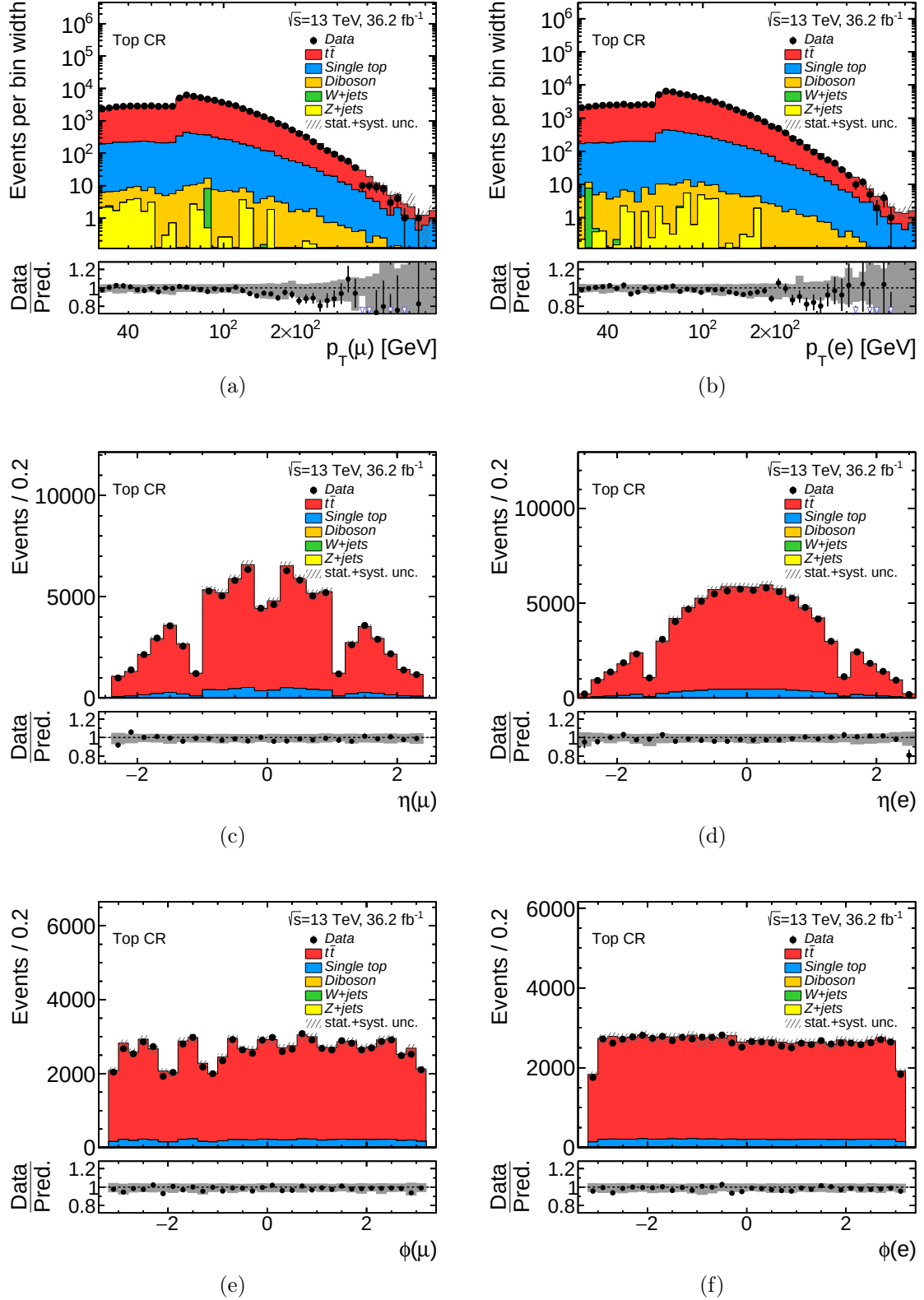


Figure A.12.: MC-data comparisons in the third top control region (no m_T^W and E_T^{miss} cuts, at least 1 b-jet). The transverse momentum, pseudorapidity and azimuthal angle of the muon (left) and electron (right), respectively, are shown.

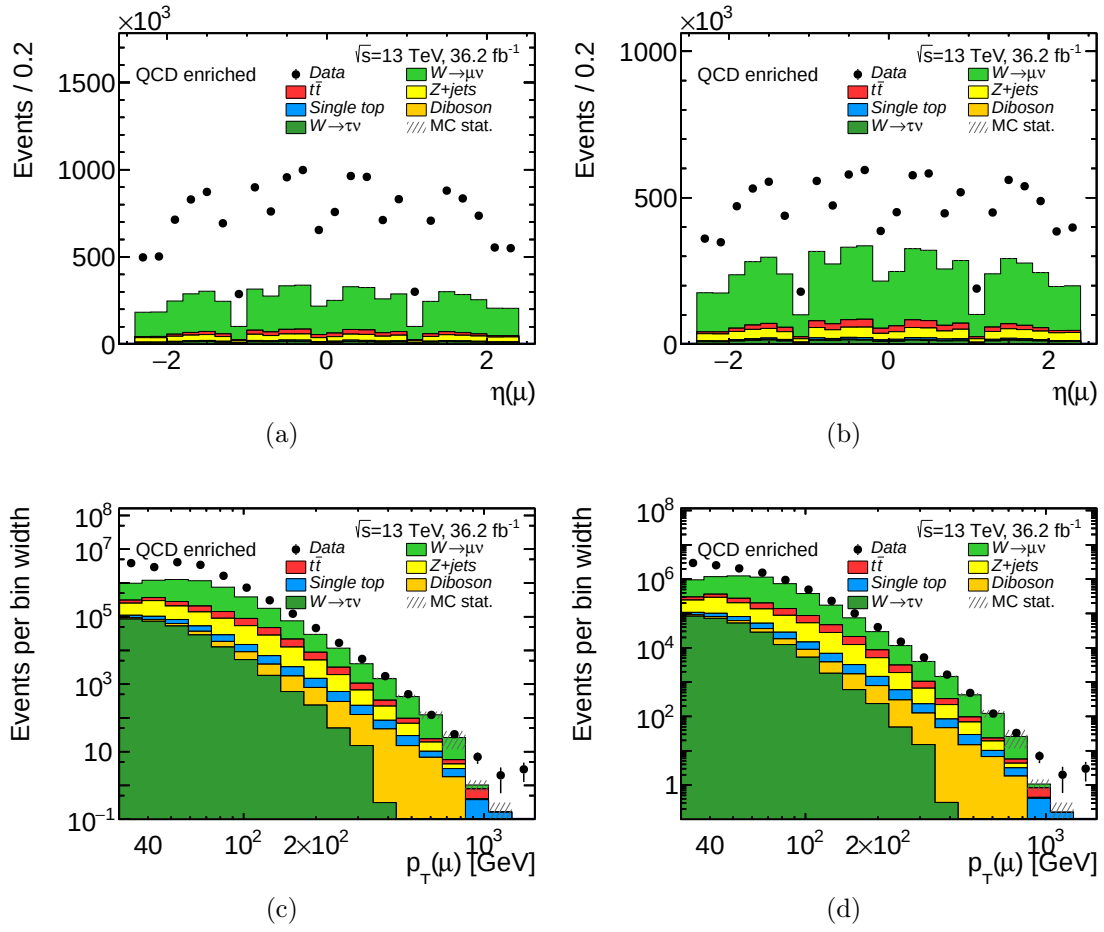


Figure A.13.: Distribution of the pseudorapidity (upper row) and transverse momentum (lower row) of a loose/tight (left/right) level muon in data and MC in the QCD enriched region. The plot shown in (b) agrees with Fig. 7.13a and is shown for the purpose of a direct comparison here again.

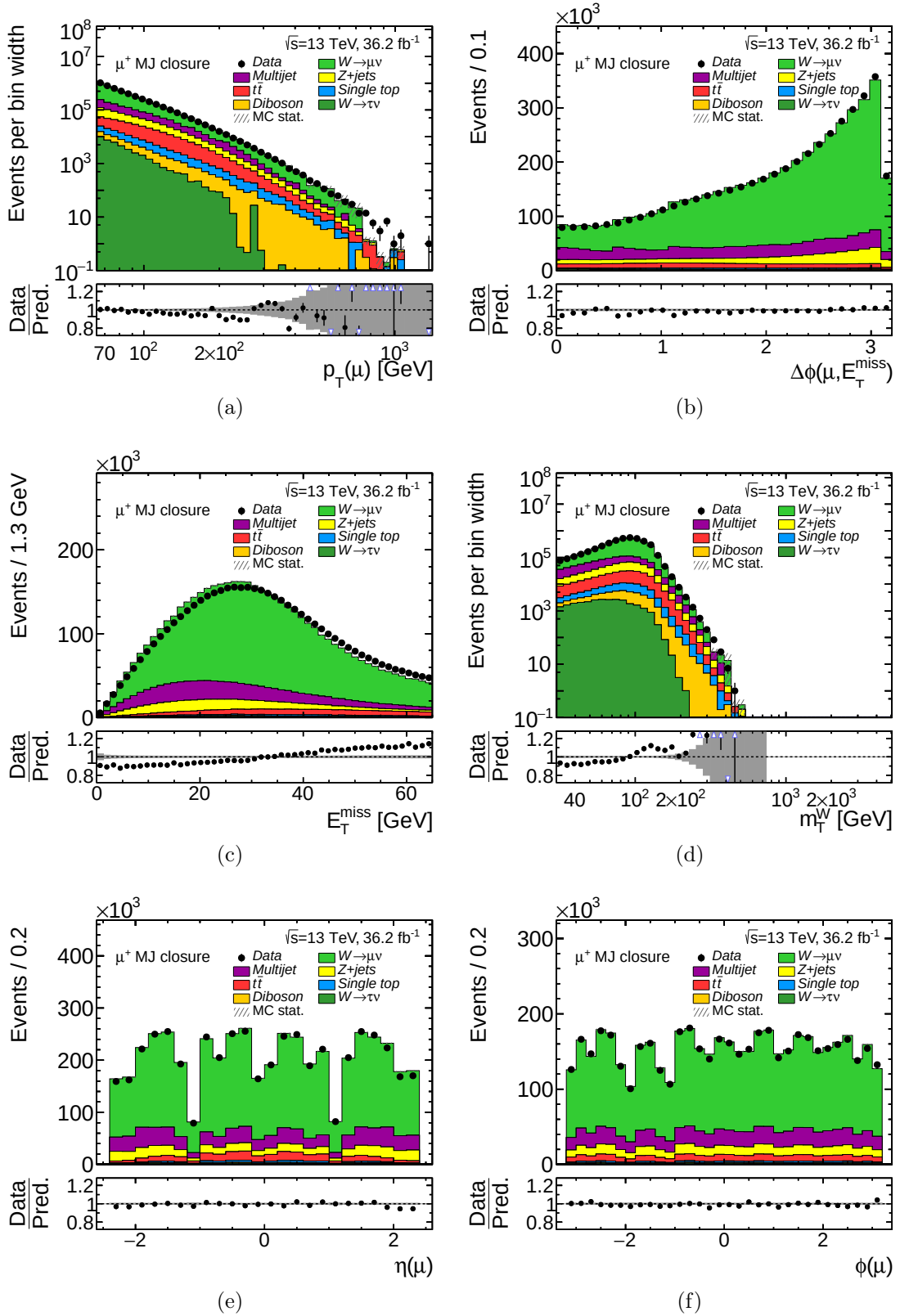


Figure A.14.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon are shown in the closure region for a μ^+ final state.

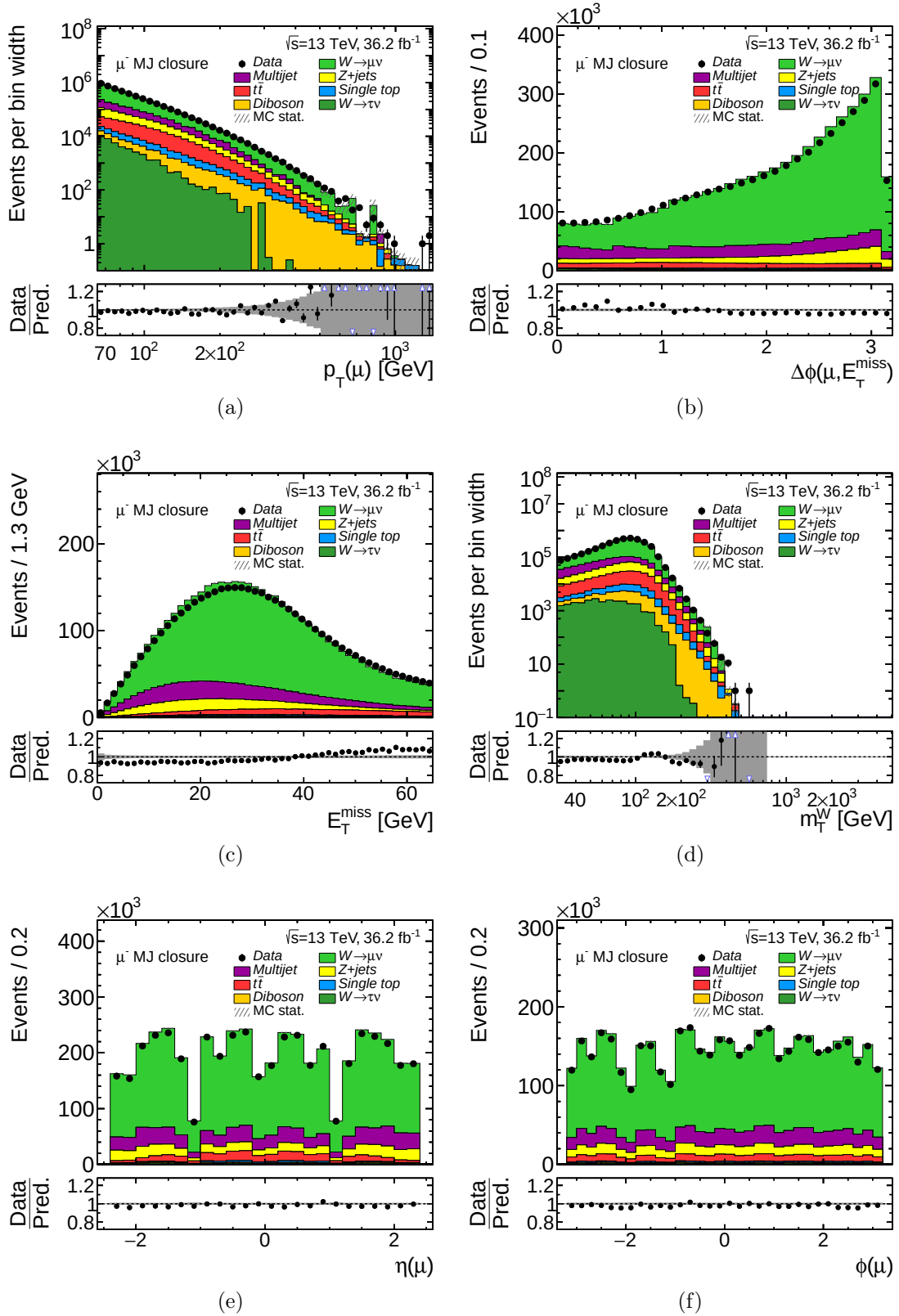


Figure A.15.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon are shown in the closure region for a μ^- final state.

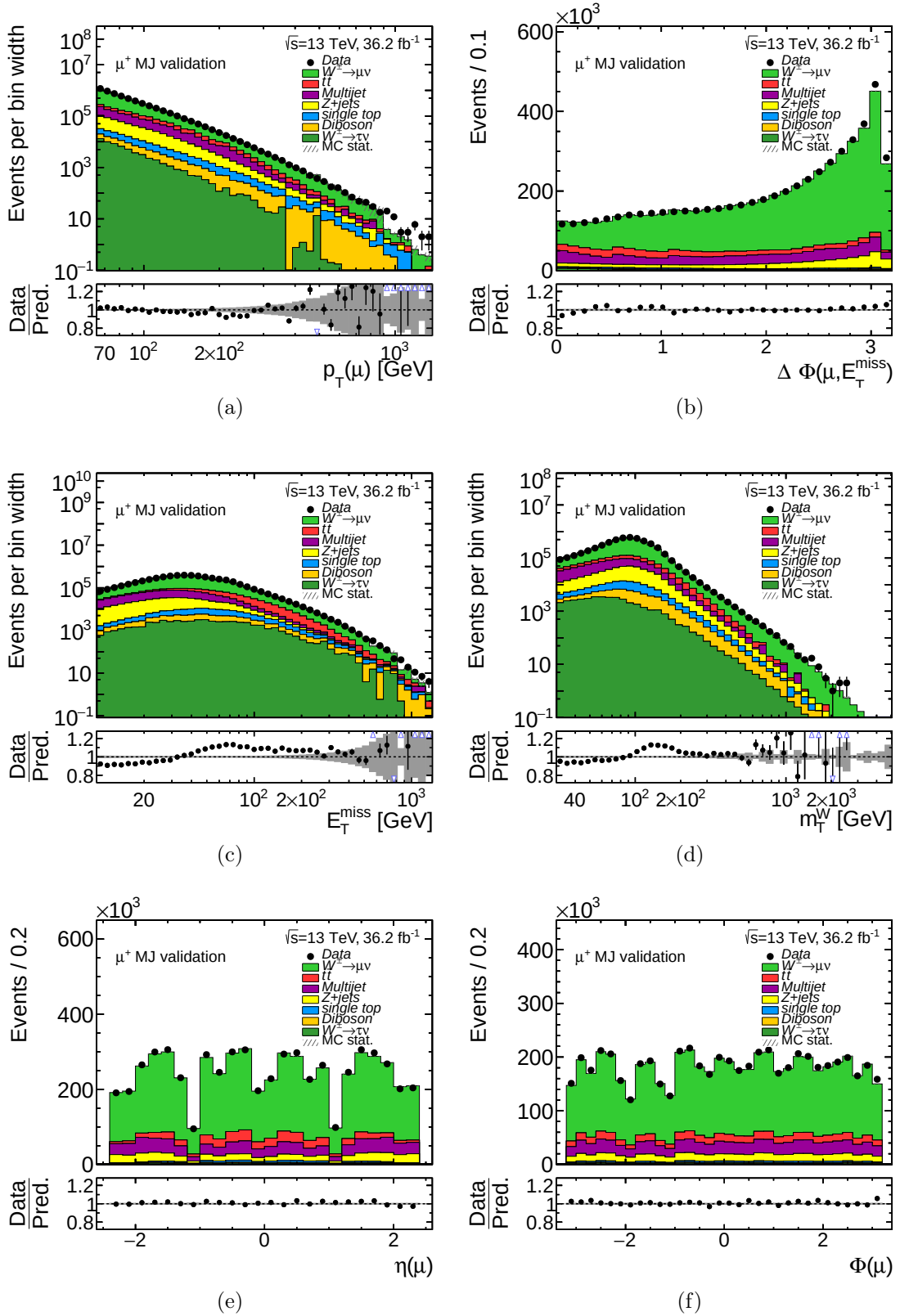


Figure A.16.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon are shown in the validation region for a μ^+ final state.

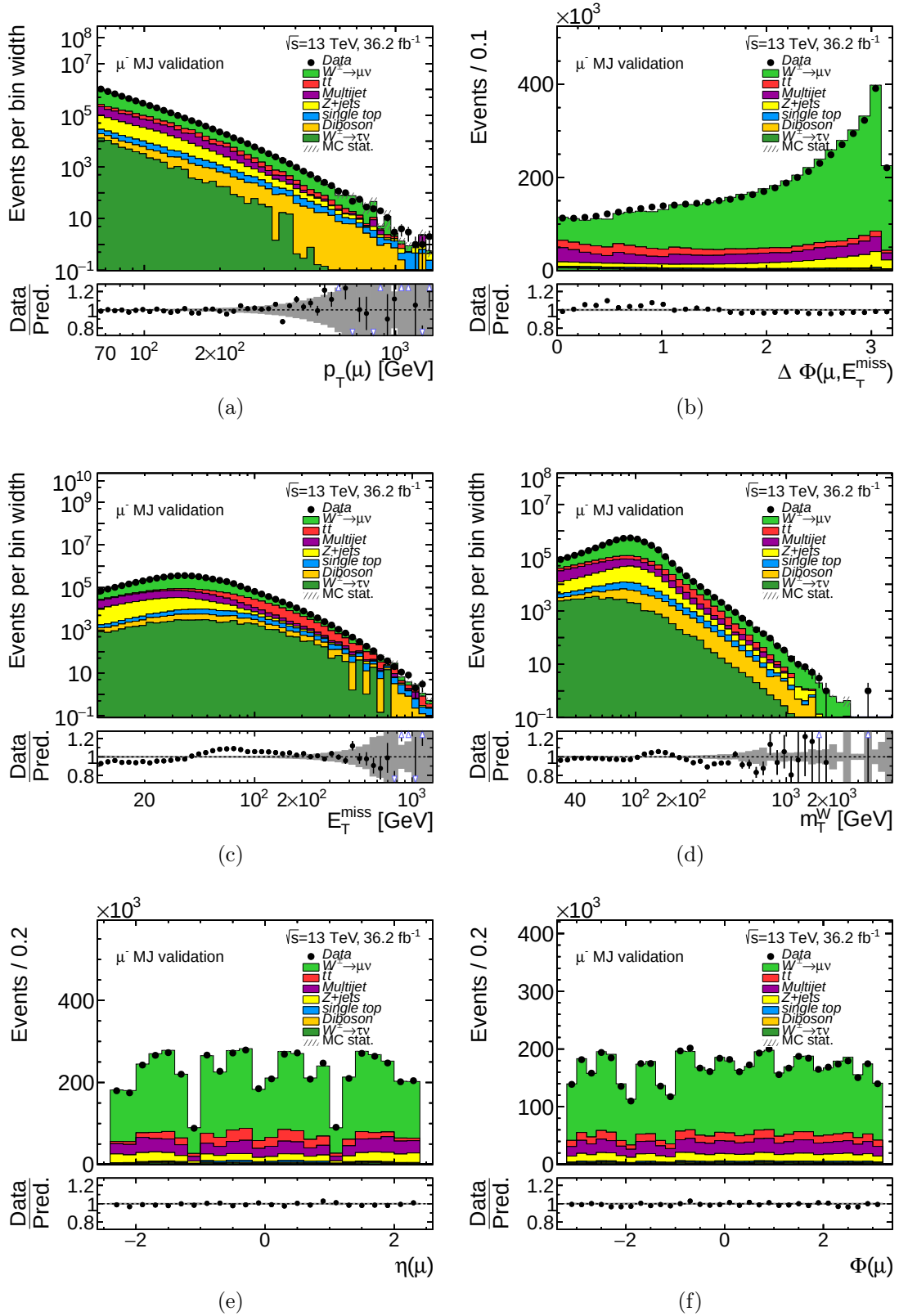


Figure A.17.: MC-data comparisons binned in the (a) transverse momentum of the muon, (b) azimuthal angle between muon and E_T^{miss} , (c) missing transverse momentum, (d) transverse mass of the W boson, (e) pseudorapidity and (f) azimuthal angle of the muon are shown in the validation region for a μ^- final state.

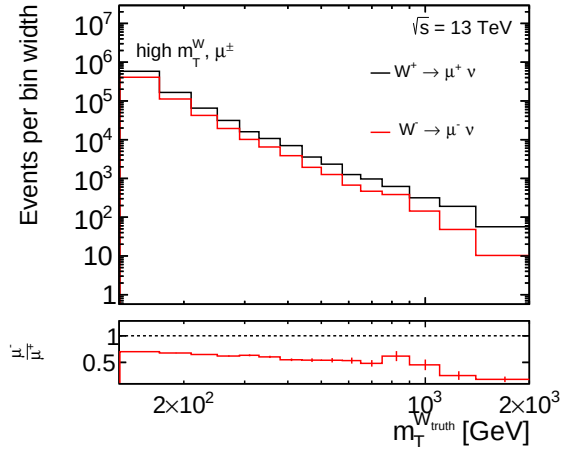


Figure A.18.: Distribution of the truth level transverse mass of the W boson, separated per charge. The full truth level is considered.

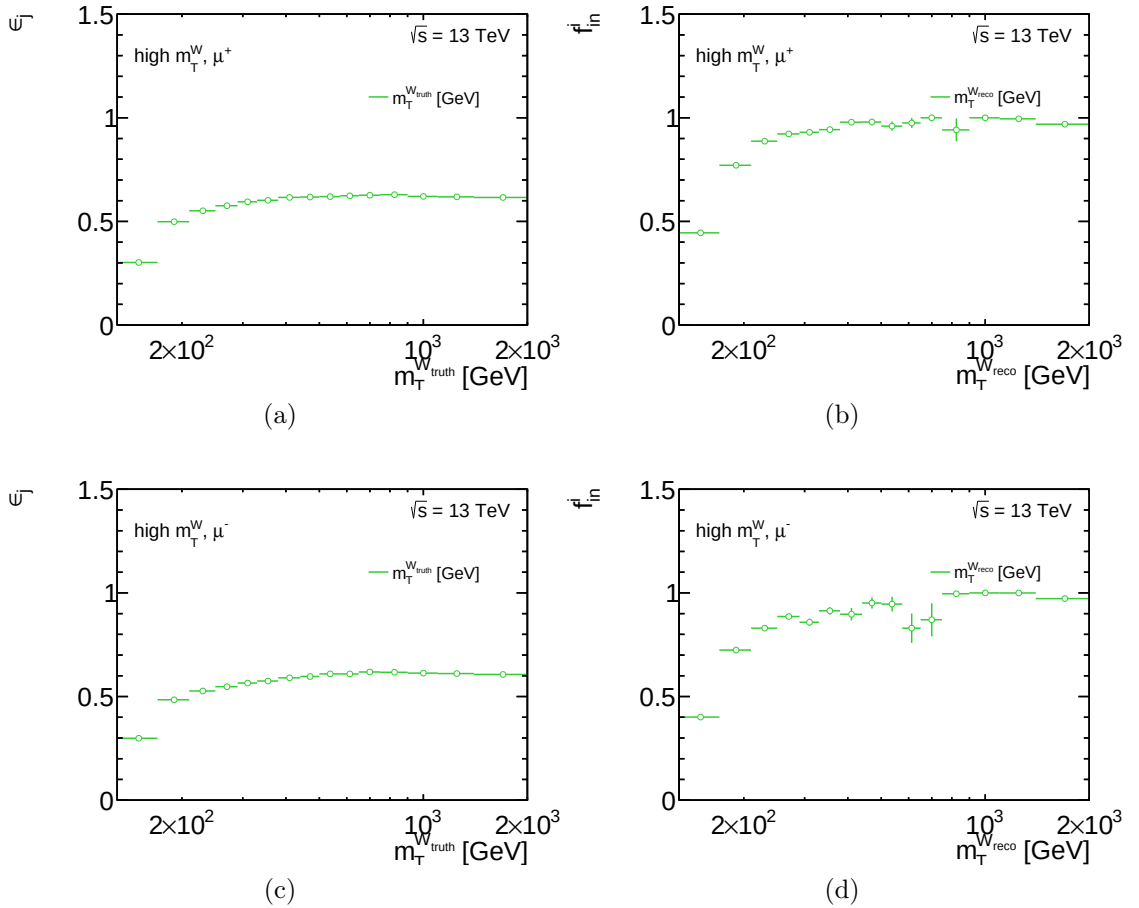
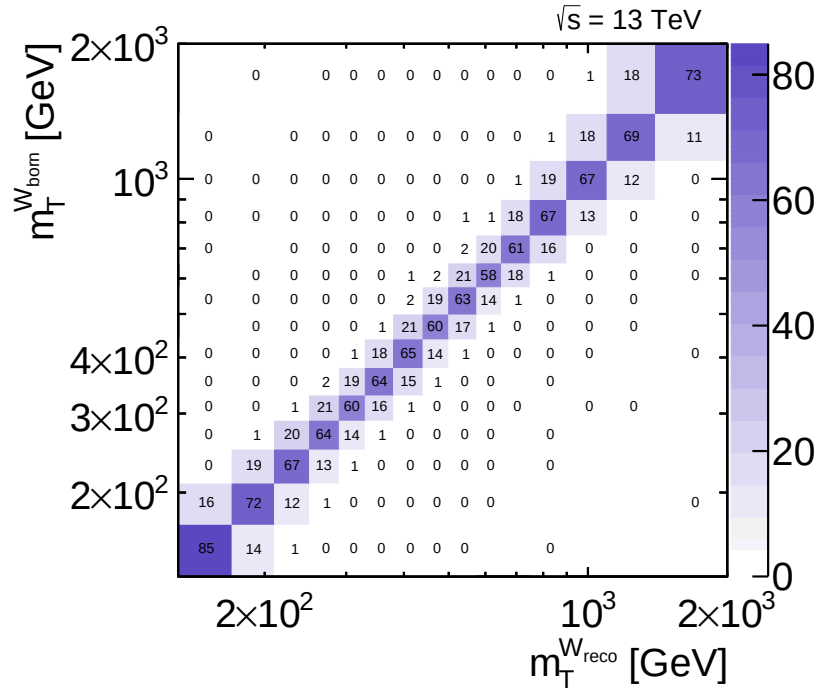
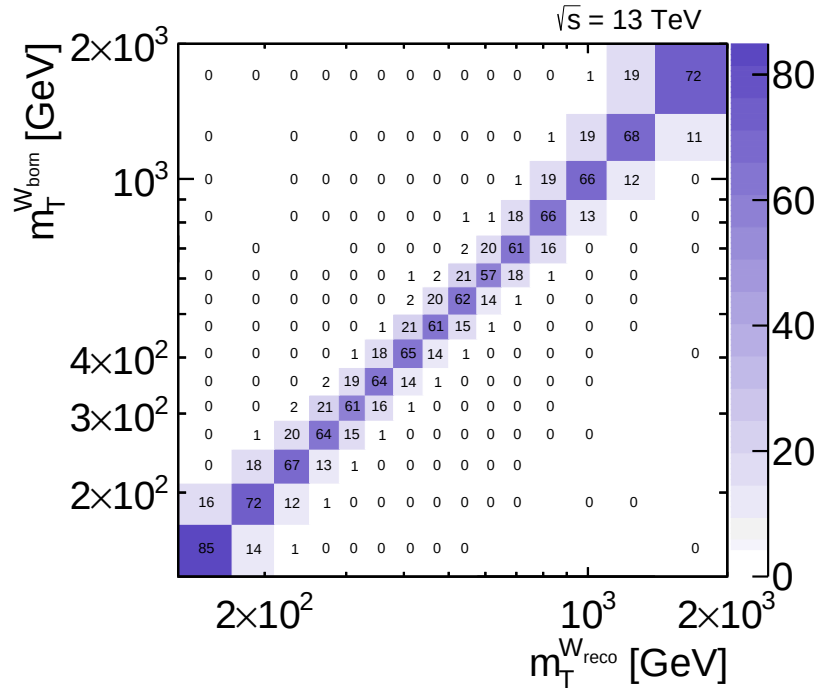


Figure A.19.: Efficiency and acceptance factors applied in the unfolding procedure. The upper row corresponds to the μ^+ -channel and the lower row to the μ^- -channel.



(a)



(b)

Figure A.20.: Response matrix $M_{\text{truth},\text{reco}}^{[130,2000]}$ as used in the Iterative Bayesian Unfolding for the (a) μ^+ - and (b) μ^- -channel. The numbers are given in percent, while under- or overflow bin are not considered in the normalization.

Table A.1.: Event yield on reconstruction level in the signal region in data, signal and each background as well as the total background for each $m_W^\pm$ bin including the statistical uncertainty. The upper table shows the combination of both charges, the middle table the μ^+ -channel and the lower table the μ^- -channel.

$m_W^\pm$ [GeV]	Data	$W^\pm \rightarrow \mu^\pm \nu$	Total Bkg.	$t\bar{t}$	Z+jets	Multijet	Single top	Diboson	$W \rightarrow \tau \nu$
130-170	450090 ± 670.89	295863.94 ± 1211.71	105290.30 ± 211.95	43690.70 ± 76.21	27750.55 ± 82.79	19756.83 ± 143.08	5805.50 ± 24.24	5515.54 ± 28.73	2771.26 ± 101.87
170-210	153776 ± 394.68	92827.02 ± 477.50	55129.11 ± 148.33	26429.74 ± 59.34	10822.25 ± 42.62	10657.26 ± 122.12	3015.02 ± 18.61	3060.90 ± 20.06	1143.89 ± 31.63
210-250	58217 ± 241.28	33456.52 ± 217.27	24644.57 ± 118.70	12612.56 ± 41.07	4172.26 ± 23.05	4439.13 ± 102.71	1417.42 ± 13.20	1418.43 ± 13.72	554.33 ± 30.97
250-290	26354 ± 162.34	15133.14 ± 123.25	11394.55 ± 89.17	5877.05 ± 28.05	1816.40 ± 12.98	1971.10 ± 77.15	753.59 ± 9.62	710.39 ± 9.14	266.02 ± 29.46
290-330	13070 ± 114.32	8088.79 ± 91.14	5632.62 ± 78.38	2770.97 ± 19.32	916.26 ± 9.59	1053.16 ± 74.63	389.30 ± 6.96	383.69 ± 6.26	119.24 ± 4.49
330-380	8570 ± 92.57	5265.89 ± 62.88	3370.51 ± 64.24	1571.59 ± 14.61	558.31 ± 6.51	648.89 ± 61.67	250.88 ± 5.60	264.43 ± 5.24	76.41 ± 2.81
380-440	4980 ± 70.57	3233.92 ± 48.94	1729.40 ± 35.80	804.01 ± 10.46	319.95 ± 5.64	253.04 ± 33.22	143.21 ± 4.26	161.42 ± 3.92	47.78 ± 1.81
440-500	2500 ± 50	1680.77 ± 25.36	790.88 ± 30.11	333.98 ± 6.75	152.68 ± 3.34	133.47 ± 28.82	64.26 ± 2.91	79.08 ± 3.07	27.42 ± 1.17
500-575	1547 ± 39.33	1136.60 ± 24.28	487.29 ± 32.69	169.15 ± 4.85	87.56 ± 2.55	125.23 ± 32.05	39.36 ± 2.38	49.14 ± 2.15	16.84 ± 0.76
575-650	804 ± 28.35	620.49 ± 22.50	193.98 ± 13.39	69.63 ± 3.13	39.85 ± 1.09	30.33 ± 12.75	20.40 ± 1.66	25.36 ± 1.71	8.42 ± 0.40
650-750	568 ± 23.83	423.22 ± 14.58	140.27 ± 14.18	37.35 ± 2.32	26.24 ± 1.60	43.71 ± 13.75	10.63 ± 1.19	16.47 ± 1.63	5.87 ± 0.28
750-900	369 ± 19.21	281.70 ± 11.61	60.23 ± 4.07	19.72 ± 1.69	15.41 ± 0.70	4.53 ± 3.37	6.19 ± 0.92	10.92 ± 1.00	3.47 ± 0.13
900-1100	168 ± 12.96	132.98 ± 0.92	27.96 ± 4.77	6.71 ± 1.00	6.56 ± 0.35	4.83 ± 4.55	2.49 ± 0.62	5.71 ± 0.76	1.65 ± 0.07
1100-1400	68 ± 8.25	61.21 ± 0.46	9.70 ± 2.01	1.88 ± 0.55	3.47 ± 0.38	2.01 ± 1.81	0.56 ± 0.39	1.38 ± 0.42	0.70 ± 0.03
1400-2000	37 ± 6.08	23.53 ± 0.19	2.71 ± 0.48	0.30 ± 0.21	1.15 ± 0.02	0 ± 0	0.36 ± 0.21	0.67 ± 0.38	0.23 ± 0.01

m_W^+ [GeV]	Data	$W^+ \rightarrow \mu^+ \nu$	Total Bkg.	$t\bar{t}$	Z+jets	Multijet	Single top	Diboson	$W \rightarrow \tau \nu$
130-170	260332 ± 510.23	168863.23 ± 906.60	57173.57 ± 157.08	21840.53 ± 53.88	17148.22 ± 64.05	10395.83 ± 102.44	3170.97 ± 17.93	2870.19 ± 20.38	1747.83 ± 80.24
170-210	90666 ± 301.11	54740.18 ± 356.88	29669.19 ± 104.93	13204.07 ± 41.95	6931.52 ± 32.88	5688.59 ± 84.44	1569.34 ± 13.41	1558.71 ± 14.58	716.96 ± 25.45
210-250	34535 ± 185.84	20080.13 ± 157.52	13149.47 ± 84.87	6281.59 ± 28.97	2716.69 ± 17.25	2367.78 ± 72.25	727.41 ± 9.35	702.64 ± 10.42	353.36 ± 25.51
250-290	15632 ± 125.03	9296.71 ± 89.50	6097.47 ± 64.48	2928.28 ± 19.80	1193.50 ± 9.53	1077.94 ± 57.47	382.95 ± 6.85	349.18 ± 6.43	165.62 ± 16.85
290-330	7951 ± 89.17	4933.60 ± 62.65	3032.25 ± 53.92	1390.49 ± 13.69	596.09 ± 6.71	574.68 ± 51.13	207.93 ± 5.10	183.77 ± 4.41	79.29 ± 3.93
330-380	5356 ± 73.18	3327.24 ± 47.90	1833.58 ± 50.31	796.60 ± 10.40	363.38 ± 4.60	376.89 ± 48.64	123.57 ± 3.92	124.24 ± 3.89	48.94 ± 2.36
380-440	3113 ± 55.79	2019.10 ± 25.02	932.62 ± 28.93	403.16 ± 7.39	203.45 ± 3.69	146.81 ± 27.37	72.85 ± 3.04	74.17 ± 2.81	32.18 ± 1.61
440-500	1558 ± 39.47	1079.39 ± 18.09	422.85 ± 18.60	166.51 ± 4.78	99.35 ± 2.26	68.11 ± 17.51	32.88 ± 2.05	37.16 ± 2.44	18.84 ± 1.04
500-575	955 ± 30.90	744.19 ± 18.80	294.73 ± 29.01	84.64 ± 3.43	52.75 ± 1.03	103.91 ± 28.69	19.05 ± 1.70	22.81 ± 1.46	11.57 ± 0.69
575-650	543 ± 23.30	388.04 ± 10.43	98.43 ± 11.06	34.06 ± 2.19	23.65 ± 0.65	16.05 ± 10.68	8.09 ± 1.04	10.85 ± 1.36	5.73 ± 0.35
650-750	372 ± 19.29	268.76 ± 3.01	82.88 ± 12.63	18.23 ± 1.61	16.89 ± 1.55	30.00 ± 12.37	5.68 ± 0.82	8.03 ± 0.83	4.05 ± 0.24
750-900	249 ± 15.78	195.72 ± 11.57	31.88 ± 2.97	11.10 ± 1.24	8.66 ± 0.55	1.64 ± 2.46	2.61 ± 0.61	5.46 ± 0.72	2.41 ± 0.11
900-1100	116 ± 10.77	91.27 ± 0.82	14.77 ± 4.45	2.40 ± 0.56	3.28 ± 0.20	4.33 ± 4.36	1.23 ± 0.44	2.37 ± 0.45	1.16 ± 0.06
1100-1400	46 ± 6.78	43.41 ± 0.42	6.30 ± 1.91	0.72 ± 0.36	1.66 ± 0.28	2.35 ± 1.80	0.44 ± 0.30	0.61 ± 0.35	0.52 ± 0.02
1400-2000	28 ± 5.29	17.21 ± 0.18	1.27 ± 0.32	0.14 ± 0.14	0.51 ± 0.01	0 ± 0	0.23 ± 0.17	0.22 ± 0.23	0.17 ± 0.01

m_W^- [GeV]	Data	$W^- \rightarrow \mu^- \bar{\nu}$	Total Bkg.	$t\bar{t}$	Z+jets	Multijet	Single top	Diboson	$W \rightarrow \tau \nu$
130-170	189758 ± 435.61	127000.69 ± 803.93	48116.81 ± 142.30	21850.17 ± 53.90	10602.33 ± 52.45	9361 ± 99.89	2634.53 ± 16.31	2645.35 ± 20.25	1023.43 ± 62.76
170-210	65110 ± 255.17	38086.85 ± 317.25	25459.89 ± 104.83	13225.67 ± 41.98	3890.74 ± 27.11	4968.68 ± 88.22	1445.68 ± 12.91	1502.19 ± 13.78	426.93 ± 18.79
210-250	23682 ± 153.89	13376.39 ± 149.64	11495.13 ± 82.98	6330.96 ± 29.11	1455.57 ± 15.29	2071.35 ± 73.00	720.51 ± 9.33	715.78 ± 8.93	200.96 ± 17.57
250-290	10722 ± 103.55	5836.44 ± 84.74	5297.09 ± 61.59	2948.78 ± 19.87	622.90 ± 8.81	893.16 ± 51.47	370.64 ± 6.75	361.21 ± 6.49	100.40 ± 24.17
290-330	5119 ± 71.55	3155.19 ± 66.19	2600.37 ± 56.88	1380.48 ± 13.63	320.17 ± 6.86	478.48 ± 54.37	181.37 ± 4.73	199.91 ± 4.45	39.96 ± 2.18
330-380	3214 ± 56.69	1938.65 ± 40.74	1536.92 ± 39.94	774.99 ± 10.26	194.93 ± 4.61	272.04 ± 37.92	127.31 ± 4.01	140.19 ± 3.51	27.46 ± 1.53
380-440	1867 ± 43.21	1214.81 ± 41.88	796.79 ± 21.09	400.85 ± 7.41	116.51 ± 4.26	106.23 ± 18.83	70.36 ± 2.98	87.24 ± 2.74	15.60 ± 0.82
440-500	942 ± 30.69	601.38 ± 17.78	368.03 ± 23.68	167.47 ± 4.76	53.33 ± 2.46	65.35 ± 22.89	31.38 ± 2.06	41.92 ± 1.86	8.58 ± 0.53
500-575	592 ± 24.33	392.41 ± 15.37	192.56 ± 15.06	84.51 ± 3.44	34.81 ± 2.33	21.32 ± 14.29	20.31 ± 1.66	26.33 ± 1.59	5.28 ± 0.32
575-650	261 ± 16.16	232.45 ± 19.94	95.56 ± 7.55	35.37 ± 2.24	16.19 ± 0.88	14.28 ± 6.96	12.31 ± 1.29	14.51 ± 1.03	2.70 ± 0.19
650-750	196 ± 14	154.45 ± 14.27	57.4 ± 6.46	19.13 ± 1.67	9.35 ± 0.41	13.71 ± 6.00	4.95 ± 0.86	8.44 ± 1.40	1.82 ± 0.13
750-900	120 ± 10.95	85.99 ± 0.95	28.33 ± 2.79	8.62 ± 1.16	6.74 ± 0.43	2.89 ± 2.31	3.57 ± 0.68	5.45 ± 0.69	1.06 ± 0.06
900-1100	52 ± 7.21	41.71 ± 0.42	13.19 ± 1.73	4.31 ± 0.83	3.28 ± 0.29	0.50 ± 1.29	1.27 ± 0.44	3.34 ± 0.61	0.49 ± 0.03
1100-1400	22 ± 4.69	17.81 ± 0.19	3.74 ± 0.59	0.86 ± 0.41	1.81 ± 0.26	0 ± 0	0.12 ± 0.25	0.77 ± 0.23	0.18 ± 0.01
1400-2000	9 ± 3	6.32 ± 0.06	1.45 ± 0.36	0.17 ± 0.17	0.64 ± 0.01	0 ± 0	0.13 ± 0.13	0.45 ± 0.29	0.06 ± 0.00

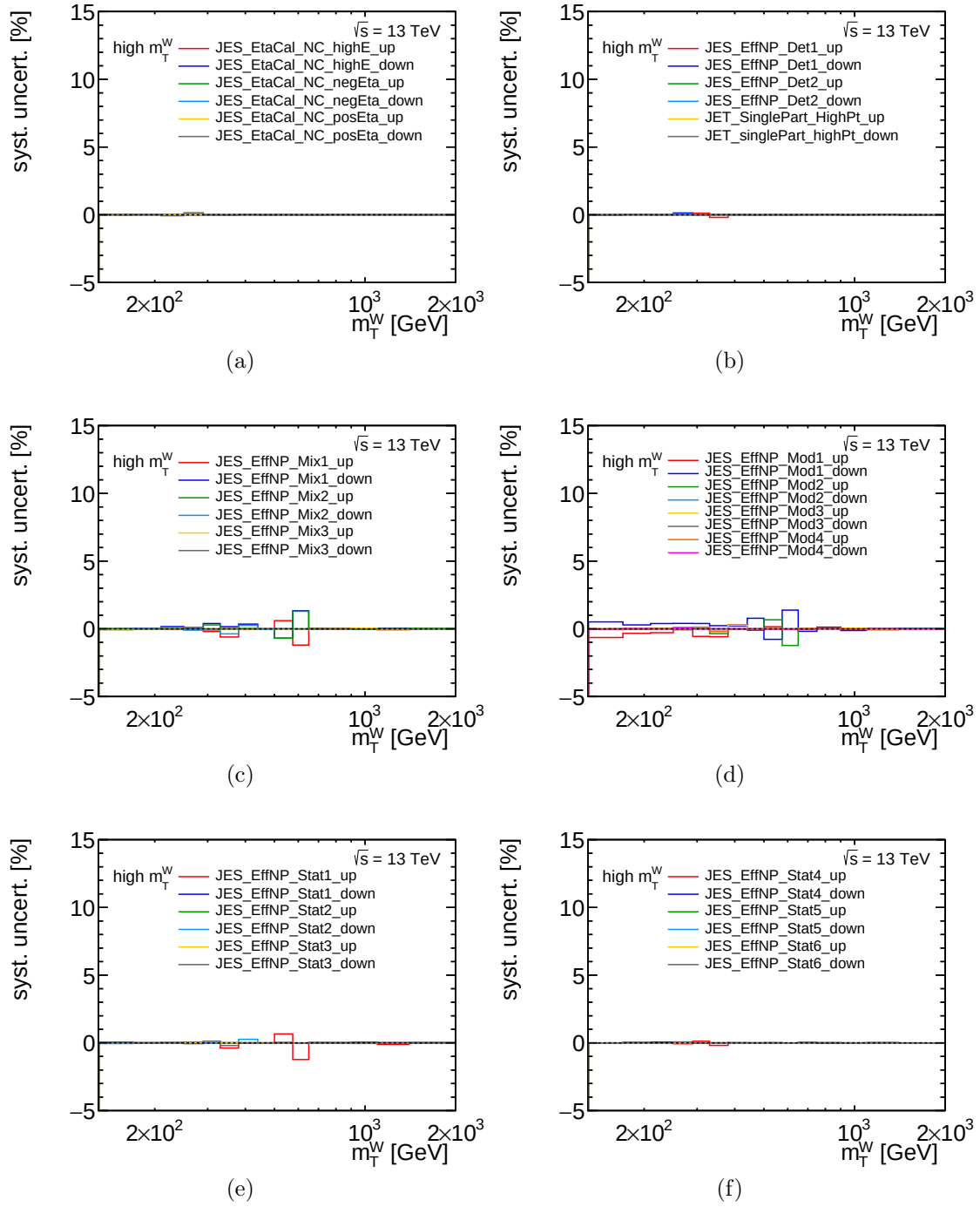


Figure A.21.: Remaining systematic uncertainties associated with the jet energy scale, normalized to the nominal signal MC.

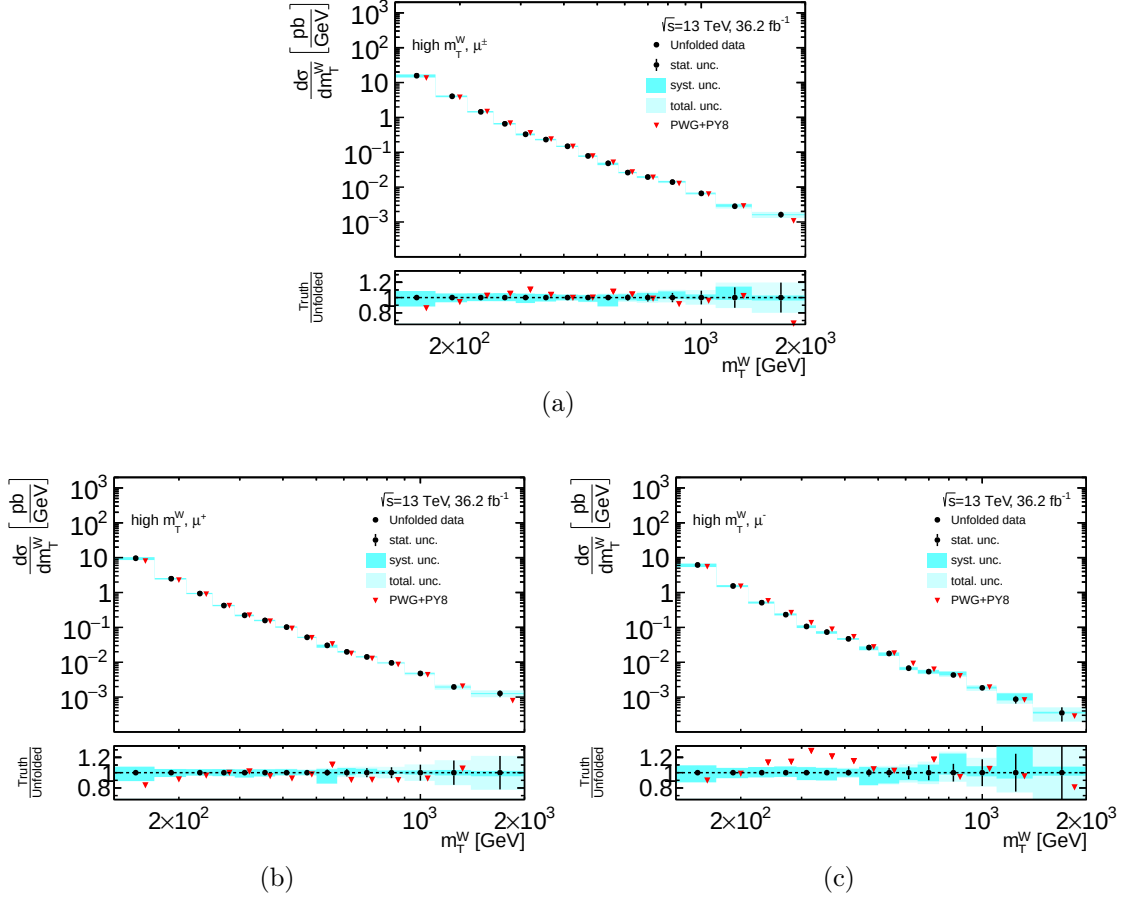


Figure A.22.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range 130 GeV to 2000 GeV for the (a) combined process $W^\pm \rightarrow \mu^\pm \nu$ as well as the charge-separated processes (b) $W^+ \rightarrow \mu^+ \nu$ and (c) $W^- \rightarrow \mu^- \bar{\nu}$. Statistical and systematic uncertainties are included, while only systematic uncertainties with a contribution larger than 1% in any m_T^W bin are considered. The luminosity uncertainty is excluded. A comparison to the POWHEG-BOX+PYTHIA 8 fiducial born level is made. The number of iterations in the IBU is here set to two.

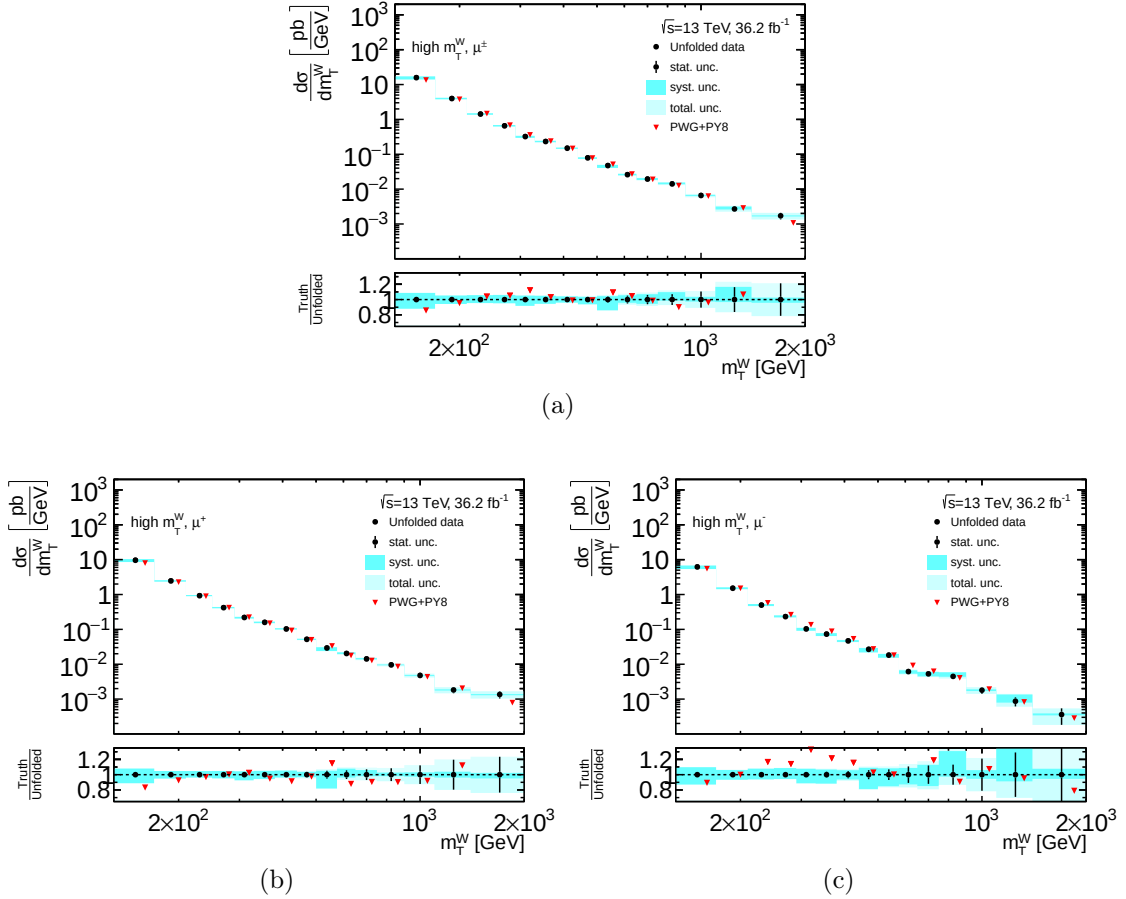


Figure A.23.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range 130 GeV to 2000 GeV for the (a) combined process $W^\pm \rightarrow \mu^\pm \nu$ as well as the charge-separated processes (b) $W^+ \rightarrow \mu^+ \nu$ and (c) $W^- \rightarrow \mu^- \bar{\nu}$. Statistical and systematic uncertainties are included, while only systematic uncertainties with a contribution larger than 1% in any m_T^W bin are considered. The luminosity uncertainty is excluded. A comparison to the POWHEG-BOX+PYTHIA 8 fiducial born level is made. The number of iterations in the IBU is here set to three.

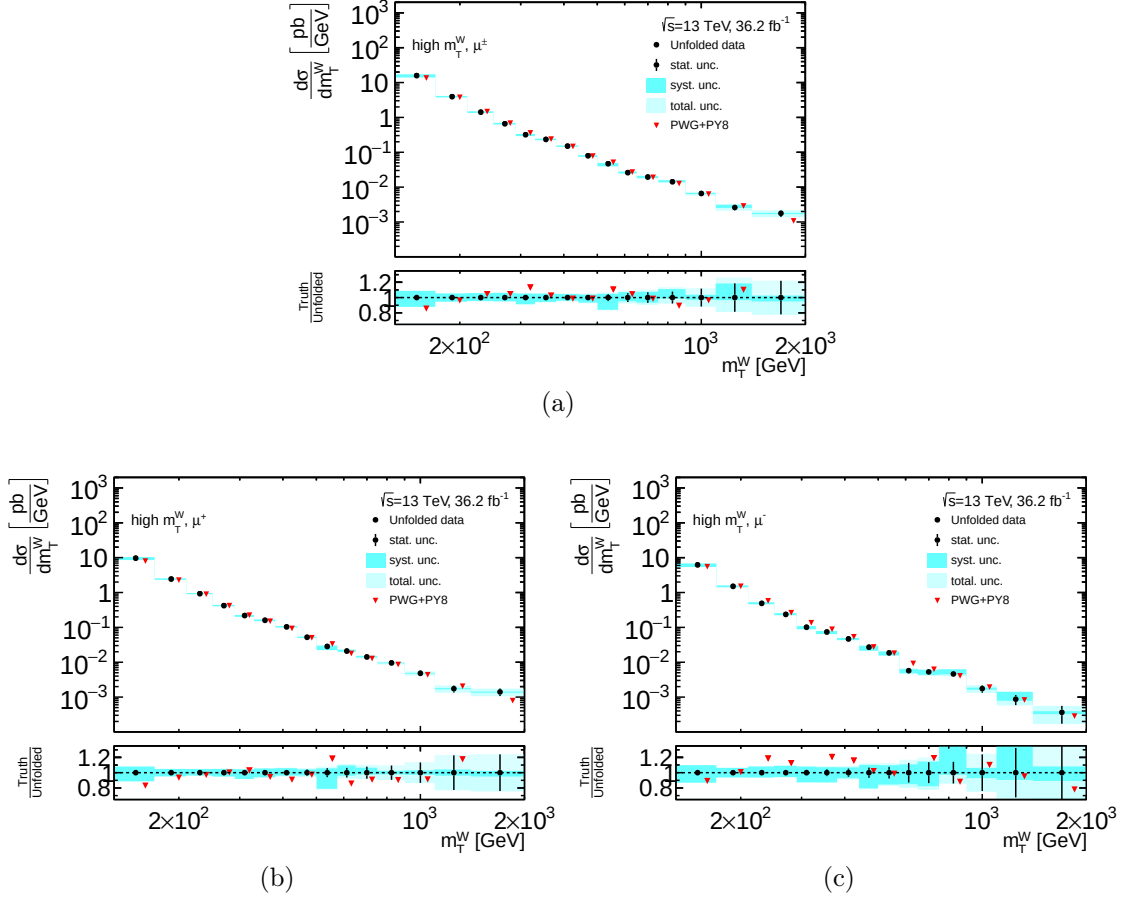


Figure A.24.: Measured charged-current Drell-Yan cross section binned in the transverse mass m_T^W in the range 130 GeV to 2000 GeV for the (a) combined process $W^\pm \rightarrow \mu^\pm \nu$ as well as the charge-separated processes (b) $W^+ \rightarrow \mu^+ \nu$ and (c) $W^- \rightarrow \mu^- \bar{\nu}$. Statistical and systematic uncertainties are included, while only systematic uncertainties with a contribution larger than 1% in any m_T^W bin are considered. The luminosity uncertainty is excluded. A comparison to the POWHEG-BOX+PYTHIA 8 fiducial born level is made. The number of iterations in the IBU is here set to four.

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