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Measurement of double-differential charged-current Drell–Yan cross-sections at high transverse masses in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

This paper presents a first measurement of the cross-section for the charged-current Drell–Yan process $pp \rightarrow W^\pm \rightarrow \ell^\pm \nu$ above the resonance region, where ℓ is an electron or muon. The measurement is performed for transverse masses, m_T^W , between 200 GeV and 5000 GeV, using a sample of 140 fb^{-1} of pp collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the LHC during 2015–2018. The data are presented single differentially in transverse mass and double differentially in transverse mass and absolute lepton pseudorapidity. A test of lepton flavour universality shows no significant deviations from the Standard Model. The electron and muon channel measurements are combined to achieve a total experimental precision of 3% at low m_T^W . The single- and double differential W -boson charge asymmetries are evaluated from the measurements. A comparison to next-to-next-to-leading-order perturbative QCD predictions using several recent parton distribution functions and including next-to-leading-order electroweak effects indicates the potential of the data to constrain parton distribution functions. The data are also used to constrain four fermion operators in the Standard Model Effective Field Theory formalism, in particular the lepton-quark operator Wilson coefficient $c_{\ell q}^{(3)}$.

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1 Introduction

The Drell–Yan process [1] of lepton pair production in hadronic interactions is a powerful tool in understanding the nature of partonic interactions and hadronic structure, and it can be a probe of the electroweak sector of the Standard Model. It has been fundamental in developing perturbative quantum chromodynamics (QCD) with calculations now available at next-to-next-to-next-to-leading-order (N³LO) accuracy [2–5].

Cross-section measurements from the Large Hadron Collider (LHC) of inclusive neutral-current ($pp \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$) and charged-current ($pp \rightarrow W^\pm \rightarrow \ell^\pm\nu$) Drell–Yan processes at centre-of-mass energies of $\sqrt{s} = 5.02$ TeV, 13 TeV and at 13.6 TeV have recently been published by the ATLAS [6, 7], CMS [8–10] and LHCb [11] collaborations. These measurements, performed at the resonant peaks where event yields are very large and background contributions are extremely small, reach high experimental accuracy. They provide new constraints on the parton distribution functions (PDFs) of the proton and offer insights into the initial-state QCD radiation dynamics in vector boson production [6]. They are however restricted in the kinematic range of partonic momentum fraction x and four-momentum transfer $Q = m_{\ell\ell}$, where $m_{\ell\ell}$ denotes the invariant mass of the dilepton pair.

Measurements extending to lower or higher invariant masses have been performed in the neutral-current channel only [12–18] and access wider x and Q kinematic regions. At low Q the measurements are sensitive to QCD resummation effects. At large Q they are sensitive to new physics beyond the Standard Model and also provide new constraints on the poorly known high- x anti-quark PDFs.

The charged-current process is highly complementary to the neutral-current process. The charge-separated cross-sections for W^+ and W^- production depend on different flavour combinations, while the Z production depends on same-flavour combinations. The dominant partonic contributions are $(u, \bar{d})$ and $(c, \bar{s})$ for W^+ , and $(d, \bar{u})$ and $(s, \bar{c})$ for W^- production.

Since the final-state neutrino is not observed, the dilepton invariant mass cannot be experimentally determined, and the transverse mass m_T^W is used instead, defined by $m_T^W = \sqrt{2p_T^\ell p_T^\nu (1 - \cos \Delta\phi(\ell, \nu))}$. Here p_T^ℓ is the charged lepton transverse momentum, p_T^ν is the neutrino or missing transverse momentum, and $\Delta\phi(\ell, \nu)$ is the azimuthal angle between them.

To date no cross-section measurements of the charged-current process above the W -boson resonance region have been made. This kinematic region is of particular interest as at the highest transverse masses accessible at the LHC, the observed m_T^W spectrum in the decay to electron or muon final states is sensitive to new physics. Such effects could manifest as a localised resonance [19, 20], a violation of lepton flavour universality or an enhancement or suppression of the continuum spectrum. Modifications to the Standard Model predictions can be described in terms of an Effective Field Theory (EFT). In this formalism the Standard Model Lagrangian is extended with new operators which are suppressed by an energy cut-off scale. The charged-current Drell–Yan process is sensitive to operators which modify the couplings between fermions and the W -boson, and operators which allow for a direct interaction between four fermions without a mediator. The effects of four-fermion operators grow quadratically with energy, so the measurement of charged-current Drell–Yan at high m_T^W therefore provides strong sensitivity to such effects. This measurement is thus expected to provide electroweak precision tests that surpass LEP in sensitivity [21].

This article reports a first measurement of the cross-section for the process $pp \rightarrow \ell\nu + X$ above the W -boson resonance production region. The measurements are performed using a sample of 140 fb⁻¹ of

pp collision data at $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the LHC in both electron and muon channels. The double-differential measurement is reported as a function of m_{T}^{W} and absolute charged-lepton pseudorapidity $|\eta|$. The data are also presented as single-differential cross-sections $d\sigma/dm_{\text{T}}^{\text{W}}$. The data cover the kinematic region of $200 \leq m_{\text{T}}^{\text{W}} \leq 5000$ GeV and access partonic momentum fractions from $x \sim 10^{-2}$ up to $x \sim 1$.

2 ATLAS detector

The ATLAS detector [22] at the LHC covers nearly the entire solid angle around the collision point.¹ It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit generally being in the insertable B-layer (IBL) installed before Run 2 [23, 24]. It is followed by the SemiConductor Tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic energy measurements respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

The luminosity is measured mainly by the LUCID-2 [25] detector that records Cherenkov light produced in the quartz windows of photomultipliers located close to the beam pipe.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

Events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [26]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate close to 100 kHz, which the high-level trigger further reduces in order to record complete events to disk at about 1.25 kHz.

A software suite [27] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Simulated event samples

Monte Carlo (MC) simulation samples are used to model the expected signal and background yields, with the exception of certain data-driven background estimates. The MC samples are normalised using higher-order cross-section predictions in perturbation theory.

The neutral and charged current Drell-Yan processes are generated at next-to-leading-order (NLO) using POWHEG BOX v1 [28–31] and the CT10_{NLO} PDF [32], with PYTHIA 8.1 [33] to model the parton showers (PS) and hadronisation. The effect of QED final-state radiation was simulated with PHOTOS++ 3.52 [34, 35]. The EVTGEN 1.2.0 program [36] was used to decay bottom and charm hadrons. This MC sample is hereafter referred to as the POWHEG+PYTHIA sample. Using invariant-mass dependent k -factors [37] these predictions are corrected to account for next-to-next-to-leading-order (NNLO) QCD and NLO electroweak (EW) effects. The QCD corrections are computed using VRAP v0.9 [38] and also weight the predictions to the CT14_{NNLO} PDF set [39]. The EW corrections excluding QED final state radiation (FSR) are computed using MCSANC [40] and vary from about -3% at low m_T^W to about -10% at $m_T^W = 1$ TeV. The additive approach is used to combine the EW and QCD corrections.

An alternative simulation of the signal process is used for the assessment of systematic uncertainties arising from different modelling choices. It is generated using SHERPA 2.2.11 [41] at NLO in QCD for up to two additional partons and at LO for up to five partons, using the NNPDF3.0_{NNLO} PDF set [42]. The sample is then reweighted to the CT18_{NNLO} PDF set [43]. The prediction is corrected to approximate NNLO accuracy with a k -factor of 0.95 calculated using MATRIX v2 [44, 45]. NLO EW corrections are implemented in SHERPA. The exponentiated approach for combining EW and QCD corrections is used, which yields corrections lying between the additive and multiplicative approaches. The differences between all three corrections is however small and typically below 1%.

The background from $t\bar{t}$ production is the dominant background with isolated prompt leptons from electroweak boson decays. It is estimated at NLO using POWHEG BOX v2 [46] with a top-quark mass of $m_{\text{top}} = 172.5$ GeV and the NNPDF3.0_{NLO} PDF set [42], with PYTHIA 8.2 [47] for parton showering and hadronisation. The decays of bottom and charm hadrons were performed by EVTGEN 1.6.0. The $t\bar{t}$ MC samples are reweighted in the p_T of the top quark and in the mass of the $t\bar{t}$ pair to inclusive cross-section calculations at NNLO accuracy in QCD including NLO EW corrections [48]. The single-top-quark background, consisting of s - and t -channel processes and the tW process, is also simulated under the same conditions. The dynamic scale diagram subtraction scheme [49] is used to account for the interference between the tW and $t\bar{t}$ production diagrams.

Further important background contributions are due to diboson (WW , WZ and ZZ) production decaying into final states with at least one charged lepton. The diboson processes are generated with SHERPA 2.2.1 or SHERPA 2.2.2 depending on the process, using the NNPDF3.0_{NNLO} PDF set. They were generated using

matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions.

All MC samples used in the analysis include the effects of QED FSR, multiple pp interactions per bunch crossing (“pile-up”), and detector simulation. The QED FSR is simulated using PHOTOS [50], except for samples generated by SHERPA which includes a native FSR simulation. The effect of pile-up was modelled by overlaying the simulated hard-scattering event with inelastic pp events generated with PYTHIA 8.1 using the NNPDF2.3_{LO} PDF set [51] and the A3 set of tuned parameters [52]. The interactions of particles with the detector are modelled using a full ATLAS detector simulation [53] based on GEANT4 [54]. Finally, several corrections are applied to the simulated samples, accounting for differences between data and simulation in the lepton trigger, reconstruction, identification, and isolation efficiencies as well as lepton resolution and muon momentum scale.

4 Event reconstruction and selection

Events are required to be recorded during stable beam condition periods and must pass detector and data-quality requirements [55]. Due to differences in the detector response to electrons and muons the nominal selection is optimised separately for each channel and is described in the following. In addition to the nominal selection two further selections are defined. Both correspond to less stringent selections needed for either the background estimation (“loose”) or in order to veto events with a second lepton (“veto”).

4.1 Object reconstruction and selection

4.1.1 Electrons

Electrons are reconstructed from clusters of energy deposited in the EM calorimeter and matched to tracks reconstructed in the ID [56]. An energy scale correction determined from $Z \rightarrow e^+e^-$, and $J/\psi \rightarrow e^+e^-$ decays is applied to data. Electron candidates are required to have a pseudorapidity within the inner detector tracking region, $|\eta| < 2.4$, excluding a region, $1.37 < |\eta| < 1.52$, where the transition between the barrel and endcap electromagnetic calorimeters is not well modelled in the simulation.

The primary interaction vertex is taken to be the one with the largest sum of squared transverse momenta of all associated tracks [57]. Electrons must originate from the primary vertex and are selected by requiring $|z_0 \sin \theta| < 0.5$ mm, where z_0 is the coordinate of the track at the point of closest approach to the beam-line. The significance of the transverse impact parameter, defined by the distance of closest approach of the track to the beam-spot in the $r - \phi$ projection $|d_0|$, divided by its estimated uncertainty $\sigma(d_0)$, is required to satisfy $|d_0|/\sigma(d_0) < 5$.

Candidates must satisfy the *LooseAndBLayer* likelihood-based identification requirements [56] based on EM shower shapes, track quality, and track–cluster matching.

Leptons produced in the Drell–Yan process are expected to be well isolated from energy depositions not associated with the lepton. Therefore the electron candidates also need to fulfil the *FCLoose* isolation working point [56], which has two distinct definitions of the degree of isolation: one is based on calorimeter information and one is based on tracks in the ID. The calorimeter-based isolation is defined as the scalar sum of transverse energy, $\sum E_T$, contained in a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ around the electron,

omitting the electron transverse energy, E_T . It is given by $\sum E_T(\Delta R = 0.2) < 0.20 \cdot E_T$. The track-based criterion is based on the scalar sum of transverse momenta, $\sum p_T$, of additional tracks around the electron, and is required to be below 15% of the electron p_T , i.e. $\sum p_T(\Delta R) < 0.15 \cdot p_T$. Here, the ΔR cone size shrinks with increasing transverse momentum of the electron, $\Delta R = \min(\frac{10 \text{ GeV}}{p_T}, 0.2)$.

The criteria above define the “loose” and the “veto” level as they are identical for electrons. The nominal selection requires electrons to in addition satisfy the *Tight* likelihood-based identification requirements and an additional electron isolation requirement that uses the *FCHighPtCaloOnly* isolation working point [56], based on calorimeter information only via $\sum E_T(\Delta R = 0.2) < \max(0.015 \cdot E_T, 3.5 \text{ GeV})$.

4.1.2 Muons

Muon candidates are reconstructed from tracks in the muon spectrometer matched to tracks from the ID and satisfy $|\eta| < 2.4$. Muons originating from the primary vertex are selected by requiring $|z_0 \sin \theta| < 0.5 \text{ mm}$ and $|d_0|/\sigma(d_0) < 3$.

Except for the “veto” level the muon identification uses the *High- p_T* working point [58] designed to optimise the resolution for muons with p_T above 100 GeV. This working point requires: agreement in the charge-to-momentum ratio of the muon as measured in the ID and the MS, taking into account their uncertainties; at least three precision space-points in the MS for improved sagitta measurement; and upper limits on the uncertainty of the charge-to-momentum ratio. These requirements cannot be fulfilled in some regions of the MS, for example in the transition region between barrel and endcap with $1.01 < |\eta| < 1.1$. The *Medium* working point [58], which particularly requires only two precision space-points in the MS, is used when vetoing additional muons.

The nominal selection requires muons to in addition fulfil an isolation criteria. It is defined using the scalar sum of transverse momenta, $\sum p_T$, of additional tracks divided by p_T , the transverse momentum of the muon. The selection requires $\sum p_T(\Delta R = 0.2) < 0.06 \cdot p_T$, providing a good discrimination against the background arising from the semileptonic decays of heavy quarks.

4.1.3 Jets

Jets are reconstructed and used in the determination of the missing transverse momentum in the event. A particle flow algorithm [59] is used which optimally combines calorimetric and tracking information. The anti- k_t algorithm [60, 61] is used with radius parameter $R = 0.4$. They are calibrated using in situ measurements and simulation [62]. Jets are required to satisfy transverse momentum $p_T > 25 \text{ GeV}$ and pseudorapidity $|\eta| < 2.5$. Jets with $p_T < 60 \text{ GeV}$ and $|\eta| < 2.5$ are also required to pass the *tight* jet vertex tagger criteria [63]. Identification of jets containing b -hadrons is performed with the DL1r algorithm [64] with an average tagging efficiency of b -jets from simulated dileptonic $t\bar{t}$ events of 70%.

4.1.4 Overlap removal

Particles identified by the ATLAS detector may be reconstructed as multiple different objects. Ambiguities for electrons are resolved by applying a sequential algorithm to select the best choice for each object. If a pair of electron candidates share a track, the lower p_T object is removed. Any jet within $\Delta R = 0.2$ of an electron candidate is removed. Then, any electron candidates found within $\Delta R = 0.4$ of a jet are removed.

Ambiguities for muons are not resolved at this stage as they are beneficial for the estimation of the amount of non-prompt muons in this measurement (see Section 5.2.2).

4.1.5 E_T^{miss}

The missing transverse momentum, with magnitude E_T^{miss} , is determined from the sum of transverse momenta of reconstructed and calibrated objects in the event. A so-called soft term accounts for the p_T of all remaining tracks associated to the primary vertex [65].

4.2 Event selection

The electron data are collected by a set of triggers which use calorimetric information to identify a compact electromagnetic energy deposition [66]. Identification algorithms use calorimeter shower shape information to find candidate electrons with a minimum transverse energy of 60 or 120 GeV in 2015. *Medium* identification criteria [56] are applied at the lower threshold and *loose* criteria for the higher threshold. In the remaining years the higher transverse energy threshold was changed to 140 GeV. To validate backgrounds two additional low-threshold triggers were used with trigger thresholds 24 GeV and *medium* identification criteria in 2015, and a 26 GeV threshold with *tight* identification in subsequent years. In the muon channel data are collected using a single muon trigger with a transverse momentum above 50 GeV [67].

Events are required to have exactly one reconstructed electron with $E_T > 65$ GeV or exactly one reconstructed muon with $p_T > 65$ GeV. The electron or muon has to satisfy the nominal selection criteria. In both cases the lepton is required to match a corresponding trigger. Events containing additional muons or electrons with $p_T > 20$ GeV fulfilling the “veto” level criteria are rejected. The E_T^{miss} is required to be greater than 85 GeV and the reconstructed m_T^W must exceed 200 GeV. It is determined from the relationship given in Section 1 using the reconstructed E_T^{miss} , lepton p_T , and the azimuthal angle between them.

5 Background estimation

The background from processes with one prompt isolated final-state lepton is estimated from MC simulation and includes: $Z \rightarrow \ell\ell$ where one lepton is not reconstructed due to detector acceptance or efficiency effects; $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$ where a τ -lepton decays leptonically; diboson production of ZZ , WZ and WW in which one boson decays leptonically; and $t\bar{t}$ and single top production (hereafter termed the top-quark background). The MC predictions for some of the major contributions are validated in dedicated kinematic regions.

A further background contribution arises from light- and heavy-flavour multijet production in which non-prompt leptons are produced or from the misidentification of jets as fake electrons. In the following the multijet background is defined as the sum of both contributions. This background is not well modelled in simulation and is determined using data-driven techniques described in detail below.

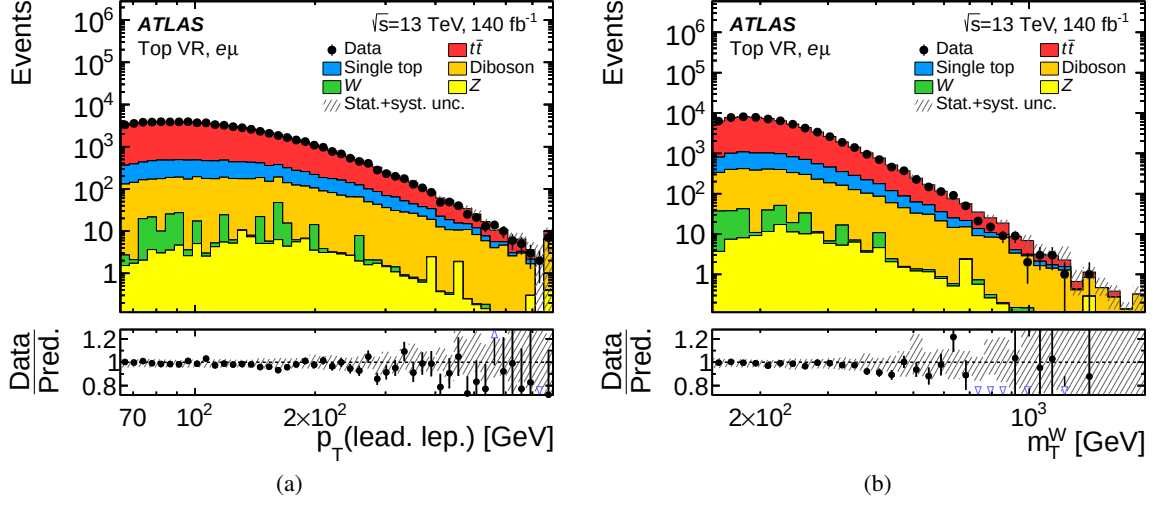


Figure 1: Comparisons of the data and prediction in the top validation region for the (a) p_T of the leading lepton and the (b) transverse mass of the W boson. Statistical and systematic uncertainties of the prediction are included in the uncertainty band. A blue triangle in the bottom panel indicates data points outside the vertical range shown.

5.1 Top-quark background contribution

The background contribution from top-quark production is estimated using the MC simulation, and is expected to be large in the phase space of this measurement. It is therefore important to check the validity of the MC simulation using data. As the dominant contribution stems from dileptonic decays of the $t\bar{t}$ pairs, a top-quark-enriched sample of events is selected by requiring two “tight” leptons – one electron and one muon both with $p_T > 30$ GeV. The leading lepton is further required to have $p_T > 65$ GeV matching the signal region selection, and this lepton is used with E_T^{miss} in the calculation of the m_T^W observable. The E_T^{miss} is required to be above 85 GeV, and the m_T^W is required to exceed 150 GeV. This validation region closely matches the kinematic region of the measurement and is found to be highly enriched in $t\bar{t}$ and single-top production with fractions of 85% and 9% respectively, where the single-top production is dominated by the tW process. The signal and multijet contributions are negligible in this sample. All kinematic observables are found to be well described in shape and in normalisation by the sum of MC expectations. Examples are shown in Figure 1 for the leading lepton p_T and the m_T^W observable.

The top-quark background is further cross checked in two variations of the validation region where the E_T^{miss} requirement is removed or where an additional b-jet is required. The former validation region allows a check of the region of small E_T^{miss} used in the multijet estimate, while the latter is a pure ($> 99\%$) top-quark control region. The simulation is again found to describe the data well in both regions.

5.2 Multijet background estimate via the matrix method

The matrix method [14] is used to estimate the multijet background in the electron and muon channels. The method makes use of the different sets of selection criteria described in Sections 4.1.1 and 4.1.2. It relates the number of observed leptons satisfying the nominal (“tight”) requirement, N_T , or only the less stringent (“loose”) requirements, N_L , to the number of prompt (“real”) leptons, N_R , and to the number of non-prompt

leptons or jets (“fake”), N_F . They are connected by a pair of linear equations, using MC estimates of the real efficiency, ϵ_r , and data-driven estimates of the fake efficiency, ϵ_f . The real efficiency is defined to be the fraction of prompt leptons satisfying at least the loose selection which also pass the tight selection, $\epsilon_r = N_R^T / (N_R^L + N_R^T)$. The fake efficiency is analogously defined as the fraction of non-prompt leptons and jets satisfying at least the loose selection which also pass the tight selection $\epsilon_f = N_F^T / (N_F^L + N_F^T)$. The relationship is given as:

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_r & \epsilon_f \\ 1 - \epsilon_r & 1 - \epsilon_f \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}.$$

The equation can be inverted to derive the multijet background as

$$N^{\text{multijet}} = \epsilon_f N_F = \frac{\epsilon_f}{\epsilon_r - \epsilon_f} [\epsilon_r (N_L + N_T) - N_T].$$

This general method is used to derive the distribution of multijet events as a function of any variable of interest for both the electron and the muon channels.

5.2.1 Multijet background estimate in the electron channel

The real efficiency is determined using the signal MC sample in which the reconstructed prompt electron is matched to the corresponding Born-level particle. The E_T^{miss} and m_T^W criteria described in Section 4.2 are not applied. The ϵ_r are determined in 132 two-dimensional bins of electron p_T and $|\eta|$. The resulting factors are found to vary between 90 – 95% except at the largest $|\eta|$ and close to the transition region between the barrel and endcap calorimeter.

The fake efficiency is measured using a data sample enriched in fake electrons by removing the m_T^W criterion and requiring the E_T^{miss} to be below 65 GeV, which also ensures orthogonality between the signal and fake enriched selections. The residual real electron contribution is subtracted using the MC predictions. The fake efficiency has the same binning in p_T and $|\eta|$ as the real efficiency, but depends simultaneously also on the difference in azimuthal angle between the electron and the E_T^{miss} , $\Delta\phi(e, E_T^{\text{miss}})$, leading to 660 three-dimensional bins. The fake efficiencies are found to be typically below 50% with a marked reduction at larger p_T . The resulting efficiencies are validated by comparing the simulation and predicted multijet background contribution to the data in a wider fake enriched region in which the E_T^{miss} condition is removed completely. Figure 2 shows the data and the predicted event yields for the m_T^W and η spectra in this region for the e^- measurement channel. The data are described by the prediction given the multijet and statistical uncertainties shown in the figure. The dominant uncertainty, particularly at low E_T^{miss} , arises from the choice of calibration applied to loose objects in the E_T^{miss} calculation as discussed in Section 7.1.

5.2.2 Multijet background estimate in the muon channel

The multijet background estimation in the muon channel largely follows that of the electron channel described above. The real efficiency is determined from the signal Drell–Yan MC simulation from events in which the reconstructed muon is matched to the Born-level particle. The E_T^{miss} and m_T^W selection criteria are dropped. The real and fake efficiencies, ϵ_r and ϵ_f , are determined in only 18 two-dimensional bins of

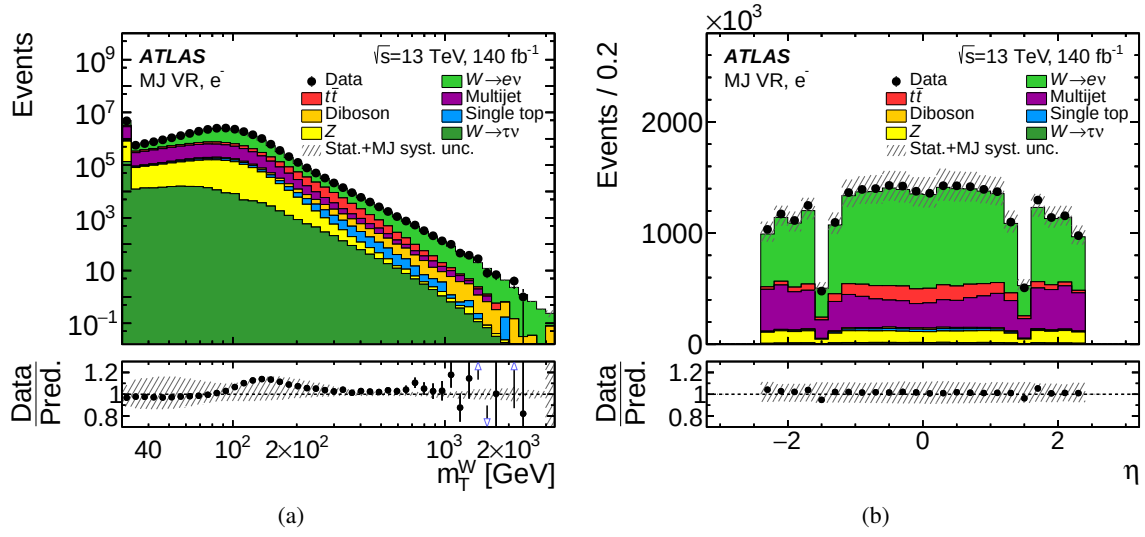


Figure 2: Comparisons of the data and prediction in the multijet validation region for the (a) transverse mass of the W boson and the (b) pseudorapidity of the electron for the e^- final state. The grey shaded band represents the statistical uncertainty of the prediction and the systematic uncertainties on only the multijet estimate. A blue triangle in the bottom panel indicates data points outside the vertical range shown.

reconstructed muon p_T and $|\eta|$ due to the limited sample size available to the fake efficiency estimate when compared to the case of electrons. The real efficiencies are found to exceed 99% in all bins.

The fake enriched region in the muon channel is created by first removing the m_T^W requirement and requiring $E_T^{\text{miss}} < 65$ GeV, as described in Section 5.2.1. Since the dominant source of fake muons arises from heavy flavour b - and c -hadron decays within jets, further selections are used to enhance the yield of this class of events. Dijet topologies are targeted in which an additional jet is required (see Section 4.1) which is back-to-back in the azimuthal angle with respect to the muon, $\Delta\phi(j, \mu) > \frac{5}{6}\pi$. The azimuthal angular separation between the muon and the E_T^{miss} is required to be less than $\frac{\pi}{6}$. This criterion efficiently suppresses the signal contribution. Finally, the transverse impact parameter significance $|d_0|/\sigma(d_0)$ is required to be greater than 1.5. The remaining contributions from EW processes and the signal process are subtracted using the predictions from MC simulation.

An algorithm similar to the one used to resolve particle object ambiguities in the electron channel within an event as described in Section 4.1 is not applied in the muon channel as non-prompt muons arise predominantly from within jets. Therefore, the contribution from non-prompt muons is increased in the fake enriched region while these muons are efficiently suppressed by the isolation requirement for muons which is part of the tight selection.

The efficiency for selecting fake muons is found to be about 10% at low p_T , rising to between 30% for central pseudorapidity and 65% at the highest pseudorapidity. It is validated by estimating the multijet background in an enlarged kinematic region with respect to the region used to estimate the fake efficiency. This is achieved by first removing the E_T^{miss} selection criterion. Figure 3 shows the data and the predicted event yields for the extrapolation in E_T^{miss} and for η for the μ^+ measurement channel. Up to $E_T^{\text{miss}} \approx 150$ GeV where the multijet contribution is large, the data are well described by the predictions within the systematic uncertainty of only the multijet estimate and the statistical uncertainty of the prediction. However, the region of high m_T^W cannot be validated as the requirement on $\Delta\phi(\mu, E_T^{\text{miss}})$ suppresses the event yield.

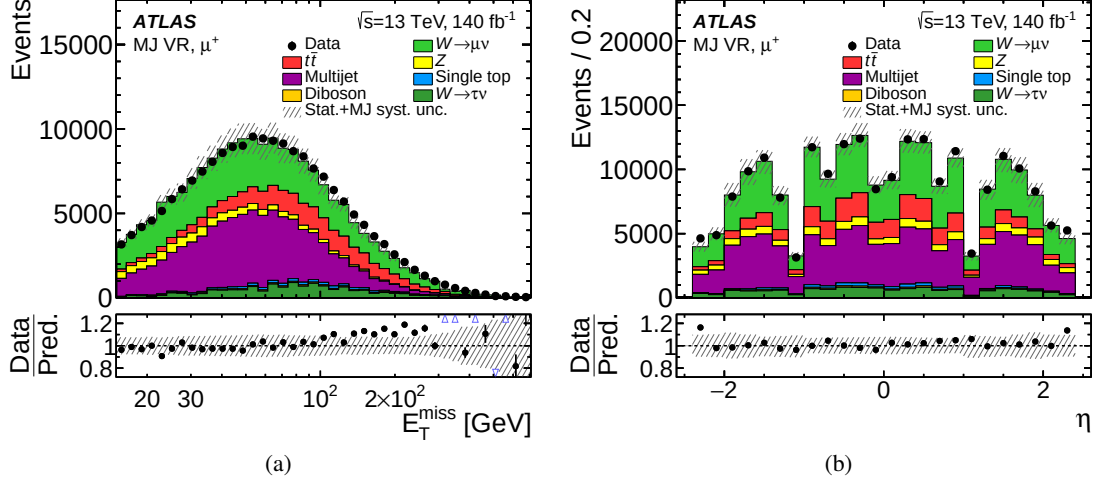


Figure 3: Comparisons of the data and prediction in the multijet validation region for the (a) missing transverse energy and the (b) pseudorapidity of the muon for the μ^+ final state. The grey shaded band represents the statistical uncertainty of the prediction and the systematic uncertainties on only the multijet estimate. A blue triangle in the bottom panel indicates data points outside the vertical range shown.

Therefore a second validation region is defined by removing the requirement on $\Delta\phi(\mu, E_T^{\text{miss}})$ and requiring at least three jets instead. The resulting phase space is found to be composed of approximately equal contributions from multijet events, signal, and top quark processes. The data in this phase space are well described by the prediction.

5.3 Data and prediction comparisons

The number of expected events is calculated as the sum of the data-driven and simulated background estimates, and the expected event yield predicted by the signal Drell–Yan MC simulations.

Figures 4 and 5 compare data and expectation for the reconstructed lepton p_T , E_T^{miss} , and m_T^W distributions. In the phase space of the measurement the three largest background contributions in the electron channel are the top-quark ($t\bar{t}$ and single top), multijet and diboson contributions which are found to be approximately 23%, 4%, and 3% respectively in the $W \rightarrow e^+\nu$ channel. The corresponding contributions in the $W \rightarrow e^-\nu$ channel are 33%, 5%, and 4%.

In the muon channel the three largest background contributions are from top-quark ($t\bar{t}$ and single top), Z +jets, and diboson production. They constitute about 20%, 8%, and 2% of the total expectation in the $W \rightarrow \mu^+\nu$ channel. In the $W \rightarrow \mu^-\nu$ measurement the contributions are found to be approximately 31%, 6%, and 3% of the expectation event yield. The multijet contribution in the muon channels is below 2%.

The data event yields and spectra are found to be well described by the expectation in both the $W^\pm \rightarrow e^\pm\nu$ and the $W^\pm \rightarrow \mu^\pm\nu$ channels.

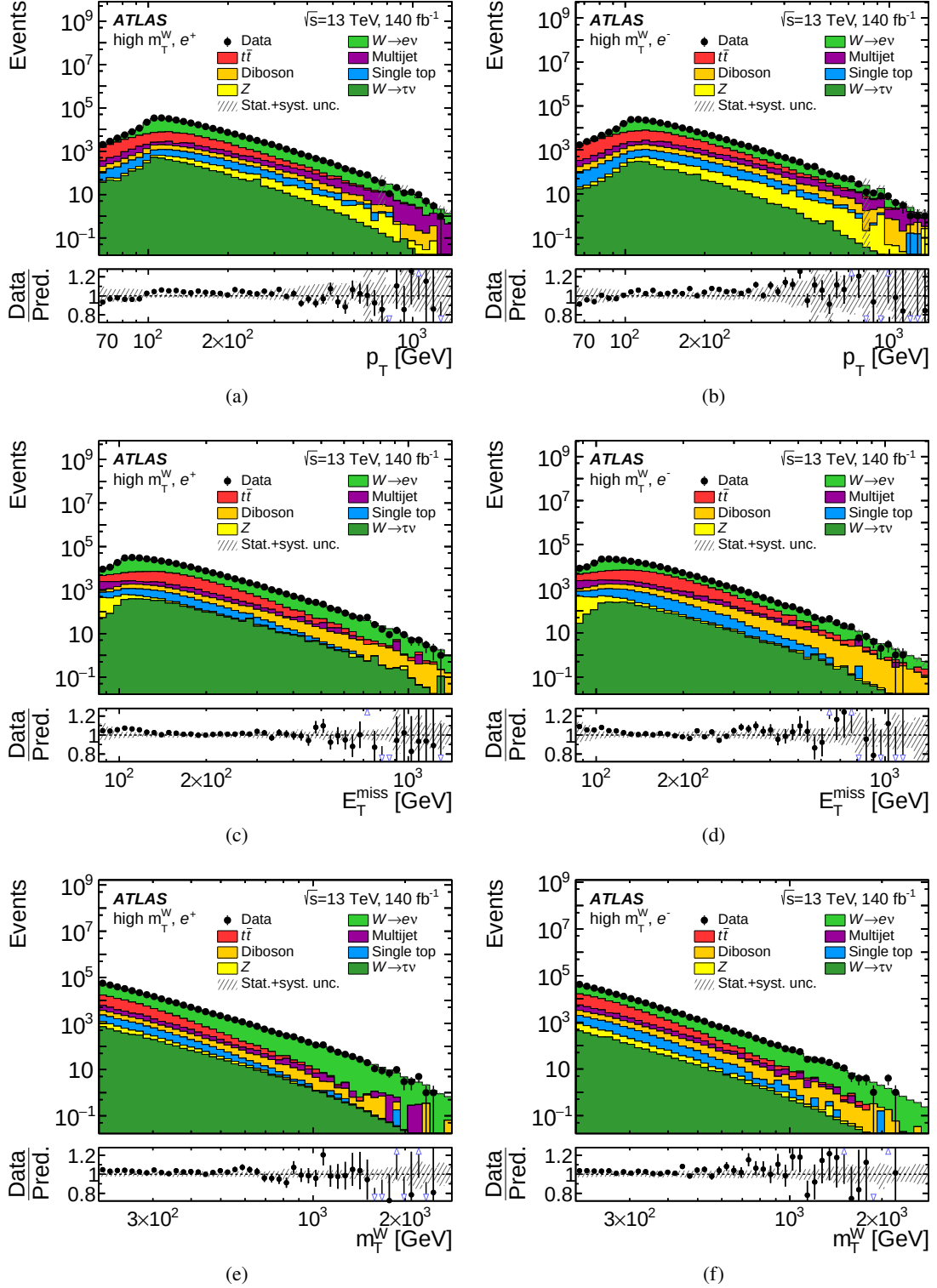


Figure 4: Comparisons of the data and prediction in the signal region for the (a, b) transverse momentum of the lepton, (c, d) missing transverse momentum, and (e, f) transverse mass m_T^W in the (a, c, e) e^+ and (b, d, f) e^- final states. Statistical and systematic uncertainties of the prediction (except for theoretical uncertainties on the signal) are included in the uncertainty band. A blue triangle in the bottom panel indicates data points outside the vertical range shown.

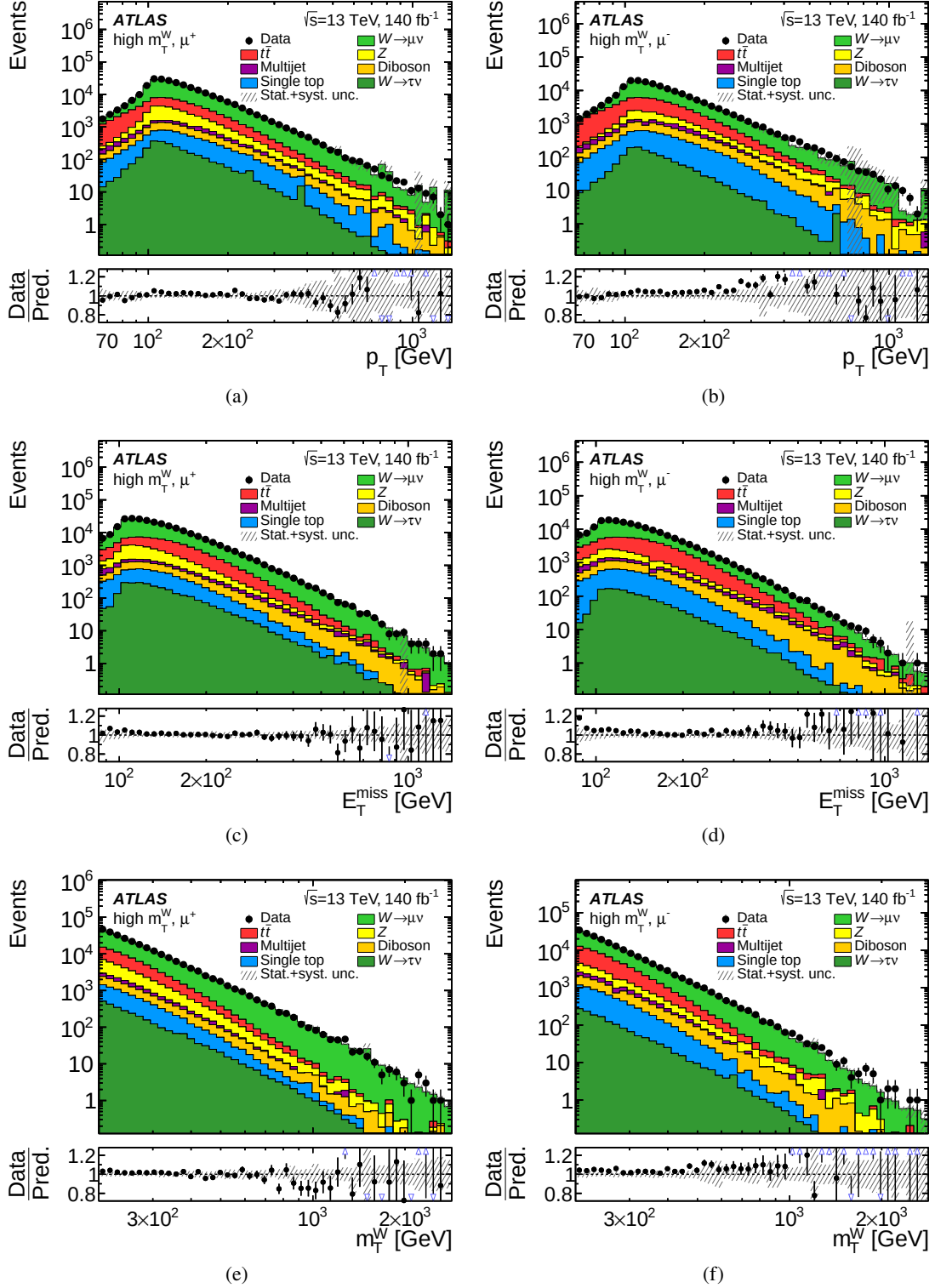


Figure 5: Comparisons of the data and prediction in the signal region for the (a, b) transverse momentum of the lepton, (c, d) missing transverse momentum, and (e, f) transverse mass m_T^W in the (a, c, e) μ^+ (right) and (b, d, f) μ^- final states. Statistical and systematic uncertainties of the prediction (except for theoretical uncertainties on the signal) are included in the uncertainty band. A blue triangle in the bottom panel indicates data points outside the vertical range shown.

6 Cross-section measurement

The charged current Drell–Yan cross-sections are measured for each charge and lepton flavour separately. The differential cross-sections are measured in 12 m_T^W bins in the range $200 \leq m_T^W \leq 5000$ GeV. Double differential cross-sections in five m_T^W bins and up to 12 $|\eta|$ bins are also presented covering the region $0 \leq |\eta| \leq 2.4$, and $200 \leq m_T^W \leq 2000$ GeV, as listed in Table 1.

The binning in m_T^W is chosen such that the bin widths are larger than the detector resolution to minimise migrations between bins and that the bins at the highest values of m_T^W have moderate statistical uncertainties. In particular, the muon channel is expected to have worse resolution at high m_T^W than the electron channel since the muon is fully reconstructed from track-based measurements only. The muon p_T dominates the resolution for $m_T^W > 400$ GeV, but below this region it is the E_T^{miss} which gives the leading contribution. In the fiducial region the single differential bin purity, defined as the yield ratio of particle-level signal MC events to reconstructed signal MC events, is found to be typically 60%. In the muon channel this decreases in the 2 – 5 TeV m_T^W bin, whereas in the electron channel it increases, reaching unity at the highest m_T^W .

6.1 Fiducial definition

The measurements are unfolded to a common fiducial region that closely matches the kinematic selection described in Section 4. It is defined at particle level as $|\eta| < 2.4$, $p_T^\ell > 65$ GeV, the transverse momentum of the (anti-)neutrino $p_T^\nu > 85$ GeV, and $200 \leq m_T^W \leq 5000$ GeV for the single differential measurements, or $200 \leq m_T^W \leq 2000$ GeV for the double differential measurements. The lepton charge is included in the definition of the fiducial region.

The fiducial region is defined at the Born particle level prior to any QED radiation from the final-state charged lepton. The measurements can also be corrected to the “dressed” particle level by multiplying the reported cross-sections by the multiplicative factor C_{fsr} defined as the ratio of the dressed-level cross-section to the Born level, and is provided in the data tables (see Section 8). The dressed particle level is obtained from MC simulation by merging the Born-level leptons with any prompt photons within a cone of $\Delta R < 0.1$ around the charged lepton. The C_{fsr} are close to unity and found to vary weakly with m_T^W .

6.2 Unfolding procedure

After the signal region selection has been applied and each of the background contributions has been subtracted from the data, the observed distributions are corrected for detector effects in an unfolding procedure [68]. The differential one-dimensional cross-section $d\sigma^j/dm_T^W$ is determined using

$$\frac{d\sigma^j}{dm_T^W} = \frac{1}{\Delta m_T^W \cdot \mathcal{L}_{\text{int}} \cdot \epsilon^j} \sum_i R_{ij}^{-1} \cdot f_{\text{in}}^i \cdot (N_d^i - N_b^i),$$

where Δm_T^W is the bin width, $\mathcal{L}_{\text{int}}$ the integrated luminosity, and N_d^i and N_b^i are the numbers of observed data and estimated background events in the i -th bin, respectively. The factor f_{in}^i corrects for signal events that pass the detector-level selection but not the fiducial selection, i.e. for events which migrate into the measurement region, also called “in-smearing”. The factor ϵ^j corrects for signal events that pass the fiducial selection but not the detector-level selection, accounting for selection efficiency and acceptance. The matrix R_{ij} is the detector response matrix containing the number of events in the i -th reconstructed

Table 1: Kinematic bin edges for the two-dimensional cross-section measurements.

m_T^W / GeV	200 , 300 , 425
$ \eta $	0.0 , 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0 , 2.2 , 2.4
m_T^W / GeV	425 , 600 , 900
$ \eta $	0.0 , 0.4, 0.8, 1.2, 1.6 , 2.0 , 2.4
m_T^W / GeV	900 , 2000
$ \eta $	0.0 , 0.6, 1.2, 1.8 , 2.4

measurement bin and the corresponding prediction in the j -th particle-level bin. It gives the probability of a selected event reconstructed in a given bin i to have originated at particle level from the fiducial bin j . The signal MC sample is used to obtain f_{in}^i , ϵ^j and R_{ij} . The equation is trivially extended for the two-dimensional case.

Iterative Bayesian unfolding [69] is used to approximate the inversion of the matrix R_{ij} . The procedure is regularised through the number of iterations in which the particle-level prediction is used as a biased prior. The prior is replaced by the unfolded output of the previous iteration, thereby reducing the bias, but potentially increasing the variance. The measurement is optimised using two iterations.

6.3 Event migration studies

The reconstructed event selection efficiency including acceptance losses, is found to be $\epsilon^j \approx 70\% - 90\%$ in the electron channel and $\epsilon^j \approx 50\% - 75\%$ in the muon channel.

The factors f_{in}^i are used to correct the data for in-smearing in particular from the W -boson resonance production region into the kinematic phase space of this analysis. As the correction is done without iteration it is better to maximise its value, reducing the impact of measurement biases. This was studied by reducing the m_T^W selection to 150 GeV and introducing an additional bin in the iterative unfolding procedure covering the region 150 – 200 GeV. This modification is found to increase the value of f_{in}^i in the measurement bin $200 < m_T^W < 250$ GeV from 70% to 85%, but has no impact at larger m_T^W .

The measurement is not extended down to $m_T^W = 150$ GeV because f_{in}^i is only 40% meaning 60% of reconstructed events in this extended bin are predicted to originate from mainly the W -boson resonance. For this reason the unfolding is performed with (a) a selection cut of $m_T^W > 150$ GeV, and (b) the introduction of a so-called “shadow bin” with $150 \leq m_T^W \leq 200$ GeV which serves to stabilise the unfolding. The final cross-section measurements are only reported for $m_T^W \geq 200$ GeV.

Figure 6 shows the two-dimensional correction factor f_{in}^i for the negatively charged electron and positively charged muon analyses. The shadow bin (shaded region) is also shown for comparison. The in-smearing factors are found to be very low in the shadow bin, but reach 85% – 90% in the first measurement bin. They are observed not to depend strongly on $|\eta|$, as expected.

6.4 Optimisation of number of iterations

The robustness of the unfolding procedure is tested in a number of studies using the signal MC. These include using the SHERPA MC as pseudo-data unfolded using the POWHEG+PYTHIA MC sample; unfolding the W^+ MC pseudo-data with the W^- MC sample and vice versa; and applying an arbitrary linear m_T^W

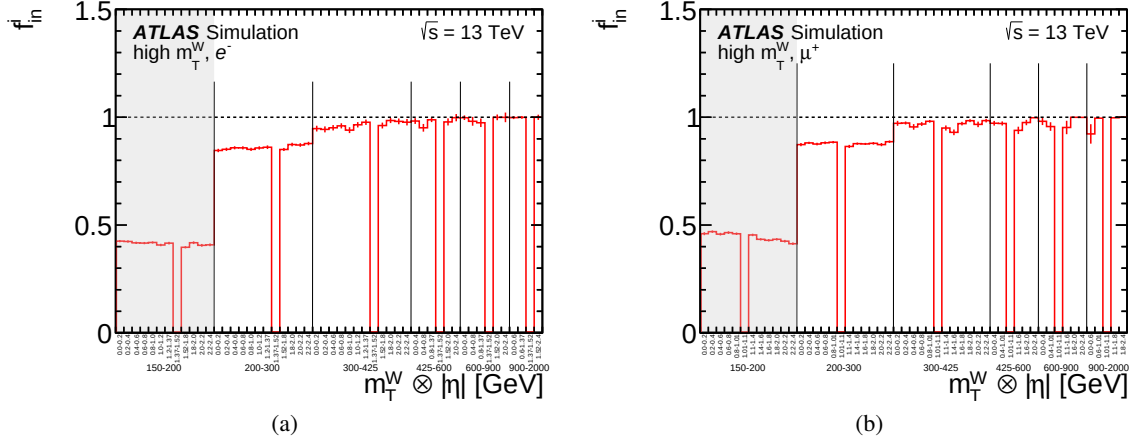


Figure 6: The correction factor f_{in}^i that corrects for events not generated in the fiducial measurement range are shown for a (a) negatively charged electron and (b) positively charged muon. On the horizontal-axis the double-differential measurement binning in the transverse mass of the W boson and the absolute pseudorapidity of the lepton is shown.

dependent event weight to the signal MC which changes the predicted cross-section by $\pm 20\%$ and $\pm 50\%$ at low m_T^W . In all cases the resulting biases and variances were studied for between one and five iterations. The optimum number of iterations is chosen to be two, mainly based on a scan of global correlation coefficients [70] but also on the linear m_T^W dependent reweighting discussed above.

6.5 Observed and predicted event yields

In Figure 7 the predicted event yields are compared to data in the one-dimensional measurement binning separated by charge and lepton flavour. The uncertainty band represents the combined statistical and systematic uncertainties. The overall agreement of data and prediction, taking into account the uncertainty band, is very good.

In Figure 8 the predicted two-dimensional event yields are compared to data separated by charge and lepton flavour. The distributions are shown in the final binning used to report the cross-section measurements. The distribution in the shadow bin is also shown for comparison.

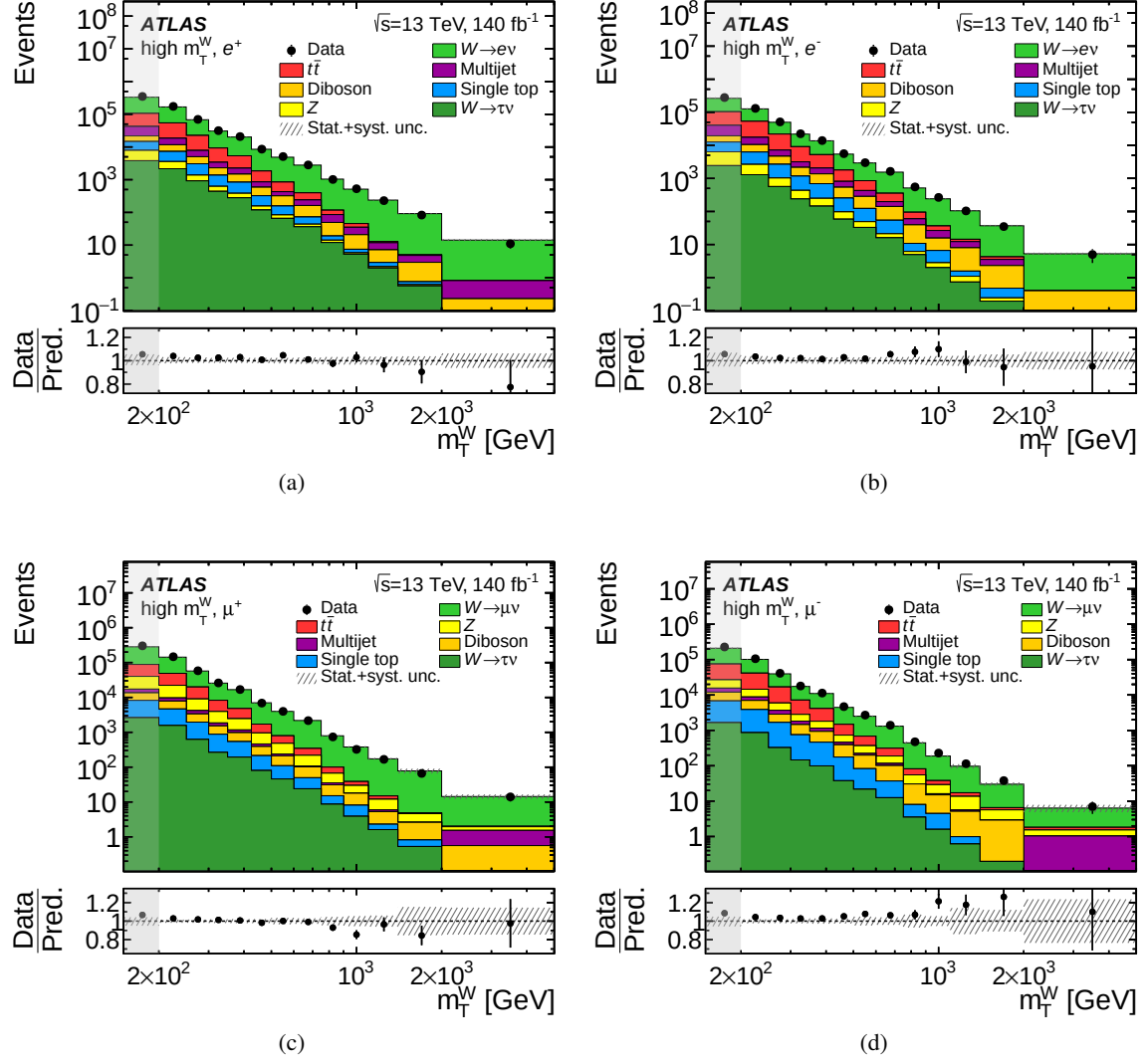


Figure 7: Comparisons of the data and the predictions in the signal region shown in the measurement binning of the transverse mass of the W boson, for the (a) e^+ , (b) e^- , (c) μ^+ and (d) μ^- final states. Statistical and systematic uncertainties of the prediction (except for theoretical uncertainties on the signal) are included in the uncertainty band.

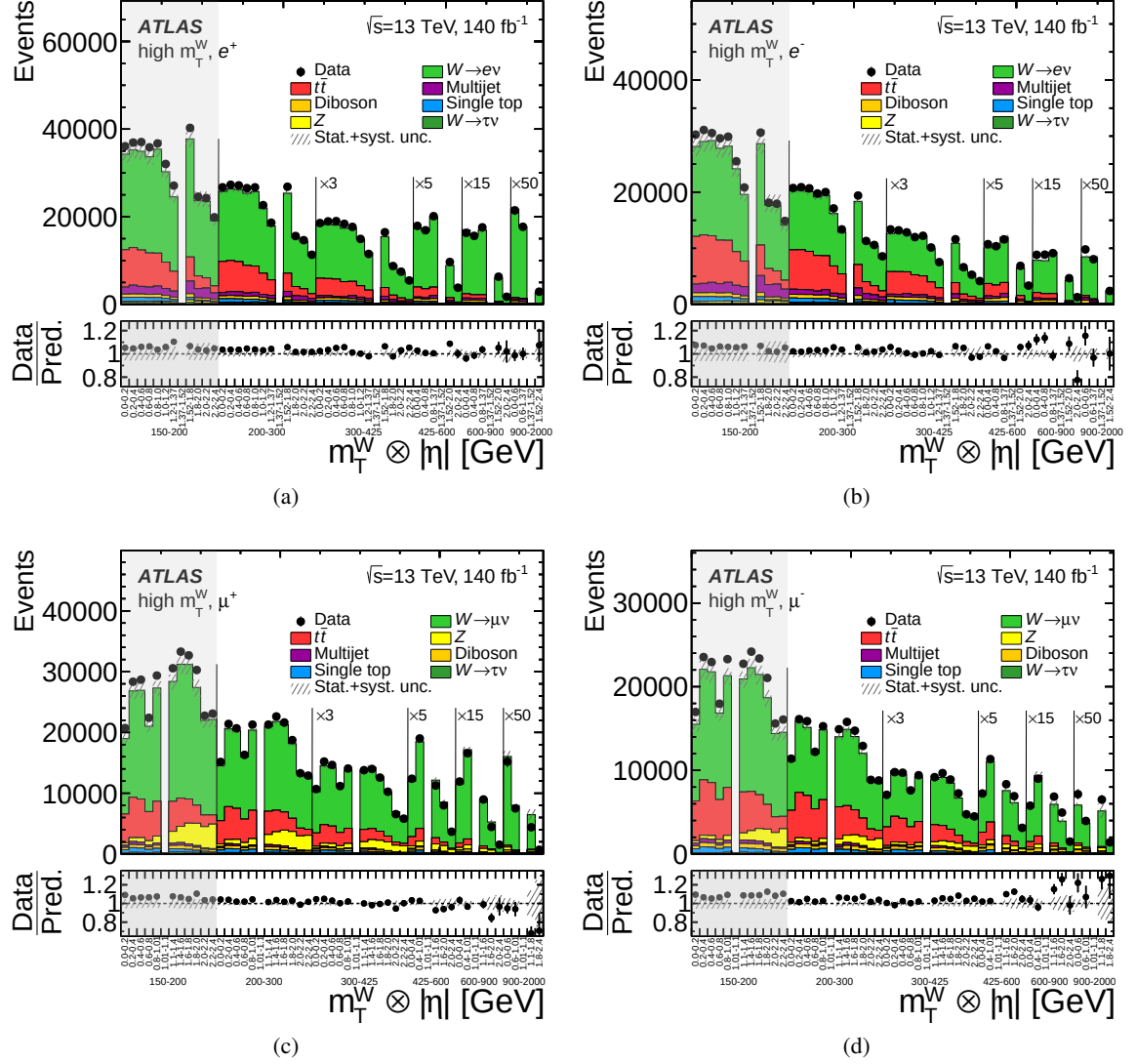


Figure 8: Comparisons of the data and the predictions in the signal region shown in the double-differential measurement binning in the transverse mass of the W boson and the absolute pseudorapidity of the lepton for the (a) e^+ , (b) e^- , (c) μ^+ and (d) μ^- final states. Statistical and systematic uncertainties of the prediction (except for theoretical uncertainties on the signal) are included in the uncertainty band. For better readability, the numbers of predicted and data events are scaled up by factors of 3, 5, 15 and 50, respectively, in the last four m_T^W bins.

7 Systematic uncertainties

The systematic uncertainties on the measurements are discussed separately for those sources which arise only in the electron channel, those which arise only in the muon channel, and those which are common to both measurements. Each source is classified as being correlated or uncorrelated between measurement bins in a single channel. All bin-to-bin correlated sources are also correlated between measurements of the same lepton flavour but opposite lepton charge. In addition, all common bin-to-bin correlated sources are considered to be correlated between the two lepton flavour channel measurements.

The correlated uncertainty contributions are propagated by the offset method in which the values from each source are coherently shifted upwards and downwards by one standard deviation and the magnitude of the change in the measurement is computed. Only the systematic uncertainties with an impact of at least 0.5% in at least one bin of any of the measurement distributions are propagated. By default the computed systematic uncertainties are symmetrised unless they are one-sided or strongly asymmetric.

A summary of the statistical and systematic uncertainties in the single- and double-differential cross-sections are shown in Figure 9 for the electron channel and Figure 10 for the muon channel. The systematic uncertainties in the cross-section in the electron channel are dominated primarily by the uncertainties in the determination of the multijet background described in Section 5.2.1 and by the electron energy scale. In the muon channel the charge-dependent impact in the muon momentum scale calibration (sagitta bias) is the dominant uncertainty at larger values of m_T^W and $|\eta|$, while various sources contribute on a similar level at smaller values of m_T^W .

7.1 Electron channel

Multijet background The uncertainty in the multijet background is driven by the statistical and systematic uncertainties in the fake efficiency estimate, as the real efficiency is taken from the MC simulation directly. The fake efficiency depends on the selections used to define the multijet enriched regions and the modelling of the backgrounds with real electrons in these regions. Biases from the selection are estimated by varying the E_T^{miss} range from $E_T^{\text{miss}} < 65$ GeV to $E_T^{\text{miss}} < 30$ GeV and $30 < E_T^{\text{miss}} < 65$ GeV and by asking for an additional jet well separated from the electron. The modelling of the real electron contributions is varied by using the alternative Sherpa signal sample normalised to the POWHEG+PYTHIA prediction and by scaling the cross-sections of the MC samples by $\pm 10\%$. The value of 10% used here is larger than the uncertainties used in the main analysis due to the unusual phase space of the fake enriched region, see Section 5.2.1. Finally, as E_T^{miss} itself depends on the sum of transverse momenta of all reconstructed and calibrated objects in the event an ambiguity can arise depending on which calibration is applied to a certain object. Applying e.g. a jet calibration or an electron calibration to a certain reconstructed object typically results in a factor of two difference in transverse momentum. While not a problem for well identified (“tight”) objects this is different for objects that only satisfy the less stringent (“loose”) requirements utilised in the matrix method, for which the true nature (electron or jet) is unknown. A systematic uncertainty is assigned by attempting to estimate the actual contribution of true electrons and jets as a function of the event kinematics.

While asking for an additional jet leads to negligible differences, all other uncertainties have a 1%-3% impact on the measurement at low m_T^W , which is decreasing for higher values of m_T^W . They constitute the dominant source of uncertainty in the measurement at low m_T^W .

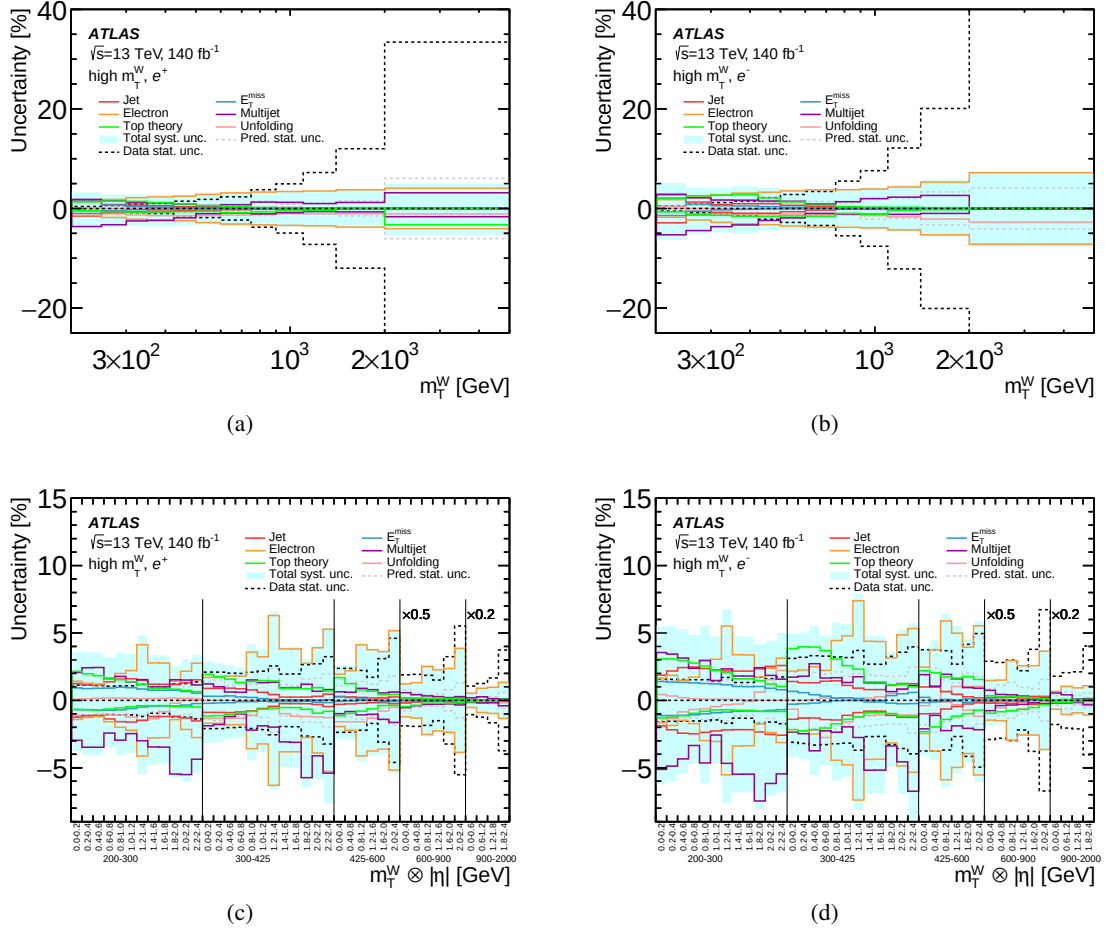


Figure 9: Summary of the uncertainties in the unfolded (a, b) single-differential and (c, d) double-differential cross-sections for the (a, c) e^+ and (b, d) e^- final state. Similar sources of uncertainties are combined via their quadratic sum. The light blue band indicates the total systematic uncertainty. In addition the statistical uncertainties in the prediction and in the data are shown.

Electron trigger, reconstruction, identification and isolation efficiencies The efficiencies of the trigger, electron reconstruction and identification, and of the isolation criteria are estimated with $Z \rightarrow e^+e^-$ data using a tag-and-probe method [66, 71]. The uncertainties are given in a scheme using a single nuisance parameter for each of the isolation, reconstruction and trigger efficiency contributions and two nuisance parameters for the charge misidentification. The remaining identification uncertainties are given by 16 sources correlated between measurement bins. An additional 24 nuisance parameters describe the impact of sources uncorrelated in $|\eta|$ and p_T , but fully correlated between electron charges.

Among those, the largest uncertainties are due to the isolation and identification efficiencies. The former is largest for $m_T^W \sim 1$ TeV where it reaches 2%. The latter is dominated by one bin-to-bin correlated source in particular which reaches 1% in size for m_T^W above 0.5 TeV, while the uncorrelated sources contribute typically at the level of 1% in their respective $|\eta|$ bin.

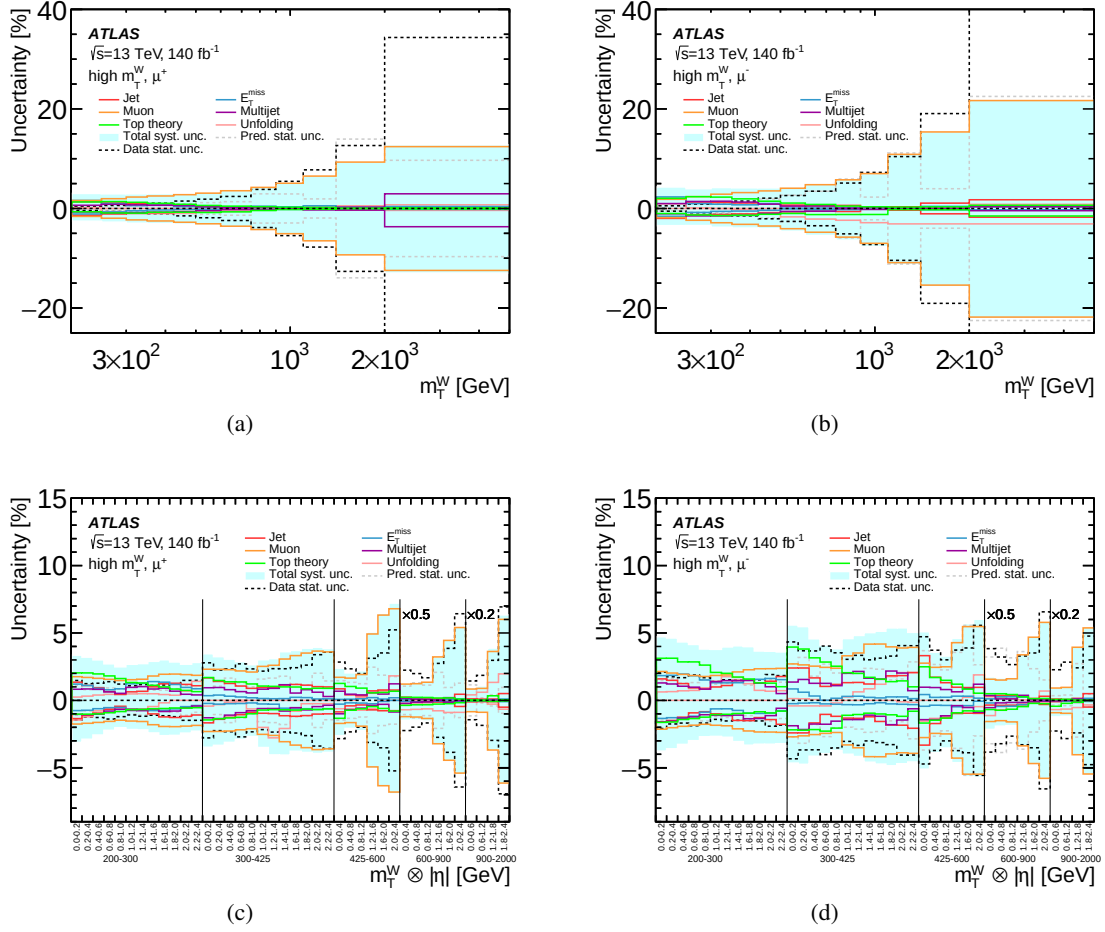


Figure 10: Summary of the uncertainties in the unfolded (a, b) single-differential and (c, d) double-differential cross-sections for the (a, c) μ^+ and (b, d) μ^- final state. Similar sources of uncertainties are combined via their quadratic sum. The light blue band indicates the total systematic uncertainty. In addition the statistical uncertainties in the prediction and in the data are shown.

Electron energy scale and resolution The determination of the electron energy scale and resolution is presented in Ref. [56]. The related uncertainties are described by 25 nuisance parameters for the energy scale and a further nine for the resolution. The energy scale is the larger contribution to the measurement uncertainty rising from 0.5% at low m_T^W to 3% in the highest m_T^W bin.

7.2 Muon channel

Multijet background As for the electron channel, the multijet background estimation in the muon channel depends on the selections used to define the fake enriched region and the modelling of the real electron contribution in this region. Biases from these contributions are estimated by varying the E_T^{miss} range used in the same way as in the electron channel and, additionally, varying the jet multiplicity, the impact parameter selection, or the $\Delta\phi(\mu, E_T^{\text{miss}})$ selection individually. The modelling of the real muon

contribution is varied in the same way as described for the electron channel in Section 7.1. All of these uncertainty estimates are found to contribute less than 1% to the final cross-section measurement.

Muon trigger, identification, vertex association and isolation efficiency The muon efficiency corrections are obtained for the full Run 2 data using $Z \rightarrow \mu^+ \mu^-$ data and simulation with a tag-and-probe method described in Refs. [58, 67]. The vertex association efficiency corrects for losses arising from the d_0 and z_0 impact parameter selection criteria. Each of these contributions is associated with two nuisance parameters for a correlated and uncorrelated statistical component of the uncertainty. The largest impact on the measurement is from the identification efficiency which rises from 1% at low m_T^W to 5% in the highest bin.

Muon momentum scale and resolution The uncertainties in the determination of the muon momentum and resolution are discussed in Ref. [72], and are determined using similar samples as for the muon efficiency corrections above. In total six nuisance parameters are used to describe the impacts of these uncertainties. They relate to separate resolution effects in the ID and muon spectrometer, biases in the momentum scale, and three contributions related to the sagitta bias, which are anti-correlated between the muon charges. The three contributions are a global residual bias, a specific component for the high- p_T extrapolation of muons with $|\eta| > 1.1$ and $p_T > 450$ GeV, and a contribution from local biases in $|\eta|$ and ϕ of the muon. The first two of these three contributions have the largest impact and dominate the overall uncertainty for $m_T^W > 600$ GeV, reaching up to 10% at the highest values of m_T^W for the former and up to 20% at the highest values of m_T^W and $|\eta|$ for the latter.

7.3 Common uncertainties

Top-quark background The $t\bar{t}$ background uncertainties are divided into a number of contributions. The influence of hadronisation and fragmentation models is determined by re-showering the nominal top-quark generator-level events with HERWIG 7 [73]. The sensitivity to initial (ISR) and final (FSR) state QCD radiation is determined by varying a parameter of the A14 tune [74] corresponding to a variation of α_S for the ISR, and by variations of the renormalisation scale in the FSR part of the PS sample. The PowHEG h_{damp} parameter is a resummation damping factor that effectively regulates the high- p_T radiation against which the $t\bar{t}$ system recoils. It is changed from 1.5 to 3 times the top-quark mass. The p_T -hard parameter controlling the matching of PowHEG matrix elements to the PS is also varied. The PDF uncertainty is evaluated by using the RMS of one hundred replicas of the nominal NNPDF3.0NLO PDF set.

The relative size of the systematic uncertainties discussed above are evaluated before the reweighting of the $t\bar{t}$ MC sample to the NNLO QCD calculations including NLO EW corrections described in Section 3. The sequence (top p_T , $t\bar{t}$ mass) in which the reweighting is performed is another source of uncertainty. Potential differences in the modelling of additional radiation between the NNLO calculation and the PS are also taken into account, separately for the p_T of the top quark and the $t\bar{t}$ mass. The choice of PDF has also been varied in order to assess the impact on the EW corrections. Finally, separate variations of the factorisation and renormalisation scales μ_R and μ_F , in the NNLO calculation are taken into account by varying the scales independently by factors of two.

The interference between the tW and $t\bar{t}$ production processes is accounted for in the simulation through the diagram subtraction scheme [45] as discussed above, and the difference to the dynamic scale diagram

removal scheme [75] is used as uncertainty. The POWHEG h_{damp} parameter is varied for the tW samples in the same way as for the $t\bar{t}$ samples. In addition, a normalization uncertainty of 4% is assigned, arising from the uncertainty in the theoretical prediction at NNLO [76]. This is also assigned to all single-top channels which is 90% dominated by tW production.

The largest uncertainties are due to the hadronisation and fragmentation models, the interference between tW and $t\bar{t}$, and the differences in the modelling of additional radiation between the NNLO calculation and the PS. At small $|\eta|$ and for the negative lepton charges, where the contribution from top background is largest, these uncertainties extend up to 2-3% each.

EW background The remaining EW background processes lead to small contributions in the signal region. A correlated normalisation uncertainty is applied for each process separately, taken to be 5% for $Z \rightarrow \ell\ell$ and $W \rightarrow \tau\nu$ [77], and 6% for diboson processes.

Jet uncertainties The uncertainties in the jet energy scale and resolution directly influence the $E_{\text{T}}^{\text{miss}}$ reconstruction and are described in detail in Ref. [62]. The Jet Energy Scale (JES) uncertainties are described using the 29 nuisance parameter scheme, which considers uncertainties arising from the pile-up correction to jets, calibration biases, the jet flavour response, the modelling of jets and of the detector, as well as punch through and the response of high p_{T} jets. The Jet Energy Resolution (JER) uncertainties use an eight-parameter scheme. They are larger than the JES contributions but still remain below 1.5% throughout the measurement range.

Uncertainties in the $E_{\text{T}}^{\text{miss}}$ soft term The $E_{\text{T}}^{\text{miss}}$ soft term uncertainties arise from the momentum scale of this contribution to the $E_{\text{T}}^{\text{miss}}$, and from the separate parallel and perpendicular resolution modelling of the tracks comprising the soft term with respect to the mean p_{T} of the tracks [65]. These contributions are largest at low m_{T}^{W} , and dominate the uncertainty in the lowest m_{T}^{W} bin reaching 1.5%. In the shadow bin this rises to 4%.

Pile-up modelling To account for differences between simulation and data in the pile-up distribution, the pile-up profile in the simulation is corrected to match the one in data. The uncertainty in the correction factor is $\pm 4\%$ and is applied in the measurement as a variation of the event weight.

MC statistics The size of the MC samples used in the analysis leads to uncertainties that are considered uncorrelated between measurements bins, charges and flavours.

Luminosity The uncertainty of the ATLAS luminosity measurement is 0.83% and is discussed in detail in Ref. [78].

Unfolding uncertainties The uncertainty in the unfolding procedure is estimated for two sources. The first contribution assesses the bias arising from differences between data and MC simulation in the measured observables m_T^W and $|\eta|$. This is estimated by reweighting the MC simulation at the particle level such that its resulting distribution at reconstruction level matches the distributions observed in the data. The uncertainty is derived by unfolding the resulting distribution on reconstruction level with the nominal unfolding procedure and comparing the result to the reweighted particle level MC spectra. The uncertainty is found to be below 1% throughout the range of the measurement.

A second contribution to the unfolding uncertainty quantifies the impact of poor modelling in unmeasured observables for example (but not only) the transverse momentum of the W boson which is modelled differently by the POWHEG+PYTHIA and SHERPA signal MC samples. The uncertainty is estimated by reweighting the alternative SHERPA signal MC sample to the POWHEG+PYTHIA spectra at the particle level in m_T^W and $|\eta|$ and then unfolding the resulting distribution on reconstruction level with the nominal unfolding procedure. The difference between the unfolded distribution and the reweighted one at particle level is taken as the uncertainty, and has an impact on the measurement of typically 1%.

8 Results

8.1 Separate differential cross-sections in the electron and muon channels

The unfolded Born-level cross-section measurements $d\sigma/dm_T^W$ including their statistical, systematic and total uncertainties are presented in Figure 11 separately for each lepton charge and flavour. Note that here and in the following the luminosity uncertainty of 0.83% is not shown and not included in the overall systematic and total uncertainty bands. Detailed tables for all results including the systematic uncertainties separately for each source can be found in HEPDATA [79, 80].

The data are compared to predictions from SHERPA, using the CT18NNLO PDF set, and POWHEG+PYTHIA using the CT14NNLO PDF set. The lower panels in each of the figures show the ratio of the two predictions to the data measurement and the uncertainty contributions.

The cross-sections are observed to fall over seven orders of magnitude as the m_T^W increases from 200 – 5000 GeV. The e^+ and μ^+ cross-sections are everywhere larger than the corresponding e^- and μ^- cross-sections as expected from the difference between the u - and d -quark PDFs in the proton. The predictions describe the data well within the measurement uncertainties.

The measurements have a data statistical uncertainty ranging from about 0.5% at low m_T^W to about 33% in the e^+ and μ^+ channels and about 50% in the e^- and μ^- channels at the highest values of m_T^W .

In the e^+ channel the total systematic uncertainty varies from 3% – 5% over the m_T^W range, compared to 5% – 8% for the e^- measurement. At low m_T^W , the largest contribution to the systematic uncertainty in both cases are from the E_T^{miss} , JER, and multijet background estimations. At higher m_T^W the largest contributions to the experimental uncertainty are from the multijet estimation, the electron calibration, and the top-quark background, specifically the choice of the single-top tW subtraction scheme.

In comparison, the muon channel measurements achieve a better systematic uncertainty at low m_T^W , 3% and 4% for μ^+ and μ^- respectively, due to a variety of smaller contributions. However, the systematic uncertainty is worse at large values of m_T^W , reaching 13% for μ^+ and 22% for μ^- , driven by two muon sagitta uncertainty sources.

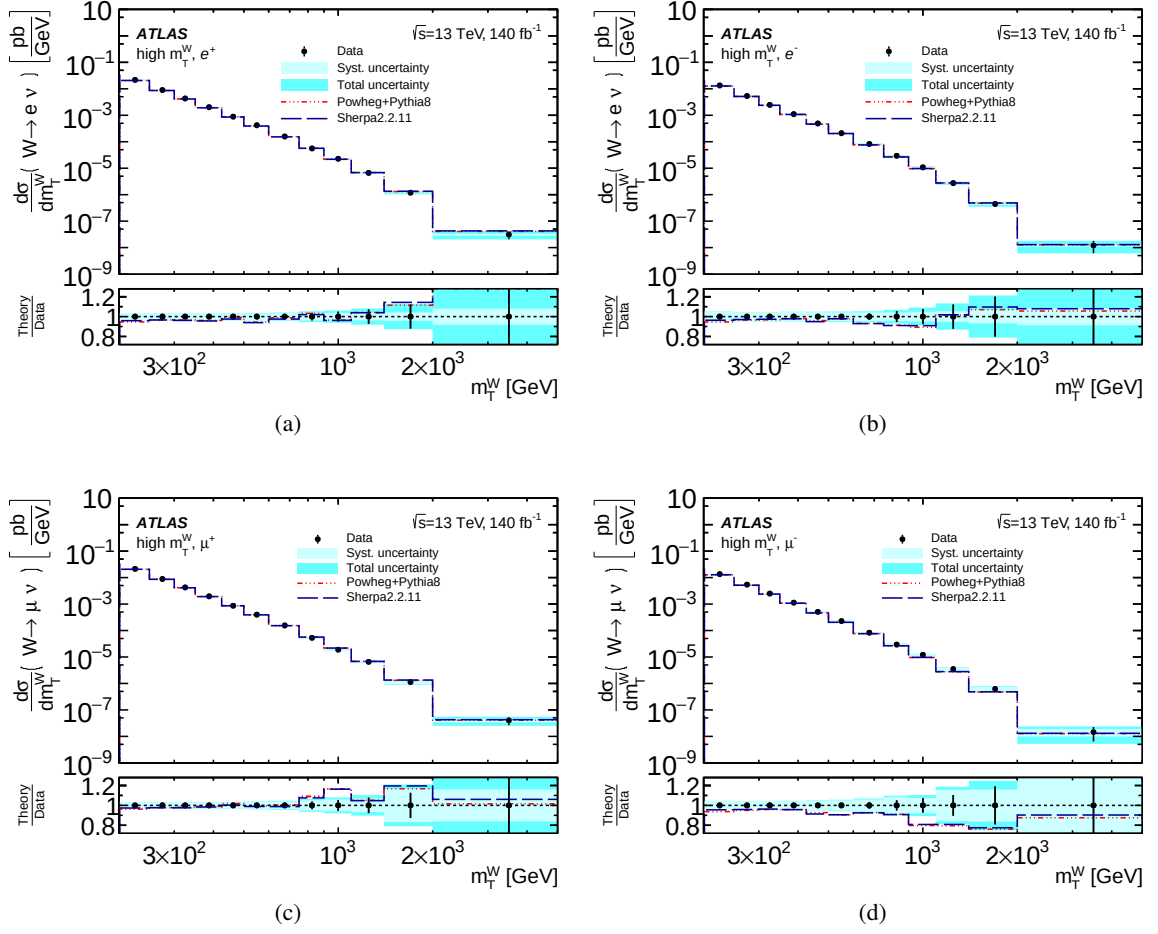


Figure 11: Unfolded differential cross-section binned in m_T^W region for the (a) e^+ , (b) e^- , (c) μ^+ and (d) μ^- final states. The error bars represent the statistical uncertainty. The inner shaded band represents the systematic uncertainty in the cross-sections, and the outer shaded band represents the total measurement uncertainty (excluding the luminosity uncertainty). The data are compared to predictions from SHERPA and POWHEG+PYTHIA.

The Born-level two-dimensional cross-sections $d^2\sigma/dm_T^W d|\eta|$ are shown in Figure 12 separately for each lepton charge and flavour. The data are presented in each m_T^W bin separated by the vertical lines, and the measurements for $m_T^W \geq 300$ GeV are scaled by the factors shown for presentation purposes only. The measurements are compared to the SHERPA and POWHEG+PYTHIA predictions which describe the data well.

The cross-sections at low m_T^W show a plateau-like behavior for $|\eta|$ up to 1.4, and then decrease at larger pseudorapidity. With increasing m_T^W the plateau region narrows.

8.2 Electron-muon ratios of charge-integrated cross-sections

Charge-integrated single- and double-differential cross-sections have also been extracted separately for the electron ($e^\pm$) and muon ($\mu^\pm$) channel and can be found in HEPDATA.

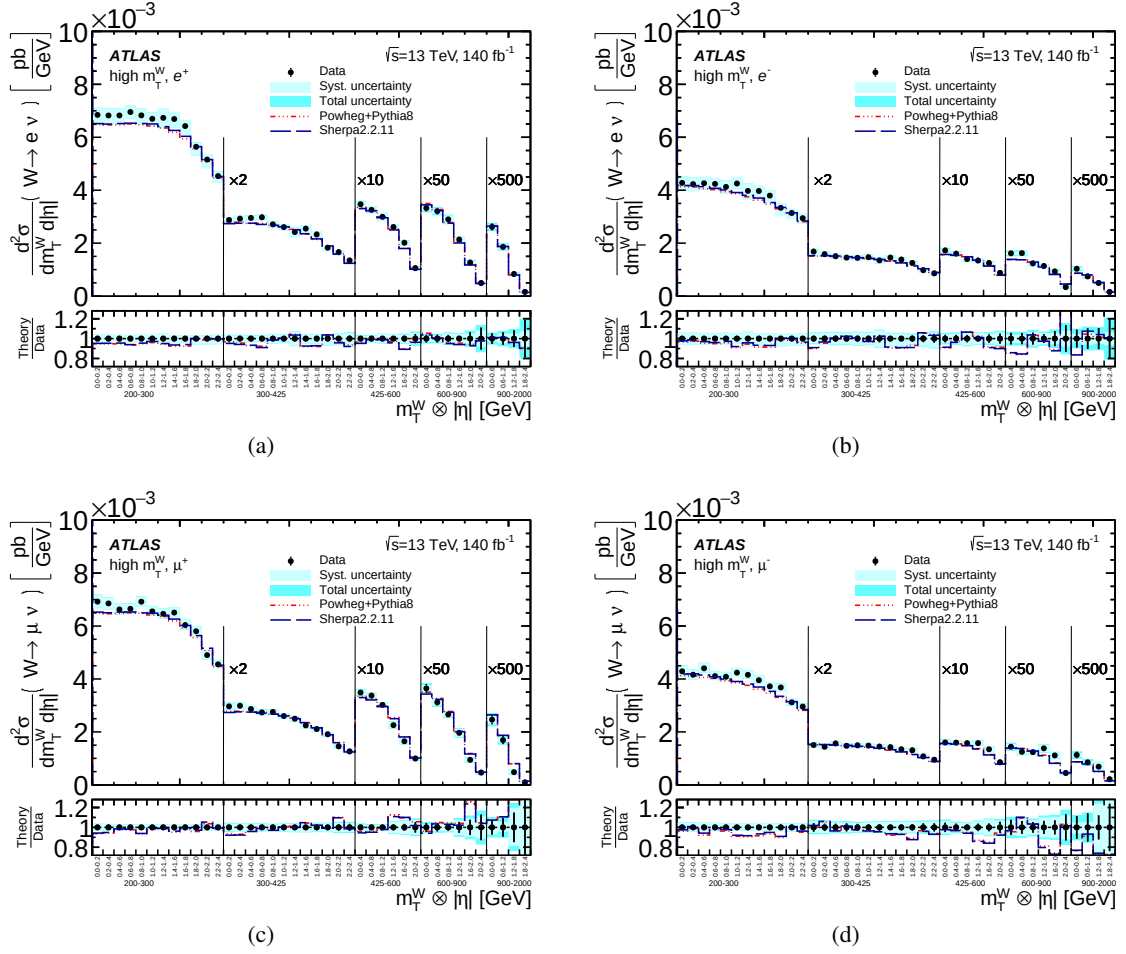


Figure 12: Two-dimensional unfolded cross-section binned in $|\eta|$ and m_T^W for the (a) e^+ , (b) e^- , (c) μ^+ and (d) μ^- final states. The error bars represent the statistical uncertainty. The inner shaded band represents the systematic uncertainty in the cross-sections, and the outer shaded band represents the total measurement uncertainty (excluding the luminosity uncertainty). The data are compared to predictions from SHERPA and POWHEG+PYTHIA. For better readability, the cross-sections in the last four m_T^W bins are scaled up by factors of 2, 10, 50 and 500, respectively.

Ratios of the charge-integrated cross-sections for the $e^\pm$ to the $\mu^\pm$ final state are shown in Figure 13. Here all asymmetric uncertainties are symmetrized and the one-sided uncertainties are mirrored. This ratio provides a test of lepton flavour universality and is consistent with unity within the uncertainties.

8.3 Combination of electron and muon channels

The measurements in the $e^\pm$ and $\mu^\pm$ final states are combined using a χ^2 minimisation procedure [81–83] under the assumption that the unfolded measurements for the same charge should agree. The technique improves the statistical precision of the data as well as the systematic uncertainty in case of uncertainties that are not (fully) correlated between the lepton flavours. The bin-to-bin correlated systematic uncertainties are taken into account by introducing a nuisance parameter for each source of uncertainty modelled as a unit Gaussian probability density contributing to the χ^2 definition. The systematic sources and their correlations

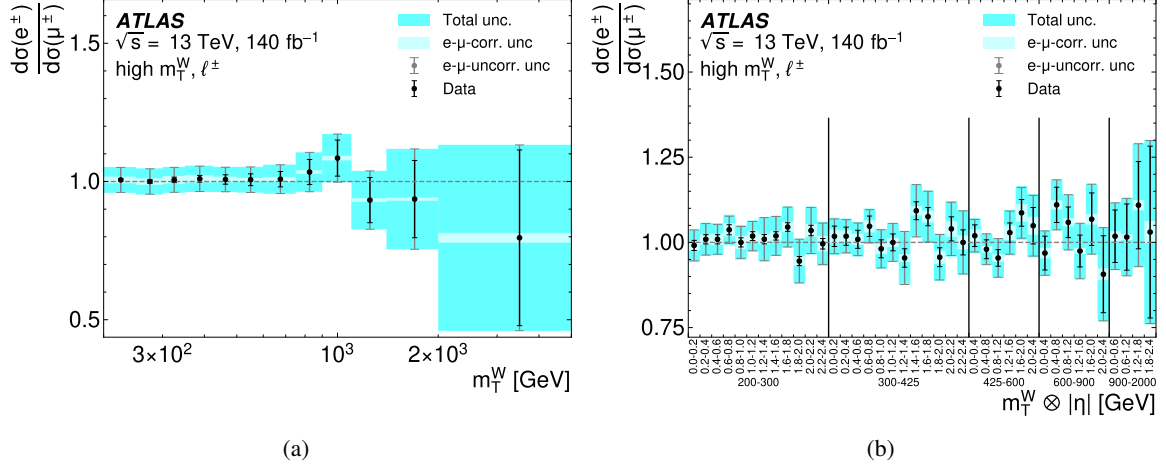


Figure 13: Ratio of the unfolded (a) single- and (b) double-differential electron- and muon-channel cross-sections in the combined $\ell^\pm$ -channel. The error bars represent the uncorrelated (systematic and statistical) uncertainties between the electron and muon channels, while the inner uncertainty band corresponds to the correlated uncertainties. The total uncertainty in the ratio is presented with the outer uncertainty band.

between channels are discussed in Section 7. The nuisance parameter values are optimised in the fit which minimises the χ^2 difference between the combined cross-section and the separate flavour channels, summed over the measurement bins. The combination provides new orthogonal systematic uncertainty sources which are linear combinations of the original sources, and therefore lose their association to specific experimental causes. In order to aid interpretation, the covariance matrix is rotated back to the (approximately) original physical source decomposition. Both versions are available in HEPDATA. The combination is first performed for the double-differential cross-sections, and simultaneously for both lepton charges, which allows optimal systematic constraints from the separate charge combinations and from the additional information encoded in the $|\eta|$ variable. The resulting shifts and constraints on the nuisance parameters are then transferred to the combination of the single-differential cross-sections.

The combined cross-sections $d^2\sigma/dm_T^W d|\eta|$ for the ℓ^+ and ℓ^- final states are shown in Figure 14. The double-differential cross-section combination shows good agreement between the lepton flavours. The fit has 80 degrees of freedom, and the total χ^2 is found to be 74 yielding $\chi^2/\text{dof} = 0.92$. In each figure the upper panels show the measured Born-level cross-sections for the electron channel, muon channel and the combination. The ratio of the pre-fit individual channels to the combined measurement is shown in the middle panel. The lower panel displays the pulls of the two channels, defined as the difference between the post-fit single-channel measurement and the combined result in units of the bin-to-bin uncorrelated uncertainty. No coherent trends between the measurements are observed and the pulls are found to be below two standard deviations everywhere.

The post-fit nuisance parameters shown in Figure 15 fluctuate around a mean of zero with shifts typically below one standard deviation. The exception to this is the high- p_T sagitta bias parameter with a shift of 1.8 standard deviations indicating a small residual undercalibration. This systematic source only affects the region $|\eta| > 1.1$. The parameter is also highly constrained by the combination indicating the calibration potential of this measurement. In addition, two of the twelve η binned electron identification systematics have pulls greater than one standard deviation. These sources arise from the limited sample sizes of the $Z \rightarrow e^+e^-$ data and are therefore statistical in nature.

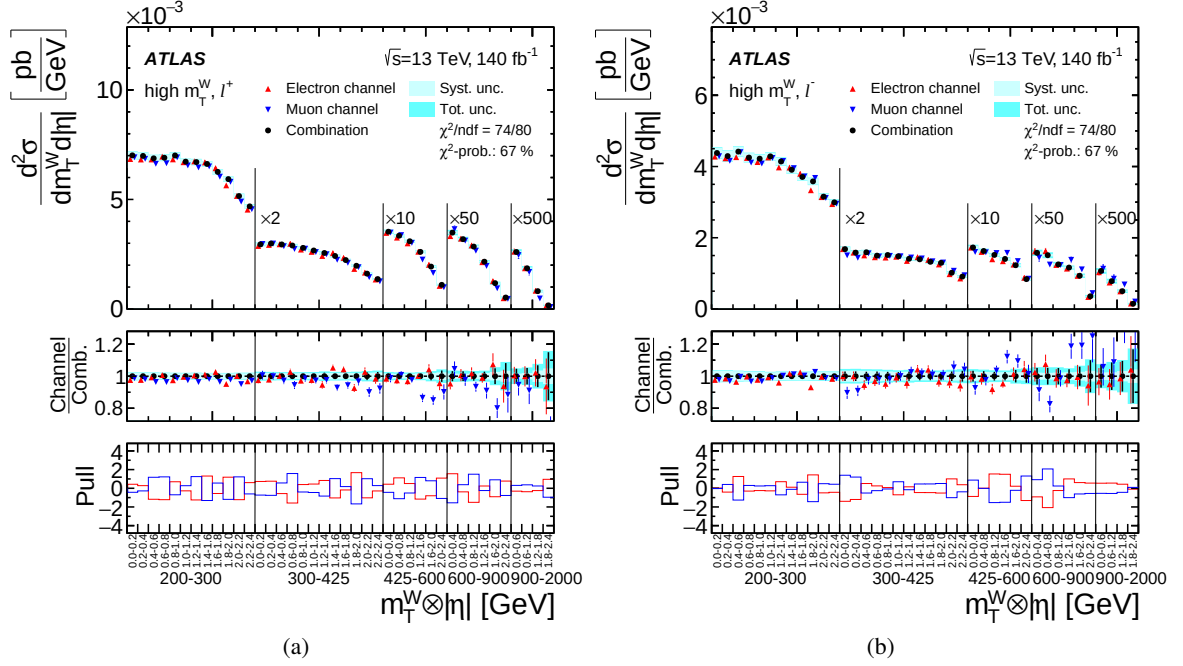


Figure 14: Electron, muon and combined fiducial Born-level cross-sections binned in m_T^W and $|\eta|$, for the (a) positive and (b) negative lepton charge. The error bars represent the statistical uncertainty. The inner shaded band represents the systematic uncertainty in the combined cross-sections, and the outer shaded band represents the total measurement uncertainty (excluding the luminosity uncertainty). For better readability, the cross-sections in the last four m_T^W bins are scaled up by factors of 2, 10, 50 and 500, respectively. The central panel shows the ratio of each measurement channel to the combined data, and the lower panel shows the pull of the post-fit electron and muon channel measurements with respect to the combined data.

8.4 Charge asymmetry of combined cross-sections

An asymmetry in the production of W bosons arises from the purely weak coupling to the quarks, the relative sizes of the production helicity amplitudes, and the PDFs. As the rapidity of the W boson is not directly accessible, measurements of the lepton charge asymmetry, A_ℓ , have been performed at the LHC [9, 84, 85] at 7, 8 and 13 TeV centre-of-mass energies in the resonant production region of the W boson.

The measurements presented here extend the experimental determination of the asymmetry to large m_T^W for the first time. The single- and double-differential lepton charge asymmetries are defined as

$$A_\ell = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} ,$$

where $d\sigma_\pm$ represents the cross-section for the ℓ^+ or the ℓ^- final state respectively. The charge asymmetry uses the Born-level flavour-combined measurements with orthogonal uncertainty sources provided by the post-fit combination. They include correlations between the cross-sections for both charges as the flavour combination is performed over both charges simultaneously as described in Section 8.3.

The single- and double-differential determinations of A_ℓ are shown in Figure 16. The asymmetry is found to be large and positive, increasing with m_T^W , as expected from the increasing contribution of the u -valence PDF at larger Bjorken x . The $|\eta|$ dependence of A_ℓ is observed to be approximately constant for $|\eta| \lesssim 1.2$

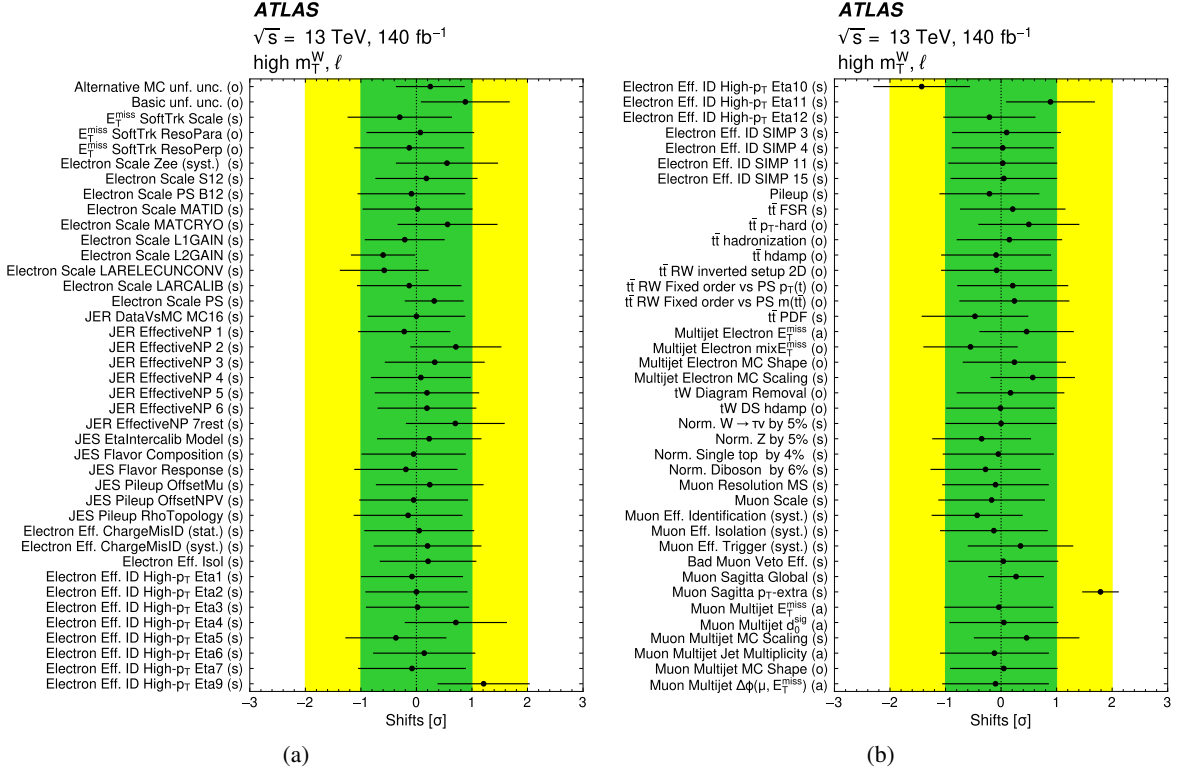


Figure 15: Shifts of the systematic uncertainty nuisance parameters after the combination of the double-differential electron and muon cross-sections. The systematic uncertainties are related to the unfolding procedure (“unf.”), the jet energy resolution/scale (“JER/JES”), the E_T^{miss} scale and resolution, the electron and muon scale, resolution and efficiency (“Eff.”), the multijet and $t\bar{t}$ (where RW refers to a reweighting to NNLO) background estimates and normalization of small background processes (“Norm.”). The uncertainties are marked whether they are symmetric (“s”), asymmetric (“a”) or one-sided (“o”). The systematic uncertainties labeled with “Electron” or “Muon” are not correlated between the lepton flavours.

and to fall rapidly at higher values of $|\eta|$ for larger values of m_T^W . The POWHEG+PYTHIA predictions are here updated to the CT18NNLO PDF set, which is already used for SHERPA. Both predictions provide a good overall description of the measurements. In the highest m_T^W and $|\eta|$ bins the predicted asymmetry from SHERPA and POWHEG+PYTHIA becomes slightly negative. However the measurements do not have the statistical precision to confirm this behaviour.

9 Interpretation and discussion

9.1 Comparison to QCD predictions

The measured cross-sections are compared to a selection of QCD predictions. In particular the MC predictions from POWHEG+PYTHIA and SHERPA are presented together with a fixed-order calculation performed at NNLO with DYTURBO [86, 87]. The NLO EW corrections applied to POWHEG+PYTHIA (see Section 3) are also added to DYTURBO, whereas SHERPA includes these contributions natively. The

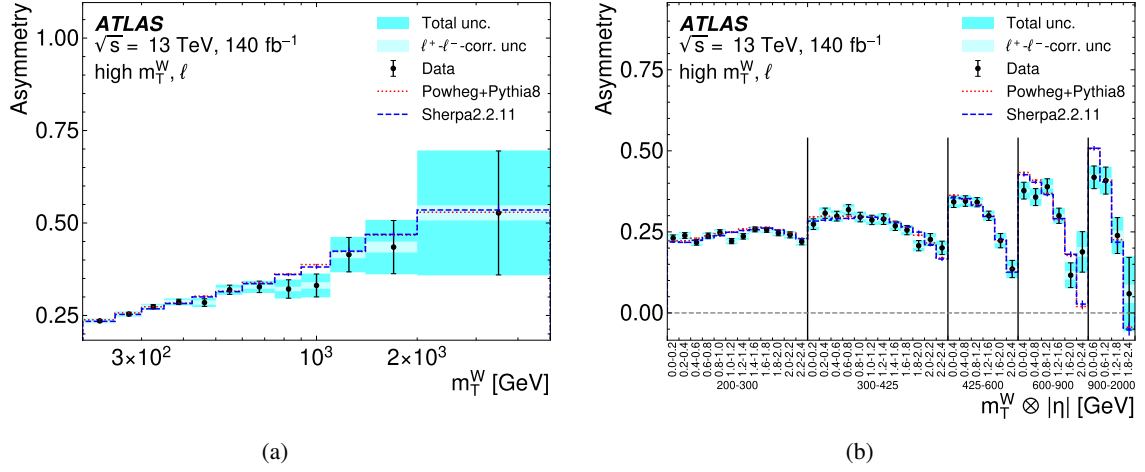


Figure 16: Charge asymmetry of the (a) single- and (b) double-differential electron/muon combined cross-section. The error bars represent the statistical uncertainties. The inner shaded band represents the systematic uncertainties that are correlated between the charges, and the outer shaded band represents the total measurement uncertainty. The data are compared to predictions from SHERPA and POWHEG+PYTHIA, both using the CT18NNLO PDF set.

predictions from POWHEG+PYTHIA, SHERPA and DYTURBO are shown for the CT18NNLO PDF set. In addition the DYTURBO prediction is shown for four alternative PDF sets - MSHT20NNLO [88], NNPDF4.0NNLO [89], ATLASPDF21NNLO ($T = 3$) [90], and CT18QED [91].

The flavour-combined single- and double-differential cross-sections for the ℓ^+ and ℓ^- final states are compared to the predictions in Figures 17, 18, and 19. The middle panels of Figure 17 and the left panels of Figures 18 and 19 show that the POWHEG+PYTHIA, SHERPA and DYTURBO predictions using the CT18NNLO PDF set agree very well for both lepton charges. They are consistent with the measurements, although a moderate undershoot of the predictions is observed for low m_T^W . The panels also display the DYTURBO calculation using the CT18QED PDF which exhibits a consistently lower cross-section than from the CT18NNLO PDFs. This difference is however small and increases with increasing m_T^W and increasing $|\eta|$ to up to 3%.

The middle panels of Figure 17 and the left panels of Figures 18 and 19 show DYTURBO predictions using different PDF sets as well as the 90% confidence level PDF uncertainty bands from the CT18NNLO PDF. The prediction using MSHT20NNLO is typically rather similar to the one from the CT18NNLO PDF set, while the one using NNPDF4.0NNLO is above the CT18NNLO uncertainty band in the ℓ^+ channel in the region $m_T^W < 900$ GeV. The calculations with the ATLASPDF21NNLO are typically above the CT18NNLO uncertainty band. The DYTURBO predictions using different PDF sets are also compared to the measured single- and double-differential charge asymmetry A_ℓ in Figure 20. For the asymmetries the predictions agree well with the measurements and also for the separate ℓ^+ and ℓ^- final states the predictions are consistent with the measurements taking into account the sizeable uncertainties due to the PDFs. These uncertainties are found to be larger than the experimental uncertainties for $m_T^W \lesssim 1$ TeV, indicating the potential of these measurements to improve PDF determinations.

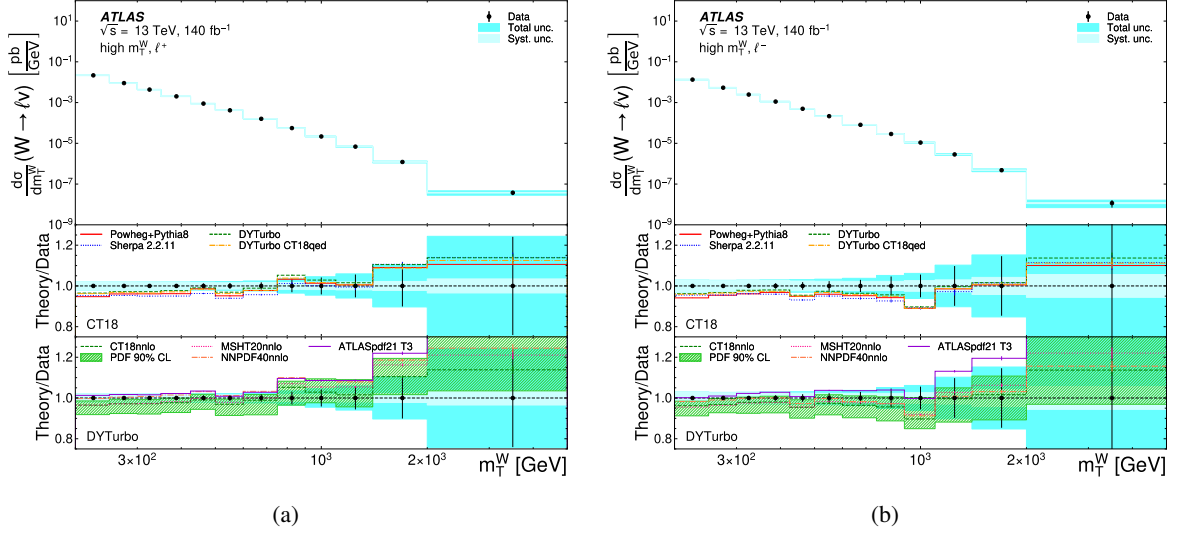


Figure 17: The combined Born-level cross-sections for the single-differential distributions are shown for the (a) ℓ^+ and (b) ℓ^- final state. The middle panels show a comparison to the predictions from SHERPA, POWHEG+PYTHIA and the fixed-order calculation from DYTURBO, each using the CT18NNLO PDF. In addition, a fixed-order calculation using DYTURBO and the CT18QED proton PDF is shown. A comparison to predictions with different PDFs using DYTURBO is displayed in the lower panel. The 90% CL PDF uncertainty is shown for CT18NNLO prediction. The statistical uncertainty of the combination is displayed with the error bars. The inner uncertainty band indicates the systematic uncertainty while the outer band corresponds to the total measurement uncertainty (excluding the luminosity uncertainty).

9.2 Effective Field Theory constraints

The measurements presented here may be sensitive to potential new physics beyond the direct energy reach of the LHC. EFTs are a useful tool for describing the physics below a defined energy cutoff scale Λ . The SMEFT is a generalised extension of the Standard Model, offering a broad and largely model-independent approach to search for new physics [92]. This approach is adopted here to interpret the cross-section measurements in terms of indirect contributions from physics beyond the Standard Model.

The SMEFT Lagrangian includes all possible operators constructed out of the SM field content:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{c_{i,d}}{\Lambda^{d-4}} \mathcal{O}_{i,d},$$

where $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian, and $\mathcal{O}_{i,d}$ are SMEFT operators of dimension $d > 4$. Each operator is weighted by a dimensionless parameter, the Wilson coefficient $c_{i,d}$, and is additionally suppressed by powers of the energy cutoff scale Λ .

It is conventional in SMEFT analyses to set Λ to 1 TeV, with higher dimensional operators having increasingly suppressed Wilson coefficients. For this reason, it is common to truncate the SMEFT to dimension $d \leq 6$, as operators with $d > 6$ will likely have reduced impact on physical observables. Additionally, all odd mass-dimension operators in the SMEFT violate at least one of baryon or lepton number conservation, which are believed to be strong symmetries. All odd-dimension operators can therefore also be neglected, which justifies only considering the dimension-6 operators of the SMEFT.

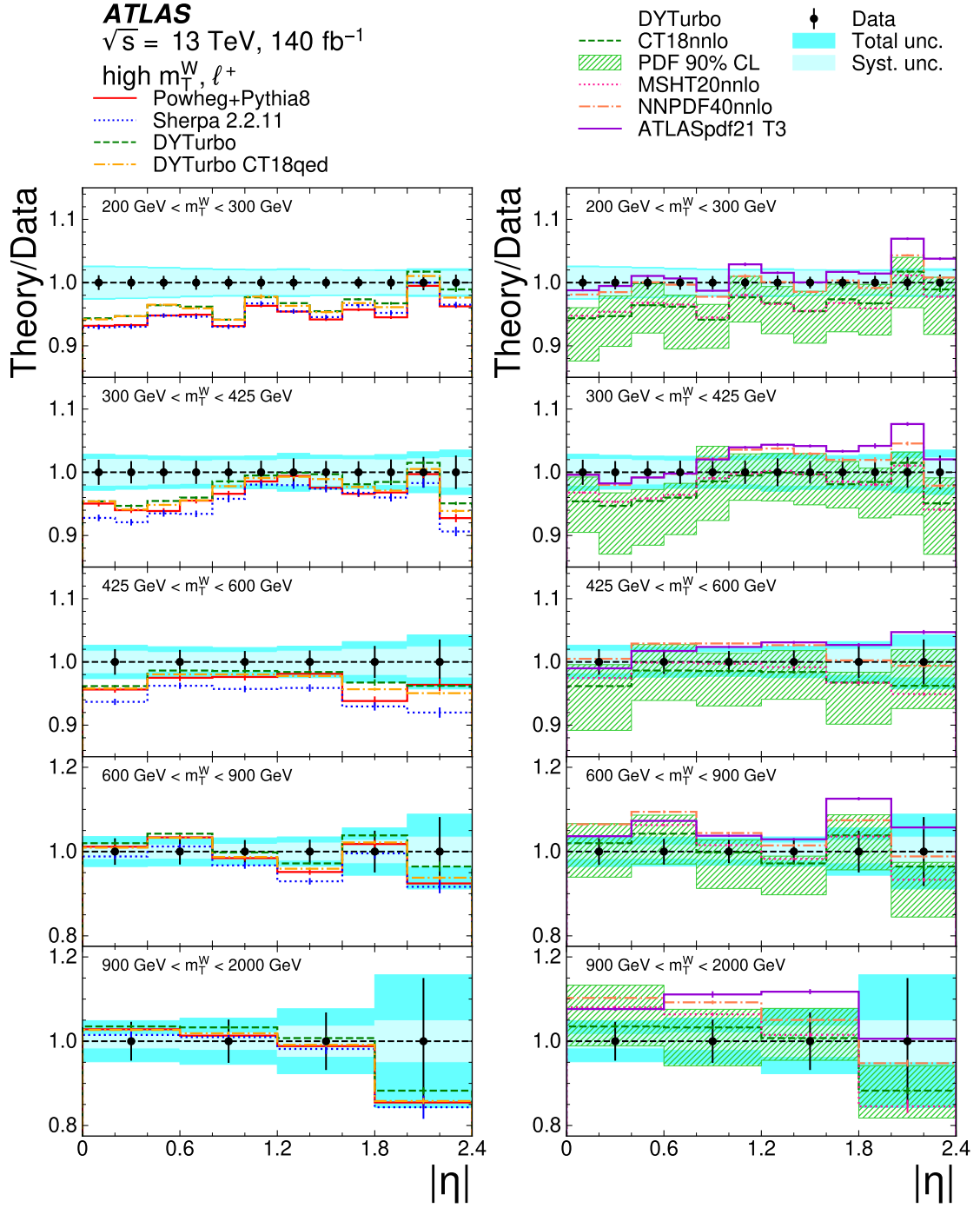


Figure 18: The combined Born-level cross-sections for the double-differential distributions are shown for the ℓ^+ final state. The left panel shows a comparison to the predictions from SHERPA, POWHEG+PYTHIA and the fixed-order calculation from DYTURBO, each using the CT18NNLO PDF. In addition, a fixed-order calculation using DYTURBO and the CT18QED proton PDF is shown. A comparison to predictions with different PDFs using DYTURBO is displayed in the right panel. The CT18NNLO 90% CL PDF uncertainty is shown for the prediction. The statistical uncertainty of the combination is displayed with the error bars. The inner uncertainty band indicates the systematic uncertainty while the outer band corresponds to the total measurement uncertainty (excluding the luminosity uncertainty).

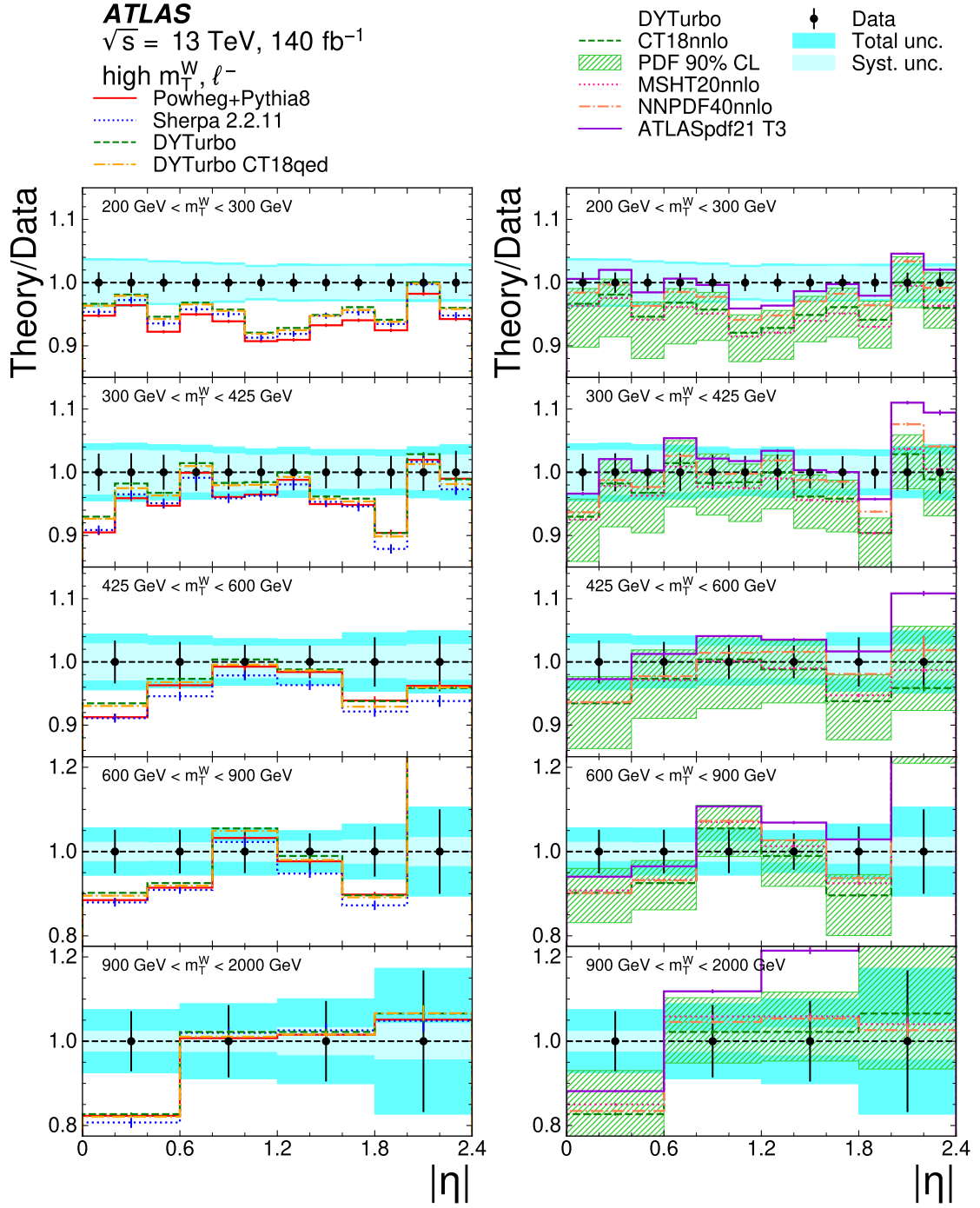


Figure 19: The combined Born-level cross-sections for the double-differential distributions are shown for the ℓ^- final state. The left panel shows a comparison to the predictions from SHERPA, POWHEG+PYTHIA and the fixed-order calculation from DYTURBO, each using the CT18NNLO PDF. In addition, a fixed-order calculation using DYTURBO and the CT18QED proton PDF is shown. A comparison to predictions with different PDFs using DYTURBO is displayed in the right panel. The CT18NNLO 90% CL PDF uncertainty is shown for the prediction. The statistical uncertainty of the combination is displayed with the error bars. The inner uncertainty band indicates the systematic uncertainty while the outer band corresponds to the total measurement uncertainty (excluding the luminosity uncertainty).

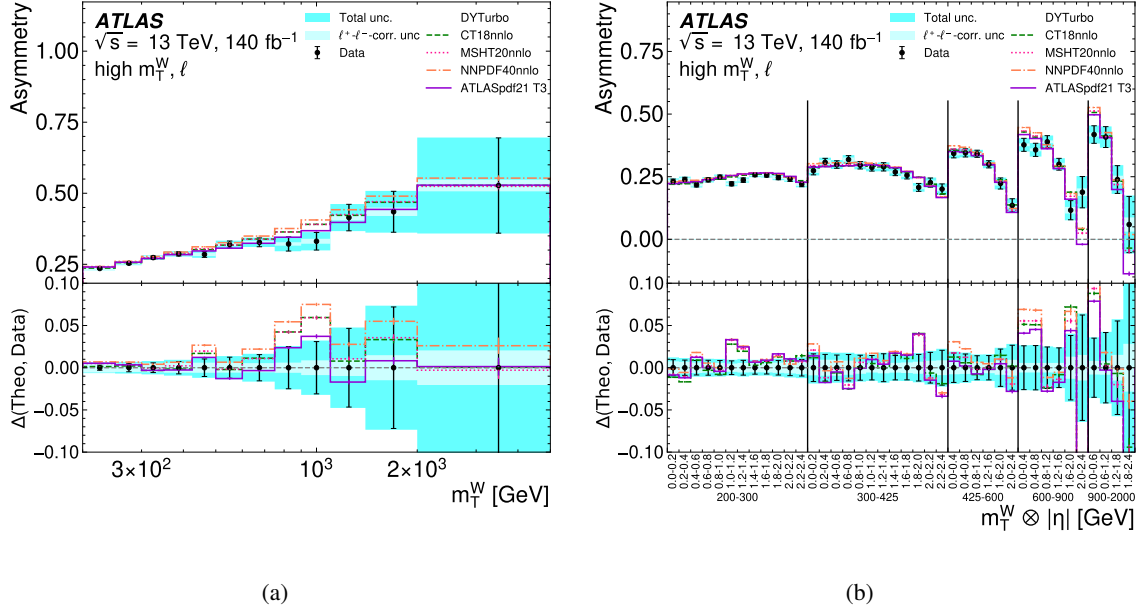


Figure 20: The Born-level lepton charge asymmetry of the combined cross-sections are shown for the (a) single- and (b) double-differential measurements. The error bars represent the statistical and uncorrelated systematic uncertainties between the ℓ^+ - and ℓ^- - channels, while the inner uncertainty band corresponds to the correlated uncertainties. The total uncertainty in the asymmetry is represented with the outer band. In addition, theoretical predictions using DYTURBO for different PDFs are displayed. The lower panels show the absolute difference between each theory calculation and the measured asymmetry.

A complete set of dimension-6 operators of the SMEFT is given by the Warsaw basis [93]. The Warsaw basis provides a minimal basis with all redundant operators removed, containing 2499 dimension-6 operators, each associated with a Wilson coefficient. The Wilson coefficients are unknown free parameters, whose values must be determined experimentally. The number of free parameters can be reduced by imposing symmetries amongst the flavour structure of the fermion generations. The most restrictive flavour symmetry is known as the $U(3)^5$ symmetry, and reduces the number of operators to 59, considering only those that conserve baryon and lepton number [92].

Physical observables receive corrections from the presence of dimension-6 SMEFT operators. The amplitude-squared for a general physics process is given by

$$|\mathcal{A}^2| = |\mathcal{A}_{\text{SM}}|^2 + \sum_i \frac{c_i}{\Lambda^2} \mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_i + \sum_i \frac{|c_i|^2}{\Lambda^4} |\mathcal{A}_i|^2 + \sum_{i,j,i \neq j} \frac{c_i c_j}{\Lambda^4} \mathcal{A}_i^\dagger \mathcal{A}_j,$$

where $\mathcal{A}_{\text{SM}}$ is the SM amplitude and $\mathcal{A}_i$ is the contribution from dimension-6 operator $\mathcal{O}_i$ to the amplitude $\mathcal{A}$. The modifications to physical observables can be separated into three terms:

- Linear interference between the SM and EFT amplitudes.
- Pure quadratic EFT contribution.
- Interference cross terms between EFT amplitudes.

The charged-current Drell–Yan process receives corrections from four different dimension-6 operators, within the $U(3)^5$ symmetry scheme of the Warsaw basis. Those operators and their Wilson coefficients are shown in Table 2.

The sensitivity of the charged-current Drell–Yan process to each operator is studied by generating MC predictions within the SMEFT and comparing against SM predictions. Both SMEFT and SM predictions at LO in QCD are produced using MADGRAPH5_AMC@NLO 2.9.9 [94] and the SMEFTSIM 3.0 package [95]. The m_W, m_Z, G_F electroweak input parameter scheme is used. Events are interfaced with PYTHIA 8.3 [96] for parton showering and hadronisation. The cutoff scale is set to $\Lambda = 1$ TeV.

The effects of each operator on the single-differential cross-section are studied by setting the Wilson coefficient of each of the four operators to unity and setting all others to zero in turn. It is observed that the quark-lepton contact operator $O_{lq}^{(3)}$ gives significant enhancements to the cross section at high m_T^W , whilst the other three operators introduce a constant scaling in the cross-section with no mass dependence. A similar analysis of the double-differential cross-sections shows there is no additional SMEFT operator sensitivity associated with the $|\eta|$ dependence of the cross-sections. Similarly, the charge-separated results do not yield additional sensitivity. Therefore the SMEFT analysis is performed on the single-differential charge-integrated cross sections for the electron, muon and combined channels only.

The statistical model employed is a likelihood function with multivariate Gaussian probability density functions representing the measurement uncertainties. The likelihood is written as

$$L = \frac{1}{\sqrt{(2\pi)^{N_{\text{bins}}|\Sigma|}}} \exp \left\{ -\frac{1}{2} \left[\vec{x} - \vec{\mu}(\vec{\theta}) \right]^T \Sigma^{-1} \left[\vec{x} - \vec{\mu}(\vec{\theta}) \right] \right\} \times \prod_i \theta_i.$$

Here, Σ is the covariance matrix, which includes statistical uncertainties only and is therefore diagonal. The vectors $\vec{x}$ and $\vec{\mu}$ represent the measured distribution and predicted distributions, respectively. Both the experimental and theoretical systematic uncertainties are included as nuisance parameters $\vec{\theta}$, where a shift of $\vec{\theta}_i = 1$ corresponds to a shift of the source i by one standard deviation.

The EFT dependence of the cross-section is parametrised as a quadratic function. In particular, the cross-section in bin i is given by a quadratic function of the Wilson coefficient c :

$$\sigma_i = \sigma_{SM,i} + c \sigma_{\text{lin},i} + c^2 \sigma_{\text{quad},i},$$

Table 2: Dimension-6 SMEFT operators and their corresponding Wilson coefficients affecting the charged current Drell–Yan, in the $U(3)^5$ symmetry of the Warsaw basis. Here, H is the Higgs doublet, and q, l represent the left-handed quark and lepton doublets respectively. The matrices $\tau^I, I = 1, 2, 3$ represent Pauli matrices, and D_μ^I is the usual Standard Model covariant derivative. The subscript of each operator and Wilson coefficient denotes the fields involved in the operator, and the superscript (1) or (3) denotes whether the operator transforms as a singlet or triplet, respectively.

Wilson Coefficient	Operator
$c_{lq}^{(3)}$	$O_{lq}^{(3)} = (\bar{l}\tau^I\gamma_\mu l)(\bar{q}\tau^I\gamma^\mu q)$
$c_{ll}^{(1)}$	$O_{ll}^{(1)} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$c_{Hl}^{(3)}$	$O_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l)$
$c_{Hq}^{(3)}$	$O_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$

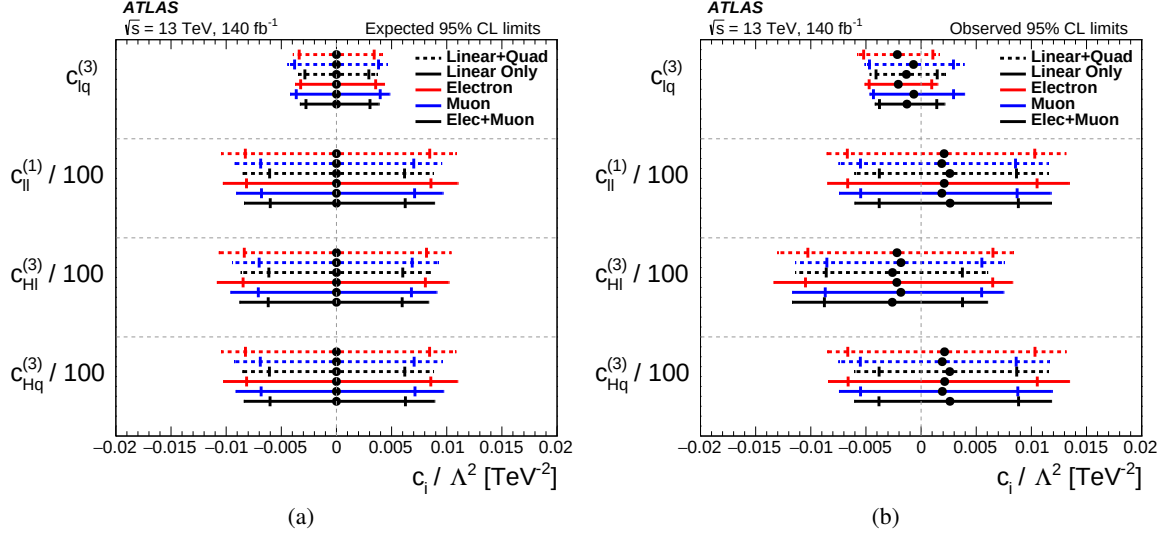


Figure 21: The (a) expected and (b) observed limits on Wilson coefficients at 95% CL. The results are shown for linear-only and linear+quadratic fits, for both the electron and muon channels, as well as their combination. The inner (outer) error bars indicate the limits when using the 68% (90%) CL for the PDF uncertainty.

where σ_i is the SM prediction, and $\sigma_{\text{lin},i}$ and $\sigma_{\text{quad},i}$ are constants describing the dependence of the cross-section on c and c^2 respectively. These two coefficients, $\sigma_{\text{lin},i}$ and $\sigma_{\text{quad},i}$, as well as b_i must be determined from MC simulation in order to infer information about the Wilson coefficients.

As the SMEFT and SM predictions are only computed at LO in QCD, the predictions are modified to account for higher-order QCD and EW corrections via

$$\sigma_i = \sigma_i^{\text{best}} \left(1 + c \frac{\sigma_{\text{lin},i}}{\sigma_i^{\text{LO}}} + c^2 \frac{\sigma_{\text{quad},i}}{\sigma_i^{\text{LO}}} \right),$$

where σ_i^{best} represents a higher-order SM prediction, and σ_i^{LO} represents the LO SM prediction. It is assumed that the relative effect of higher-order predictions does not change in the presence of dimension-six operators. The higher-order SM prediction is generated using DYTURBO, as introduced Section 9.1. The prediction uses the CT18NNLO PDF set, with $\alpha_s = 0.118$ and additive EW corrections.

Theoretical uncertainties arising from variations of α_s , PDFs, EW corrections, and the renormalisation (μ_R) and factorisation scale (μ_F) variations are implemented as follows: the value of $\alpha_s(M_Z)$ at the Z pole is varied by ± 0.001 ; μ_R and μ_F are varied independently by factors of 2 avoiding extreme variations; the EW corrections are included as multiplicative factors on the predictions, rather than additive; and the PDF eigenvector variations for the CT18NNLO set are used at the 90% CL.

Expected limits on the Wilson coefficients are derived by using the DYTURBO prediction as the measurement pseudo-data instead of using the actual measurement as for the observed limits. The fits are performed first by using only the linear SM and EFT interference terms, then by including the quadratic pure EFT contributions as well. They are obtained by allowing only one coefficient to be non-zero at a time.

The expected and observed limits on the Wilson coefficients are given in Figure 21 and are also shown in Table 3. All observed limits are compatible with the $c_i = 0$ assumption at 95% CL, indicating no

Table 3: The expected and observed EFT limits at 95% CL, shown for the linear-only and linear+quadratic electron, muon, and combined fits.

Expected (Linear + Quadratic) [TeV ⁻²]				Observed (Linear + Quadratic) [TeV ⁻²]		
	Electron	Muon	Combined	Electron	Muon	Combined
$c_{lq}^{(3)}/\Lambda^2$	[-0.0039, 0.0041]	[-0.0044, 0.0046]	[-0.0035, 0.0037]	[-0.0058, 0.0016]	[-0.0051, 0.0038]	[-0.0047, 0.0021]
$c_{ll}^{(1)}/\Lambda^2$	[-1.05, 1.08]	[-0.92, 0.95]	[-0.85, 0.87]	[-0.86, 1.31]	[-0.75, 1.15]	[-0.60, 1.15]
$c_{Hl}^{(3)}/\Lambda^2$	[-1.07, 1.03]	[-0.95, 0.92]	[-0.87, 0.84]	[-1.30, 0.83]	[-1.14, 0.75]	[-1.14, 0.60]
$c_{Hq}^{(3)}/\Lambda^2$	[-1.04, 1.08]	[-0.93, 0.95]	[-0.85, 0.88]	[-0.85, 1.31]	[-0.75, 1.16]	[-0.61, 1.15]

Expected (Linear) [TeV ⁻²]				Observed (Linear) [TeV ⁻²]		
	Electron	Muon	Combined	Electron	Muon	Combined
$c_{lq}^{(3)}/\Lambda^2$	[-0.0038, 0.0043]	[-0.0042, 0.0048]	[-0.0033, 0.0038]	[-0.0051, 0.0015]	[-0.0047, 0.0039]	[-0.0042, 0.0021]
$c_{ll}^{(1)}/\Lambda^2$	[-1.03, 1.10]	[-0.91, 0.96]	[-0.84, 0.89]	[-0.85, 1.34]	[-0.74, 1.18]	[-0.60, 1.18]
$c_{Hl}^{(3)}/\Lambda^2$	[-1.08, 1.02]	[-0.96, 0.91]	[-0.88, 0.83]	[-1.34, 0.83]	[-1.17, 0.75]	[-1.17, 0.60]
$c_{Hq}^{(3)}/\Lambda^2$	[-1.03, 1.10]	[-0.91, 0.97]	[-0.84, 0.89]	[-0.84, 1.34]	[-0.74, 1.19]	[-0.61, 1.18]

significant deviations from the SM are observed. The strongest limits are derived by using the data from the combined channel due to the reduced statistical and systematic uncertainties after the electron-muon combination. Differences between the constraints obtained using linear+quadratic and linear-only terms are negligible, indicating the constraints are driven mostly by the linear-interference terms. This suggests that the measurement is largely insensitive to the $1/\Lambda^4$ contributions arising from interference between SM and dimension-8 operators, implying the constraints are robust despite truncating the SMEFT to dimension-6.

The limits on the EFT Wilson coefficients improve by a factor 1.4 to 2.6 when the fits are performed using only experimental uncertainties. This indicates the importance of increasing the precision of the theoretical predictions, in particular for the PDFs, in future measurements. Figure 21 shows that using the 68% CL PDF uncertainty instead of the 90% CL uncertainty improves the limits on the Wilson coefficients by a factor of 1.1-1.4. The limit on the Wilson coefficient $c_{lq}^{(3)}$ exceeds previous four-fermion limits using ATLAS and CMS data [97, 98] as well as limits from low-energy data [99] and global analyses [100, 101].

10 Conclusions

This paper present a first measurement of the $W^\pm$ production cross-section above the resonant production region. The single-differential cross-sections, $d\sigma/dm_T^W$, are measured in the region $200 \leq m_T^W \leq 5000$ GeV. The measurements are also presented as double-differential cross-sections, $d^2\sigma/dm_T^W d|\eta|$, in the region $200 \leq m_T^W \leq 2000$ GeV and $0 \leq |\eta| \leq 2.4$. These fiducial measurements use 140 fb^{-1} of LHC pp collision data collected by ATLAS at a centre-of-mass energy of 13 TeV, and are performed separately for both charges and for the electron and muon final states. They are unfolded for detector effects to the Born level. Corrections to the dressed particle level are also provided.

Combinations of the charge-separated cross-sections for the electron and muon final states are performed to improve the statistical and systematic uncertainties in the measurements. These combined data

compare well to state-of-the-art theoretical predictions at NNLO in QCD including NLO EW effects. The uncertainties in the predictions arising from the PDFs are found to be typically larger than the experimental uncertainties, indicating the potential of these measurements to improve PDF determinations. The single- and double-differential lepton charge asymmetry, A_ℓ , is presented and shown to be well described by the predictions.

A test of lepton flavour universality in the range $200 \text{ GeV} < m_T^W < 5000 \text{ GeV}$ is performed by determining the ratio of the charge-combined cross-sections for the electron to the muon final state. No deviations from the Standard Model are observed.

Finally, the single-differential cross-sections are used to search for signals of new physics in an effective field theory approach within the SMEFT $U(3)^5$ symmetry model. The data constrain the Wilson coefficients of four operators in the Warsaw basis. In particular the measurements provide the world-leading constraints on the Wilson coefficient $c_{lq}^{(3)}$.

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