

Measurements and interpretations of $W^\pm Z$ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



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ABSTRACT: Measurements of integrated and differential cross-sections for $W^\pm Z$ production in proton-proton collisions are presented. The data collected by the ATLAS detector at the Large Hadron Collider from 2015 to 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV are used, corresponding to an integrated luminosity of 140 fb^{-1} . The $W^\pm Z$ candidate events are reconstructed using leptonic decay modes of the gauge bosons into electrons or muons. The integrated cross-section per lepton flavour for the production of $W^\pm Z$ is measured in the detector fiducial region with a relative precision of 4%. The measured value is compared with the Standard Model prediction at a precision of up to next-to-next-to-leading-order in QCD and next-to-leading-order in electroweak. Cross-sections for $W^+ Z$ and $W^- Z$ production and their ratio are presented. The $W^\pm Z$ production is also measured differentially as functions of various kinematic variables, including new observables sensitive to CP-violation effects. All measurements are compared with state-of-the-art Standard Model predictions from fixed-order calculations or Monte Carlo generators based on next-to-leading-order matrix elements interfaced with parton showers. An effective field theory interpretation of the measurements is performed, considering both CP-conserving and CP-violating dimension-6 operators modifying the $W^\pm Z$ production. In the absence of observed deviations from the Standard Model, limits on CP-conserving Wilson coefficients are extracted using the transverse mass of the $W^\pm Z$ system. For CP-violating coefficients a machine learning approach is used to construct an observable with enhanced sensitivity to CP-violation effects.

KEYWORDS: Hadron-Hadron Scattering, Vector Boson Production

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1 Introduction

The study of $W^\pm Z$ diboson production is an important test of the Standard Model (SM) due to its sensitivity to gauge boson self-interactions which are related to the non-Abelian structure of the electroweak interaction. It provides the means to directly probe the triple gauge boson couplings (TGC), in particular the WWZ gauge coupling, and to look for deviations from the SM. Of particular interest is the exploration of potential deviations in the boson couplings with respect to the SM predictions, inducing a violation of the combined charge conjugation and parity (CP) invariance because, according to the Sakharov condition [1], the observed baryon asymmetry of the universe requires additional sources of CP violation beyond those measured which are described in the SM by the Cabibbo-Kobayashi-Maskawa (CKM) complex phase. Additionally, the $W^\pm Z$ inclusive production

enables the search for new physics in the couplings of quarks, leptons and bosonic fields. Improved constraints on these couplings can potentially probe scales of new physics in the multi-TeV range and provide a way to look for signals of new physics in a model-independent way. The SM Effective Field Theory (SMEFT) [2–6] offers a way to set these constraints by parameterising effects of Beyond Standard Model (BSM) physics at energies below the masses of the related new particles that would be responsible for new physics. New terms are added to the SM Lagrangian without assuming the existence of any additional field. Each term is proportional to a Wilson coefficient and is suppressed by increasing powers of $1/\Lambda$, where Λ represents the new physics scale.

Measurements of the $W^\pm Z$ production cross-section in proton-antiproton collisions at a centre-of-mass energy of $\sqrt{s} = 1.96$ TeV were published by the CDF and DØ collaborations [7, 8] using integrated luminosities of 7.1 fb^{-1} and 8.6 fb^{-1} , respectively. At the Large Hadron Collider (LHC) [9], $W^\pm Z$ measurements in proton-proton (pp) collisions, were performed at centre-of-mass energies of 5 TeV, 7 TeV and 8 TeV, by the ATLAS and CMS collaborations [10–13]. Measurements of $W^\pm Z$ production at $\sqrt{s} = 13$ TeV were reported by the ATLAS [14–17] and CMS [18, 19] collaborations using integrated luminosities up to 137 fb^{-1} . The latest ATLAS analyses [16, 17], focused on polarisation measurements, provided the first observation of the joint polarisation of the two final state bosons. Recently, the CMS experiment reported a measurement of the $W^\pm Z$ production cross-section at a centre-of-mass energy of $\sqrt{s} = 13.6$ TeV [20]. Constraints on CP-conserving SMEFT terms including only gauge boson fields were considered in previous $W^\pm Z$ measurements [11–13, 18, 19]. Constraints on CP-violating terms were performed in vector-boson fusion (VBF) production of Z [21], $H \rightarrow \tau\tau$ [22] or $H \rightarrow WW^*$ [23, 24] using the azimuthal angle difference between jets, $\Delta\phi_{jj}$. Besides individual angular variables, analyses of VBF production of $H \rightarrow \gamma\gamma$ [25], $H \rightarrow ZZ^*$ [26] and the analysis of CP properties of $H \rightarrow \tau\tau$ [27] used Optimal Observables to derive limits on CP-violating terms.

This paper presents precise measurements of the integrated and differential $W^\pm Z$ production cross-sections in pp collisions using data recorded by the ATLAS detector from 2015 to 2018 (Run 2), at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, and corresponding to an integrated luminosity of 140 fb^{-1} . The W and Z bosons are reconstructed using their decays into electrons or muons and cross-sections are measured in a fiducial region close to the detector acceptance. The ratio of the $W^+ Z$ cross-section to the $W^- Z$ cross-section is also measured. The reported measurements are compared with predictions from state-of-the-art Monte Carlo (MC) event generators and with the most recent calculations at next-to-next-to-leading-order (NNLO) in QCD and next-to-leading-order (NLO) in electroweak (EW) from MATRIX [28–30].

With respect to the previous ATLAS results [15], the measurements reported in this paper extend the analysed data to the full Run-2 data sample, allowing to do differential cross-section measurements with a higher granularity and a better precision reached in the tails of distributions. The cross-section measurements of this analysis therefore supersede those of ref. [15]. In addition, the set of measured differential variables related to the kinematics of the $W^\pm Z$ system and to the jet activity in the event is significantly extended to include observables sensitive to CP-violation effects. The measured cross-sections and the Rivet [31]

routine for this measurement are published on HEPData [32]. The precision achieved in the reported cross-section measurements is important to validate the theory predictions.

Limits on several CP-conserving and CP-violating BSM terms using detector-level data are extracted in the context of the SMEFT. Constraints on CP-conserving terms including bosonic fields or describing potential new fermion-boson couplings are set using the distribution of the transverse mass of the $W^\pm Z$ pair. For constraining the CP-violating terms a machine learning approach is used to construct an observable with enhanced sensitivity to CP-violation effects.

2 ATLAS detector

The ATLAS experiment [33] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.¹ It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters and a muon spectrometer (MS). The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and 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. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to about 1.25 kHz on average depending on the data-taking conditions. An extensive software suite [34] is used 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 Signal and background simulation

A sample of simulated $W^\pm Z$ events is used to correct the signal yield for detector effects and to compare the measurements with the theory predictions. The production of $W^\pm Z$ pairs and the subsequent leptonic decays of the vector bosons were simulated with the

¹ATLAS 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 $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

SHERPA 2.2.12 [35] MC event generator. The SHERPA 2.2.12 calculation includes all diagrams with four electroweak vertices. The matrix elements were computed for up to one additional parton at NLO in QCD and up to three partons at leading-order (LO) using COMIX [36] and OPENLOOPS [37], and merged with the SHERPA parton shower (PS) [38] according to the ME+PS@NLO prescription [39]. The NNPDF3.0NNLO set of parton distribution functions (PDF) was used along with the associated set of tuned parton-shower parameters developed by the SHERPA authors.

An alternative signal sample was generated at NLO in QCD using the POWHEG BOX v2 [40–43] generator, interfaced to PYTHIA 8.210 [44] for simulation of parton showering, hadronisation and the underlying event. Final-state radiation resulting from QED interactions is simulated using PYTHIA 8.210 and the AZNLO [45] set of tuned parameters. The CT10NLO [46] PDF set was used for the hard-scattering process, while the CTEQ6L1 [47] PDF set was used for the parton shower. The sample was generated with dynamic renormalisation and factorisation QCD scales, μ_R and μ_F , equal to half of m_{WZ} , where m_{WZ} is the invariant mass of the WZ system.

A third $W^\pm Z$ sample with on-shell W and Z is also considered for comparisons to measured jet observables. It uses the MADGRAPH5_AMC@NLO 2.6.5 MC event generator, interfaced with PYTHIA 8.240 using the A14 set of tuned parameters [48] for the modelling of the PS, hadronisation and underlying event. Matrix elements containing three leptons, one neutrino and up to two jets in the final state were calculated at NLO in QCD and merged with the PS from PYTHIA 8.210 using the FxFx scheme [49]. The NNPDF3.0NLO [50] PDF set was used for the hard-scattering process, while the NNPDF2.3LO [51] PDF set was used for the PS. The default dynamic renormalisation and factorisation scales set by MADGRAPH5_AMC@NLO [52] were used.

The measured fiducial cross-sections and the differential distributions are compared with predictions provided by the state-of-the-art MATRIX 2.1 program [28–30, 37, 53–56], which implements fixed-order calculations for the full $pp \rightarrow \ell' \nu \ell \ell$ process. The calculations are performed in the fiducial phase space of the measurement defined in section 6.1 at NNLO in QCD including NLO EW corrections combined with the additive or the multiplicative prescriptions restricted to the $q\bar{q}$ channel, while photon-induced corrections are treated in an additive way. The two combination schemes are denoted by NNLO QCD + EW and NNLO QCD $\times$ EW_{qq}, respectively. The G_μ scheme [57] is used for the input EW parameters. Charged leptons are considered at dressed level as defined in section 6.1. Dynamic renormalisation and factorisation QCD scales are implemented equal to half the sum of the W and Z bosons transverse masses. The NNPDF3.1NNLO_AS_118_LUXQED [58] set, which accounts for QED effects in the DGLAP evolution, the momentum sum rule, and deep-inelastic scattering coefficient functions, is used for the PDFs.

The predictions from the POWHEG+PYTHIA sample were rescaled by a global factor of 1.18 to match the NNLO QCD cross-section predicted by MATRIX.

The background sources include processes with two or more electroweak gauge bosons, namely ZZ , WW and VVV ($V = W, Z$); processes with top quarks, such as $t\bar{t}$ and $t\bar{t} + V$, single top and tZj ; and processes with gauge bosons associated with jets or photons ($Z + j$ and $Z\gamma$). Electroweak $W^\pm Z$ production, $WZjj$ –EW, arising at the order α_{EW}^6 is also considered

as a background and not part of the measured signal. MC simulation is used to estimate the contribution from background processes with three or more prompt leptons.² Background processes with at least one misidentified lepton are evaluated using data-driven techniques and simulated events are used to assess the systematic uncertainties of these backgrounds.

The SHERPA 2.2.2 event generator was used to simulate both the $q\bar{q}$ and gg -initiated ZZ and WW processes, including $H \rightarrow VV$ production, using the NNPDF3.0NNLO PDF set. It provides a matrix element calculation accurate at NLO in α_s for 0- and 1-jet final states, and LO accuracy for 2- and 3-jet final states.

The production of $t\bar{t} + V$ events was modelled using the MADGRAPH5_AMC@NLO 2.3.3 generator at NLO with the NNPDF3.0NLO PDF. The events were interfaced to PYTHIA 8.210 using the A14 set of tuned parameters and the NNPDF2.3LO PDF set. The tZj process was modelled using the MADGRAPH5_AMC@NLO 2.3.3 generator at NLO with the NNPDF3.0NLO PDF. The events were interfaced with PYTHIA 8.230 using the A14 set of tuned parameters and the NNPDF2.3LO PDF set. The $WZjj$ -EW events, corresponding to processes of order six (zero) in α_{EW} (α_s), were generated at LO by the MADGRAPH5_AMC@NLO 2.6.5 MC generator interfaced with PYTHIA 8.240 for the modelling of the parton shower, hadronisation and underlying event. The parton distribution function set was NNPDF3.0NLO. In the simulation of the parton shower the NNPDF2.3LO PDF set was used. The $ZZjj$ -EW production was modelled using the MADGRAPH5_AMC@NLO 2.6.7 generator with matrix elements calculated at LO in QCD and with the NNPDF3.0NLO PDF set. The events were interfaced with PYTHIA 8.230 using the A14 set of tuned parameters and the NNPDF2.3LO PDF set. The on-shell production of triboson events with fully leptonic decays was simulated by the SHERPA 2.2.2 event generator at NLO accuracy with zero additional partons and at LO accuracy with one and two additional partons and using the NNPDF3.0NNLO PDF set.

The production of $t\bar{t}$ events was modelled using the POWHEG BOX v2 generator at NLO with the NNPDF3.0NLO PDF set and the h_{damp} parameter³ set to $1.5 m_{\text{top}}$ [59]. The events were interfaced to PYTHIA 8.230 to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune and using the NNPDF2.3LO set of PDFs. The production of $Z\gamma$ final states was simulated with the SHERPA 2.2.4 event generator at NLO QCD accuracy using the NNPDF3.0NNLO PDF set. Finally, the production of $Z + j$ events was modelled with the POWHEG BOX v1 MC generator interfaced to PYTHIA 8.186 [60] for the modelling of the parton shower, hadronisation, and underlying event, with parameters set according to the AZNLO set of tuned parameters. The CT10NLO PDF set was used for the hard-scattering processes, whereas the CTEQ6L1 PDF set was used for the parton shower.

The decays of bottom and charm hadrons were simulated using the EVTGEN 1.2.0 program [61], except for processes modelled using SHERPA. All generated MC events were passed through the ATLAS detector simulation [62], based on GEANT4 [63], and processed using the same reconstruction software as used for the data. Multiple interactions in the same

²A prompt lepton is a lepton that is not produced in a photon conversion or in the decay of a hadron, a τ -lepton, or their descendants.

³The h_{damp} parameter is a resummation damping factor and one of the parameters that controls the matching of POWHEG matrix elements to the parton shower and thus effectively regulates the high- p_T radiation against which the $t\bar{t}$ system recoils.

and neighbouring bunch crossings (pile-up) were modelled by overlaying the hard-scattering event with simulated inelastic pp events generated with PYTHIA 8.186 using the NNPDF2.3LO PDF set and the A3 [64] set of tuned parameters. The MC events were weighted to reproduce the distribution of the average number of interactions per bunch crossing ($\langle\mu\rangle$) observed in the data. The $\langle\mu\rangle$ value in data was rescaled by a factor of 1.03 ± 0.04 to improve agreement between data and simulation in both charged-particle track distributions and the visible inelastic pp cross-section [65].

Furthermore, the lepton and jet momentum scale and resolution, the lepton reconstruction, identification, isolation and trigger efficiencies and the pile-up jets and b -jet veto efficiencies in the simulation were corrected to match those measured in data.

4 Event reconstruction and selection

Only data recorded with stable beam conditions and with all relevant detector subsystems operational are considered [66]. Candidate events are selected using triggers that require at least one electron or muon [67–69]. These triggers require leptons to satisfy different transverse momentum thresholds and isolation criteria, which depend on the data-taking run period and the instantaneous luminosity. The combined efficiency of these triggers is 99% for $W^\pm Z$ events satisfying the offline selection criteria. Events are required to have a primary vertex compatible with the LHC luminous region inside the ATLAS detector. The primary vertex is defined as the reconstructed vertex with at least two charged-particle tracks that has the largest sum p_T^2 of its associated tracks.

Muon candidates are identified by tracks reconstructed in the MS and matched to tracks reconstructed in the ID. Muons are required to satisfy a “medium” identification selection [70]. The efficiency of this selection averaged over p_T and η is larger than 98%. The muon momentum is measured by combining the MS measurement, corrected for the energy deposited in the calorimeters, and the ID measurement. The p_T of the muon must be greater than 15 GeV and its pseudorapidity must satisfy $|\eta| < 2.5$.

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter matched to ID tracks. Electrons are identified using a discriminant that is the value of a likelihood function constructed with information about the shape of the electromagnetic showers in the calorimeter, the track properties and the quality of the track-to-cluster matching for the candidate [71, 72]. Electrons must satisfy a “medium” likelihood requirement, which provides an overall identification efficiency of 90%. The electron momentum is computed from the cluster energy and the direction of the track. The p_T of the electron must be greater than 15 GeV and the pseudorapidity of the cluster must satisfy $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$.

Electron and muon candidates are required to originate from the primary vertex. Thus, the significance of the track’s transverse impact parameter calculated relative to the beam line, $|d_0/\sigma_{d_0}|$, must be smaller than 3.0 for muons and less than 5.0 for electrons. Furthermore, the longitudinal impact parameter, z_0 (the difference between the value of z of the point on the track at which d_0 is defined and the longitudinal position of the primary vertex), is required to satisfy $|z_0 \cdot \sin(\theta)| < 0.5$ mm.

Electrons and muons are required to be isolated from other particles using both calorimeter-cluster and ID-track information. The isolation requirement for electrons is tuned for an efficiency of at least 88% for $p_T > 15$ GeV and at least 99% for $p_T > 60$ GeV [71], while particle-flow-based isolation variables are used for muons, providing an efficiency above 90% for $p_T > 15$ GeV and at least 99% for $p_T > 60$ GeV [70].

Jets of hadrons are reconstructed using a particle-flow algorithm based on noise-suppressed positive-energy topological clusters in the calorimeters [73]. Energy deposited in the calorimeters by charged particles is subtracted and replaced by the momenta of tracks which are matched to those topological clusters. Tracks which are not matched to the primary vertex are not used in jet reconstruction, which effectively removes contribution from charged particle pile-up. The jets are clustered using the anti- k_t algorithm [74, 75] with a radius parameter $R = 0.4$. They are calibrated according to in situ measurements of the jet energy scale [76]. All jets must have $p_T > 25$ GeV and be reconstructed in the pseudorapidity range $|\eta| < 4.5$. To reduce the impact of jets originating from pile-up interactions, jets with $|\eta| < 2.4$ and $p_T < 60$ GeV, or with $2.5 < |\eta| < 4.5$ and $p_T < 120$ GeV, are required to satisfy the “tight” and “loose” working points of the jet vertex [77] and forward jet vertex [78] tagging algorithms, respectively. Jets with $|\eta| < 2.5$ containing a b -hadron are identified with a deep-learning neural network (NN) [79] which uses distinctive features of b -hadron decays in terms of the impact parameters of the tracks and the displaced vertices reconstructed in the ID. Jets initiated by b -quarks are selected by setting the algorithm’s output threshold such that a b -jet selection efficiency of 70% is achieved in simulated $t\bar{t}$ events, with a rejection factor of 500 against light-flavour jets [79].

To avoid cases where the detector response to a single physical object is reconstructed as two different final-state objects, e.g. an electron reconstructed as both an electron and a jet, several steps are followed to remove such overlaps, as described in ref. [80].

The transverse momentum of the neutrino is estimated from the missing transverse momentum in the event, E_T^{miss} , calculated as the negative vector sum of the transverse momentum of all identified hard physics objects (electrons, muons, jets), with a contribution from an additional soft term. This soft term is calculated from ID tracks matched to the primary vertex and not assigned to any of the hard objects [81].

Events are required to contain exactly three lepton candidates satisfying the selection criteria described above. To ensure that the trigger efficiency is well determined, at least one of the candidate leptons is required to have $p_T > 25$ GeV for 2015 and $p_T > 27$ GeV for 2016–2018 data, and being geometrically matched to a lepton that was selected by the trigger. No requirement on the number of jets is applied.

To suppress background processes with at least four prompt leptons, events with a fourth lepton candidate satisfying looser selection criteria are rejected. For this looser selection, the lepton p_T requirement is lowered to $p_T > 5$ GeV, electrons are allowed to be reconstructed in the region $1.37 < |\eta| < 1.52$ and “loose” identification requirements [70, 71] are used for both the electrons and muons. A less stringent requirement is applied for electron isolation and is based only on ID track information. No dedicated identification algorithm is used to suppress events with electrons and muons originating from the decay of τ -leptons.

Candidate events are required to have at least one pair of leptons with the same flavour and opposite charge, with an invariant mass that is consistent with m_Z^{PDG} to within 10 GeV, where m_Z^{PDG} is the world average mass of the Z boson, as reported by the Particle Data Group [82]. This pair is considered to be the Z boson candidate. If more than one pair can be formed, the pair whose invariant mass is closest to the world-average measured Z boson mass is taken as the Z boson candidate. The remaining third lepton is assigned to the W boson decay. The transverse mass of the W candidate, computed using E_T^{miss} and the p_T of the associated lepton, is required to be greater than 30 GeV.

Backgrounds originating from candidate leptons that are not prompt leptons, also called “misidentified” leptons, are suppressed by requiring the lepton associated with the W boson to satisfy more stringent selection criteria. The transverse momentum of this lepton is therefore required to be greater than 20 GeV. This lepton is also required to satisfy the “tight” identification requirements, which results in an efficiency between 90% and 98% for muons and an overall efficiency of 85% for electrons. Finally, leptons associated with the W boson must also pass a tighter isolation requirement, tuned for an efficiency of at least 65% and 75% for electrons and muons, respectively.

5 Background estimation

The background sources are classified into two groups: events where at least one of the candidate leptons is not a prompt lepton (reducible background) and events where all candidates are prompt leptons or are produced in the decay of a τ -lepton (irreducible background). Background events amount to 19% of all selected events.

Events of reducible backgrounds mostly originate from $Z+j$, $Z\gamma$, $t\bar{t}$, and WW production processes and constitute about 5% of all selected events. This reducible background is estimated with a data-driven method based on the inversion of a matrix containing the efficiencies and misidentification probabilities for prompt and misidentified leptons [12, 15, 83, 84]. The method exploits the classification of the leptons as loose or tight candidates and the probability that a non-prompt lepton is misidentified as a loose or tight lepton. Tight leptons are leptons satisfying the selection criteria described in section 4. Loose leptons are leptons that do not meet the isolation and identification criteria for signal leptons but satisfy only looser criteria. The misidentification probabilities for leptons are determined from data using dedicated control samples each enriched in misidentified leptons from light- or heavy-flavour jets and from photon conversions, respectively. The lepton efficiencies for prompt leptons are determined as detailed in refs. [70, 71]. The lepton efficiencies and misidentification probabilities are combined with event rates in data samples of $W^\pm Z$ candidate events where at least one and up to three of the leptons is loose. Then, solving a system of linear equations, the number of events with at least one misidentified lepton is obtained, which represents the amount of reducible background in the $W^\pm Z$ sample. About 2% of this background contribution arises from events with two misidentified leptons. The background from events with three misidentified leptons, e.g. from multijet processes, is negligible. The method allows the shape of any kinematic distribution of reducible background events to be estimated. Another independent method of assessing the reducible background was also considered. This method estimates the amount of reducible background using MC simulations scaled to data

by process-dependent factors determined from data-to-MC comparisons in dedicated control regions. Agreement within 20% with the matrix method estimate is obtained in both yield and shape of the distributions of irreducible background events. Systematic uncertainties affecting the matrix method estimate are detailed in section 7.

The events contributing to irreducible background processes represent $\sim 14\%$ of all selected events. They originate from ZZ , $t\bar{t} + V$, VVV (where $V = Z$ or W) and tZj events. Events from electroweak $WZjj$ –EW production are not part of the measured signal and are therefore considered as backgrounds. The amount of irreducible background is estimated by using MC simulations. The dominant contribution in this second group is from ZZ production, where one of the leptons from the ZZ decay falls outside the detector acceptance. It represents about 7% of all selected events. The MC-based estimates of the ZZ and $t\bar{t} + V$ backgrounds are validated by comparing the MC expectations with the event yield and several kinematic distributions of data samples enriched in ZZ and $t\bar{t} + V$ events, respectively. The ZZ control sample is selected from events with a Z candidate which meets all of the analysis selection criteria and which is accompanied by two additional leptons, satisfying the lepton criteria described in section 4. The ZZ MC expectation is rescaled by a factor of 1.13 to match the observed event yield of data in this control region. This scaling factor relative to SHERPA predictions is in agreement with the ZZ cross-section measurements performed at $\sqrt{s} = 13$ TeV [85]. Good agreement is observed between the shapes of the main kinematic distributions and the MC predictions. The m_Z distribution of events in the ZZ control sample is presented in figure 1(a).

The $t\bar{t} + V$ control sample is defined as a sub-sample of $W^\pm Z$ candidate events by requiring the presence of at least two reconstructed b -jets. The observed data event yield in this validation region is matching the $t\bar{t} + V$ MC prediction rescaled by a factor of 1.3. This scaling factor relative to predictions is inline with the $t\bar{t} + Z$ cross-section measurements performed at $\sqrt{s} = 13$ TeV [86]. The contribution of $t\bar{t} + V$ events amounts to $\sim 4\%$ of all selected events. The distributions of the main kinematic variables are found to be well described by the MC predictions. The m_T^W distribution of events in the $t\bar{t} + V$ control sample is presented in figure 1(b). Systematic uncertainties affecting the rescaling of ZZ and $t\bar{t} + V$ MC predictions are discussed in section 7.

6 Measurements methodology

6.1 Phase space for cross-section measurements

The fiducial $W^\pm Z$ cross-section is measured in a phase space chosen to closely follow the event selection criteria described in section 4. It is based on the kinematics of particle-level objects as defined in ref. [87]. These are final-state prompt leptons associated with the W and Z boson decays. Charged leptons after QED final-state radiation are “dressed” by adding to the lepton four-momentum the contributions from photons with an angular distance $\Delta R < 0.1$ from the lepton. Dressed leptons, and final-state neutrinos that do not originate from hadron or τ -lepton decays, are matched to the W and Z boson decay products using an algorithm that does not depend on details of the MC generator, called the “resonant shape” algorithm [12].

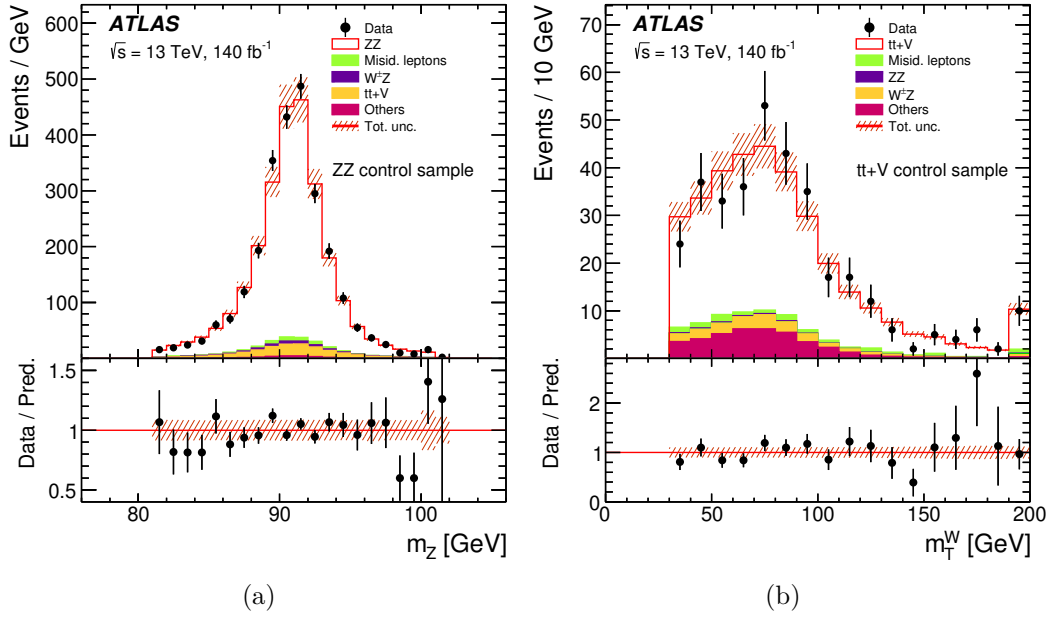


Figure 1. Distribution of (a) m_Z for events in the ZZ control sample and (b) m_T^W for events in the $t\bar{t} + V$ control sample. The points correspond to the data with the error bars representing the statistical uncertainties, and the histograms correspond to the predictions of the various SM processes. The sum of the background processes with misidentified leptons is labelled “Misid. leptons”. The red histogram shows the total prediction; the shaded band is the total uncertainty of this prediction. The last bin in (b) contains the overflow. The lower panels in each figure show the ratio of the data points to the open red histogram with their respective uncertainties.

The reported cross-sections are measured in a fiducial phase space defined at particle level as follows. The dressed leptons from Z and W boson decays must have $|\eta| < 2.5$ and transverse momentum p_T above 15 GeV and 20 GeV, respectively; the invariant mass of the two leptons from the Z boson decay must be within 10 GeV from the world average value of the Z boson mass m_Z^{PDG} . The W transverse mass, defined as $m_T^W = \sqrt{2 \cdot p_T^\ell \cdot p_T^\nu \cdot [1 - \cos \Delta\phi(\ell, \nu)]}$, where $\Delta\phi(\ell, \nu)$ is the angle between the lepton and the neutrino in the transverse plane, and p_T^ℓ and p_T^ν are the transverse momenta of the lepton from W boson decay and of the neutrino, respectively, must be greater than 30 GeV. In addition, to match isolation criteria used in the detector-level event selection, it is required that the angular distance ΔR between the charged leptons from the W and Z decay is larger than 0.3, and that ΔR between the two leptons from the Z decay is larger than 0.2. A requirement that the transverse momentum of the leading lepton be above 27 GeV reduces the acceptance of the fiducial phase space by less than 0.5%. This criterion is therefore not added to the definition of the fiducial phase space, while it is present in the selection at the detector level.

For the differential measurements related to jets, particle-level jets are reconstructed from stable particles with a lifetime of $\tau > 30$ ps in the simulation after parton showering, hadronisation, and the decay of particles with $\tau < 30$ ps. Muons, electrons, neutrinos and photons associated with W and Z decays are excluded from the jet collection. The particle-level jets are reconstructed with the anti- k_t algorithm with a radius parameter $R = 0.4$ and

Channel	C_{W^-Z}	C_{W^+Z}	$C_{W^\pm Z}$
eee	0.353 ± 0.002	0.343 ± 0.001	0.347 ± 0.001
μee	0.453 ± 0.002	0.450 ± 0.002	0.451 ± 0.001
$e\mu\mu$	0.525 ± 0.002	0.510 ± 0.002	0.516 ± 0.001
$\mu\mu\mu$	0.694 ± 0.003	0.695 ± 0.002	0.695 ± 0.002

Table 1. The C_{WZ} factors for each of the eee , μee , $e\mu\mu$, and $\mu\mu\mu$ inclusive channels. The SHERPA MC event sample with the “resonant shape” lepton assignment algorithm at particle level is used. Only statistical uncertainties are reported.

are required to have a p_T above 25 GeV and an absolute value of the pseudorapidity below 4.5. The angular distance between all selected leptons and jets is required to be $\Delta R(j, \ell) > 0.3$. If this requirement is not satisfied, the jet is discarded.

6.2 Integrated cross-section measurements

For a given channel $W^\pm Z \rightarrow \ell'^\pm \nu \ell^+ \ell^-$, where ℓ and ℓ' indicate each type of lepton (e or μ), the integrated fiducial cross-section that includes the leptonic branching fractions of the W and Z bosons is calculated as

$$\sigma_{W^\pm Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot C_{WZ}} \times \left(1 - \frac{N_\tau}{N_{\text{all}}}\right),$$

where N_{data} and N_{bkg} are the number of observed events and the estimated number of background events, respectively, $\mathcal{L}$ is the integrated luminosity, and C_{WZ} , obtained from simulation, is the ratio of the number of selected signal events at detector level to the number of events at particle level in the fiducial phase space. This factor corrects for detector efficiencies and for QED final-state radiation effects. The contribution from τ -lepton decays, amounting approximately to 4%, is removed from the cross-section definition by introducing the term in parentheses. This term is computed using simulation, where N_τ is the number of selected events at detector level in which at least one of the bosons decays into a τ -lepton and N_{all} is the number of selected WZ events with decays into any lepton.

The C_{WZ} factors for W^-Z , W^+Z , and $W^\pm Z$ inclusive processes computed with SHERPA for each of the four leptonic channels are shown in table 1.

The measured fiducial cross-sections for the four channels are combined using a χ^2 minimisation method that accounts for correlations between the sources of systematic uncertainty affecting each channel [88–90].

6.3 Differential cross-section measurements

The differential detector-level distributions within the fiducial phase space are corrected for detector resolution and for QED final-state radiation effects using simulated signal events and an iterative Bayesian unfolding method [91], as implemented in the RooUnfold toolkit [92]. Background events are subtracted from data following the estimates of section 5. Events from $W^\pm Z$ production with at least one τ -lepton decay are also subtracted from data. A fiducial correction is applied to take into account events that are selected at detector-level but

originate from outside of the fiducial phase space at particle-level. The unfolding procedure corrects for migrations of the events between bins in the distributions from the particle to the detector-level reconstruction. Finally, efficiency corrections take into account events selected in the fiducial phase space at particle-level that are not reconstructed at detector-level due to detector inefficiencies. To reduce the bias arising from using a chosen MC prediction to model the ‘true’ particle-level distribution, the method can be applied with multiple iterations, at the cost of an increased statistical uncertainty.

For the measurements of the differential distributions, all four decay channels, eee , $e\mu\mu$, μee , and $\mu\mu\mu$, are added together. The resulting distributions are unfolded with a response matrix computed using a SHERPA MC signal sample that includes all four decay channels and is divided by four such that cross-sections refer to final states where the W and Z bosons decay in a single leptonic channel with muons or electrons. The SHERPA signal sample is used for unfolding, since it provides a fair description of the data distributions. The number of iterations was tuned to obtain the best trade-off in minimising both the unfolding bias and the unfolding statistical uncertainty. For each observable, the number of iterations ranges from two to five, depending on the resolution in the unfolded variable. The width of the bins in each distribution is chosen according to the experimental resolution and to the statistical significance of the expected number of events in each bin. The fraction of signal MC events generated in a bin which are reconstructed in the same bin is always greater than 40% and around 70% on average.

7 Systematic uncertainties

Experimental and theory sources of systematic uncertainties in the measured cross-sections and limits on BSM effects are considered, including uncertainties in the correction procedure for detector effects, in the background estimate and in the luminosity.

The systematic uncertainties in the C_{WZ} factors related to the theory modelling are due to the choice of PDF set, QCD renormalisation μ_R and factorisation μ_F scales, and MC modelling of higher-order QCD effects simulated by PS and of the underlying event. The uncertainties due to the PDF and the α_s value used in the PDF determination are evaluated using the PDF4LHC prescription [93]. Uncertainties due to missing higher-order QCD corrections are evaluated by varying the μ_R and μ_F scales independently by factors of two and one-half, removing combinations where the variations differ by a factor of four. The impact of these variations in the C_{WZ} factors is of maximally 0.4%. A global MC modelling uncertainty, that includes effects of the parton shower model, is estimated by evaluating the C_{WZ} factors using the SHERPA and POWHEG+PYTHIA MC event generators. The difference between the C_{WZ} factors from the two generators amounts to 3%, independent of the decay channel and is considered as an uncertainty. This discrepancy arises mostly from differences in the isolation of decay leptons from hadronic activity from the PS and the underlying event and, to a lower extent, from a slightly harder p_T spectrum of decay leptons in one MC generator compared to the other.

Uncertainties in differential cross-section measurements arising from the imperfect description of the data by the SHERPA MC simulation are evaluated using a data-driven method [94]. Each MC differential distribution is corrected to match the data distribution

and the resulting weighted MC distribution at detector level is unfolded with the response matrix used in the actual data unfolding. The new unfolded distribution is compared with the weighted MC distribution at particle level and the difference is taken as the systematic uncertainty. This procedure results in an uncertainty in the measured cross-sections of the order of 0.2% on average, with a maximal value of 2% depending on the observable. An additional uncertainty is attributed to the measurements to account for differences between the SHERPA and POWHEG+PYTHIA generators. The POWHEG+PYTHIA generator is alternatively used to unfold the data and the deviation from the nominal result is taken as the uncertainty. To remove effects already accounted for in the data-driven method, the POWHEG+PYTHIA distributions were first reweighted to match SHERPA distributions at particle level. The resulting uncertainty in the measured differential cross-section is 3% on average.

Systematic uncertainties affecting the reconstruction and energy calibration of electrons, muons and jets are propagated through the analysis. The uncertainties due to lepton reconstruction, identification, isolation requirements and trigger efficiencies as well as in the lepton momentum scale and resolution are assessed using tag-and-probe methods in $Z \rightarrow \ell\ell$ events [70, 71, 95]. The uncertainties in the jet energy scale are obtained from $\sqrt{s} = 13$ TeV simulations and *in situ* measurements [76]. The uncertainties in the jet energy resolution [76], in the suppression of jets originating from pile-up [77], in the b -tagging efficiency and in the mistag rate [79] are also considered. The uncertainty in E_T^{miss} is estimated by propagating the uncertainties in the transverse momenta of reconstructed objects and by applying momentum scale and resolution uncertainties to the track-based soft term [81]. A variation in the pile-up reweighting of MC events is included to cover the uncertainty in the ratio of the predicted and measured pp inelastic cross-sections [65]. For the measurements of the W charge-dependent cross-sections, an uncertainty arising from the charge misidentification of electrons is also considered [71]. It affects only electrons and leads to an uncertainty of less than 0.15% in the ratio of W^+Z to W^-Z integrated cross-sections determined by combining the four decay channels.

The dominant contribution among the experimental systematic uncertainties in the eee and μee channels is due to the uncertainty in the electron reconstruction and identification efficiencies, contributing at most a 1.7% uncertainty to the integrated cross-section, while in the $e\mu\mu$ and $\mu\mu\mu$ channels it originates from the muon reconstruction and isolation efficiencies and is also at most 1.7%. The effect of pile-up uncertainties is of the order of 0.5% to 1% for muon and electron channels, respectively.

The uncertainty in the amount of background from misidentified leptons takes into account the limited number of events in the control regions as well as the difference in background composition between the control region used to determine the lepton misidentification rate and the control regions used to estimate the yield in the signal region. This results in an uncertainty of about 25% in the total misidentified-lepton background yield and in the shape of the differential distributions of the reducible background events.

Uncertainties due to the theory modelling of ZZ generated events are considered. They arise from higher-order QCD corrections and the PDFs and are evaluated in the same way as for $W^\pm Z$ events. The uncertainty due to irreducible background sources other than ZZ is evaluated by propagating the uncertainty in their MC cross-sections. These are

	eee	μee	$e\mu\mu$	$\mu\mu\mu$	Combined
Relative uncertainties [%]					
e energy scale	0.3	< 0.1	0.2	< 0.1	0.1
e efficiency	1.7	1.1	0.6	< 0.1	0.6
μ momentum scale	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ efficiency	< 0.1	1.4	0.5	1.7	0.9
$E_{\text{T}}^{\text{miss}}$ and jets	0.4	0.4	0.5	0.5	0.4
Trigger	< 0.1	< 0.1	< 0.1	0.2	0.1
Pile-up	1.0	0.9	0.6	0.4	0.6
Misid. leptons background	2.3	1.1	1.5	1.4	1.4
ZZ background	0.9	0.8	0.9	0.8	0.8
Other backgrounds	0.9	0.9	0.9	0.9	0.9
Uncorrelated	0.4	0.3	0.3	0.3	0.2
Total experimental uncertainty	3.4	2.6	2.3	2.6	2.3
Luminosity	0.9	0.9	0.9	0.9	0.9
Theoretical modelling	3.0	3.0	3.0	3.0	3.0
Data statistics	2.0	1.8	1.6	1.4	0.8
Total	5.0	4.5	4.2	4.3	4.0

Table 2. Summary of the relative uncertainties in the measured fiducial cross-section $\sigma_{W^\pm Z}^{\text{fid.}}$ for each channel and for their combination. The uncertainties are reported as percentages. The first rows indicate the main sources of systematic uncertainty for each channel and their combination, which are treated as correlated between channels. A row with uncorrelated uncertainties follows, which comprise all uncertainties of statistical origin including MC statistical uncertainty and statistical uncertainties in the reducible background estimate, which are uncorrelated between channels.

30% for VVV [96], 25% for $WZjj$ –EW [97] and 15% for tZj [98] and $t\bar{t} + V$ [86, 99]. A normalisation uncertainty of 10% is attributed to the contribution of events from $W^\pm Z$ production with at least one τ -lepton decay, corresponding to the QCD scale uncertainty of the Sherpa MC prediction.

The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [100], obtained using the LUCID-2 detector [101] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters. It is applied to the signal normalisation as well as to all background contributions that are estimated using only MC simulations.

The total systematic uncertainty in the measured $W^\pm Z$ fiducial cross-section, excluding the luminosity uncertainty, varies between 4.2% and 5% for the four measurement channels, and is dominated by the theory modelling of the C_{WZ} factors, arising from differences between the SHERPA and POWHEG+PYTHIA MC generators. Table 2 shows the statistical uncertainty

Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	3955	4600	5895	7486	21936
Total expected	4000	4900	5900	7600	22400
	± 500	± 500	± 700	± 900	± 2500
WZ	78%	83%	79%	82%	81%
ZZ	8%	7%	8%	7%	7%
Misid. leptons	7%	4%	6%	5%	5%
$t\bar{t} + V$	4%	4%	4%	4%	4%
tZj	2%	2%	2%	1%	2%
$WZjj$ –EW	1%	1%	1%	1%	1%
VVV	$< 1\%$	$< 1\%$	$< 1\%$	$< 1\%$	$< 1\%$

Table 3. Total numbers of observed and expected events after the $W^\pm Z$ inclusive selection described in section 4 in each of the considered channels and for the sum of all channels. The expected approximate size of $W^\pm Z$ events from SHERPA and the estimated amount of background events from other processes are expressed as a fraction of the total number of predicted events. The sum of background events containing misidentified leptons is labelled “Misid. leptons”. The total uncertainties in the total number of predicted events are reported.

and the main sources of systematic uncertainty in the $W^\pm Z$ fiducial cross-section for each of the four channels and for their combination.

8 Results

8.1 Detector-level results

Table 3 summarises the predicted and observed number of events resulting from the $W^\pm Z$ inclusive selection, together with the estimated background contributions. Figure 2 shows the measured distributions of the transverse momentum and the invariant mass of the Z candidate, the transverse mass of the W candidate, and for the WZ system the absolute difference between the azimuthal angle of the Z boson and the charged lepton from the decay of the W boson, $\Delta\phi(\ell^W, Z)$. The SHERPA MC prediction is used for the $W^\pm Z$ signal contribution. Figure 2 indicates that the MC predictions provide a fair description of the shapes of the data distributions.

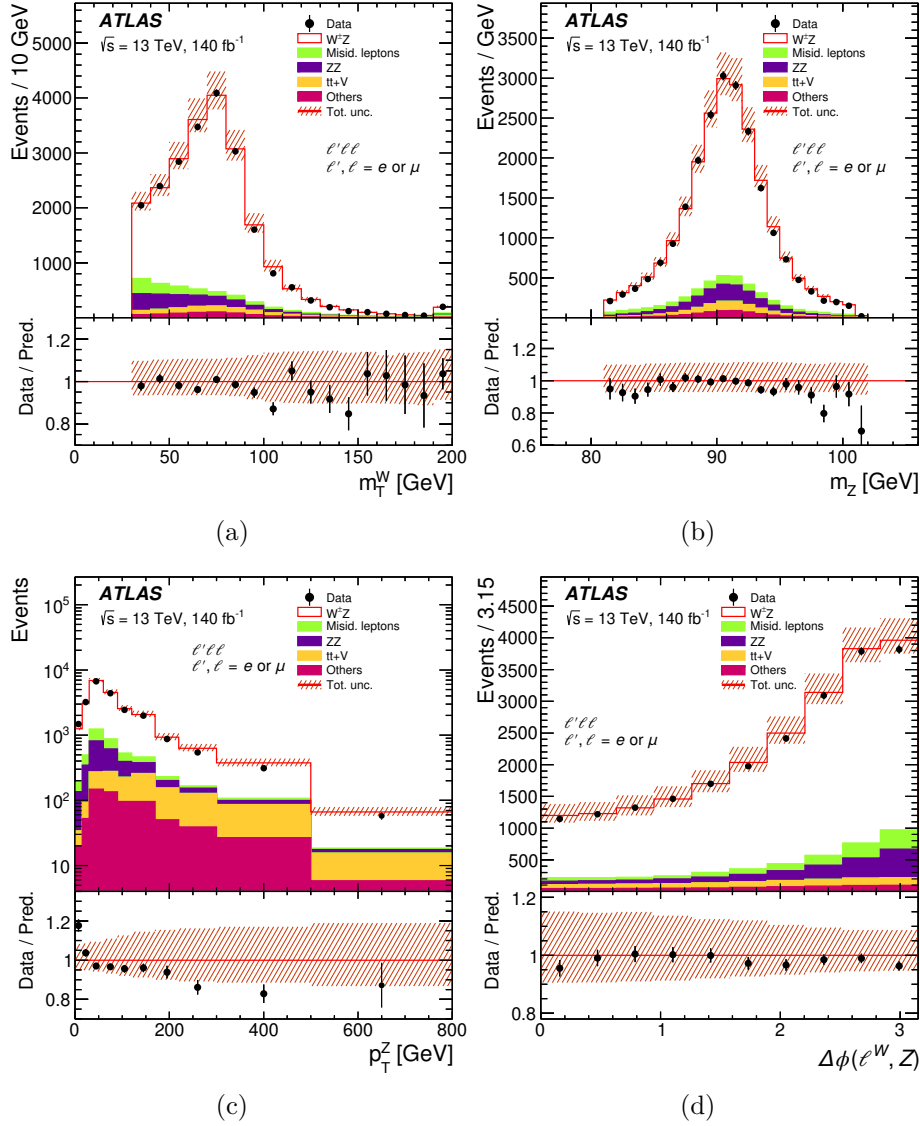


Figure 2. The distributions of observed and expected events after the $W^\pm Z$ inclusive selection described in section 4, for the sum of all channels, of the kinematic variables (a) m_T^W , (b) m_Z , (c) p_T^Z and (d) $\Delta\phi(\ell^W, Z)$. The points correspond to the data with the error bars representing the statistical uncertainties, and the histograms correspond to the predictions of the various SM processes. The sum of the background processes with misidentified leptons is labelled “Misid. leptons”. The SHERPA MC prediction is used for the $W^\pm Z$ signal contribution. The red histogram shows the total prediction; the shaded band is the total uncertainty in this prediction. The last bin in (a), (c) and (d) contains the overflow. The lower panels in each figure show the ratio of the data points to the open red histogram with their respective uncertainties.

8.2 Integrated cross-section measurements

The integrated $W^\pm Z$ cross-sections in the fiducial phase space are measured in each of the four channels. The combination of the $W^\pm Z$ cross-sections for the four channels yields a χ^2 per degree of freedom (dof) of $\chi^2/n_{\text{dof}} = 7.7/3$. The combinations of the $W^+ Z$ and $W^- Z$ cross-sections separately yield $\chi^2/n_{\text{dof}} = 1.9/3$ and $13.8/3$, respectively.

The $W^\pm Z$ production cross-section in the fiducial phase space resulting from the combination of the four channels including the W and Z branching ratio in a single leptonic channel with muons or electrons is

$$\sigma_{W^\pm Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}} = 60.7 \pm 0.5 (\text{stat.}) \pm 1.4 (\text{exp. syst.}) \pm 1.8 (\text{mod. syst.}) \pm 0.6 (\text{lumi.}) \text{ fb},$$

where the uncertainties correspond to statistical, experimental systematic, modelling systematic and luminosity uncertainties, respectively. The corresponding SM NNLO QCD $\times$ EW_{qq} prediction from MATRIX is $61.4 \pm 1.3 \text{ fb}$, where the uncertainty corresponds to the QCD scale uncertainty estimated conventionally by varying the scales μ_R and μ_F by factors of two around the nominal value with the constraint $0.5 \leq \mu_R/\mu_F \leq 2$. Changing the scheme used to combine QCD and EW corrections to NNLO QCD + EW increases the MATRIX prediction by +3%. Changing the PDF set used from NNPDF3.1NNLO_AS_118_LUXQED to MSHT20QED_NNLO_INELASTIC [102, 103] or CT18QED_PROTON_INELASTIC [104, 105] affects the MATRIX prediction by −1%.

In figure 3, the measured $W^\pm Z$ production cross-sections are compared with the SM NNLO QCD $\times$ EW_{qq} or NNLO QCD + EW predictions from MATRIX using the NNPDF3.1NNLO PDF set. The MATRIX prediction using the MSHT20NNLO PDF set is also represented. All results for $W^\pm Z$, $W^+ Z$ and $W^- Z$ final states are reported in table 4. Individual cross-section measurements in each channel are in agreement within their respective uncertainties. The MATRIX calculation at NNLO QCD $\times$ EW_{qq} reproduces well the measured cross-sections. The total uncertainty of 4% on the combined measurement is of the same order as the QCD scale uncertainty of 2% on the MATRIX prediction and as the difference of 3% in the predictions from the NNLO QCD $\times$ EW_{qq} or NNLO QCD + EW schemes.

The ratio of the $W^+ Z$ to $W^- Z$ production cross-sections is

$$\frac{\sigma_{W^+ Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}}}{\sigma_{W^- Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}}} = 1.456 \pm 0.025 (\text{stat.}) \pm 0.010 (\text{syst.}).$$

Most of the systematic uncertainties almost cancel out in the ratio, so that the measurement is dominated by the statistical uncertainty. The measured cross-section ratios, for each channel and for their combination, are compared in figure 4 with the SM prediction of $1.435^{+0.013}_{-0.014}$, calculated with MATRIX and the CT18NNLO PDF set. The same value of the cross-section ratio is predicted by the SHERPA MC simulation using the NNPDF3.0NNLO PDF set. The measured combined cross-section ratio is in agreement with the predictions. Measurements in the eee and μee channels are in agreement within 2σ with the predictions. The uncertainties in the predictions correspond to PDF uncertainties estimated at NLO with SHERPA using the NNPDF3.0NNLO eigenvectors and the envelope of the differences between the CT18NNLO, MSHT20NNLO and NNPDF3.1NNLO PDF sets. The effects of QCD scale uncertainties in the predicted cross-section ratio are negligible. The predicted cross-section

Channel	$\sigma^{\text{fid.}}$ [fb]	$\delta_{\text{stat.}}$ [%]	$\delta_{\text{exp. syst.}}$ [%]	$\delta_{\text{mod. syst.}}$ [%]	$\delta_{\text{lumi.}}$ [%]	$\delta_{\text{tot.}}$ [%]
$\sigma_{W^\pm Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}}$						
$e^\pm ee$	60.6	2.0	3.4	3.0	0.9	5.0
$\mu^\pm ee$	57.5	1.8	2.6	3.0	0.9	4.5
$e^\pm \mu\mu$	62.0	1.6	2.3	3.0	0.9	4.2
$\mu^\pm \mu\mu$	60.7	1.4	2.6	3.0	0.9	4.3
Combined	60.7	0.8	2.3	3.0	0.9	4.0
SM prediction	61.4	—	—	—	—	2.1
$\sigma_{W^+ Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}}$						
$e^+ ee$	37.0	2.6	3.1	3.0	1.0	5.1
$\mu^+ ee$	35.0	2.3	2.6	3.0	1.0	4.7
$e^+ \mu\mu$	36.1	2.2	2.1	3.0	1.0	4.4
$\mu^+ \mu\mu$	35.5	1.8	2.5	3.0	1.0	4.4
Combined	35.8	1.1	2.2	3.0	1.0	4.0
SM prediction	36.3	—	—	—	—	3.5
$\sigma_{W^- Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}}$						
$e^- ee$	23.9	3.3	3.7	3.0	1.1	5.9
$\mu^- ee$	22.5	2.9	2.8	3.0	1.1	5.1
$e^- \mu\mu$	25.9	2.6	2.5	3.0	1.1	4.8
$\mu^- \mu\mu$	25.2	2.2	2.8	3.0	1.0	4.8
Combined	24.8	1.3	2.6	3.0	1.1	4.3
SM prediction	25.1	—	—	—	—	5.1

Table 4. Fiducial integrated cross-section in fb, for $W^\pm Z$, $W^+ Z$ and $W^- Z$ production, measured in each of the channels eee , μee , $e\mu\mu$, and $\mu\mu\mu$ and for all four channels combined. The statistical ($\delta_{\text{stat.}}$), experimental systematic ($\delta_{\text{exp. syst.}}$), modelling systematic ($\delta_{\text{mod. syst.}}$), luminosity ($\delta_{\text{lumi.}}$) and total ($\delta_{\text{tot.}}$) uncertainties are given in percent. The NNLO QCD $\times$ EW_{qq} SM predictions from MATRIX using the NNPDF3.1NNLO_AS_118_LUXQED PDF set are also reported.

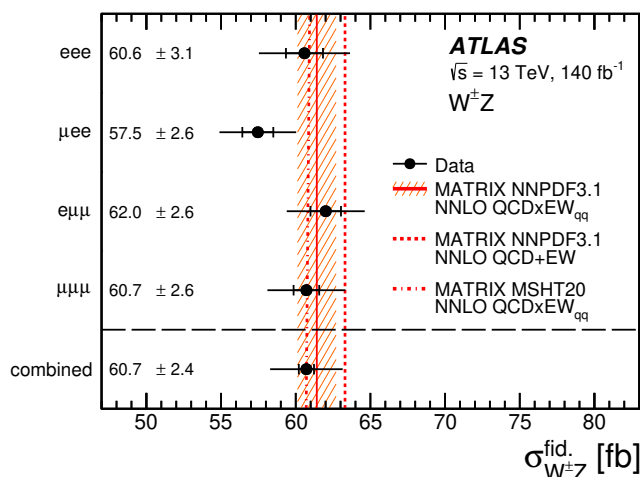


Figure 3. The measured $W^\pm Z$ integrated cross-sections in the fiducial phase space in each of the four channels and for their combination. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The NNLO QCD $\times$ EW_{qq} SM prediction from MATRIX using the NNPDF3.1NNLO_AS_118_LUXQED PDF set is shown as the red line; the shaded band shows the effect of QCD scale uncertainties on this prediction. The NNLO QCD+EW predictions from MATRIX is also represented by the dashed-red line, as well as the NNLO QCD $\times$ EW_{qq} MATRIX prediction using the MSHT20NNLO PDF set represented by the dotted-dashed red line.

ratio is also calculated with MATRIX using the NNPDF3.1NNLO PDF set, yielding a value of 1.447 as shown in figure 4. The total PDF uncertainties in the SM predictions from most recent PDF sets are 2% while the total measurement uncertainty in this cross-section ratio is 1.8%. This comparison indicates that more statistics will set significant constraints.

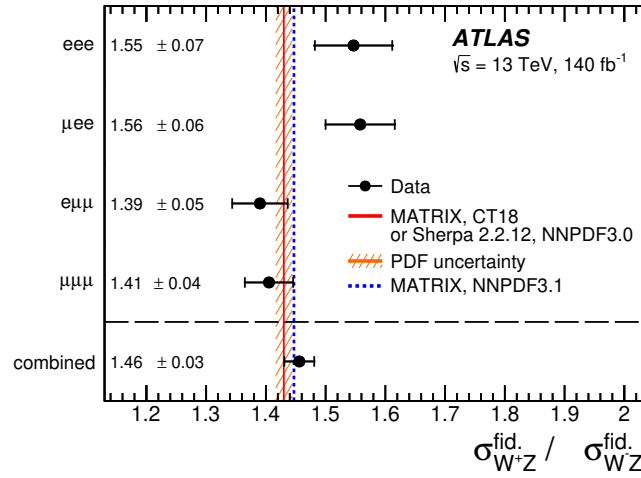


Figure 4. Measured ratio $\sigma_{W^+Z}^{\text{fid.}}/\sigma_{W^-Z}^{\text{fid.}}$ of W^+Z and W^-Z integrated cross-sections in the fiducial phase space in each of the four channels and for their combination. The error bars on the data points represent the total uncertainties, which are dominated by the statistical uncertainties. The NNLO QCD $\times$ EW_{qq} SM predictions from MATRIX using the CT18NNLO PDF set is represented as a single red line. It is equal to the prediction from SHERPA using the NNPDF3.0NNLO PDF set. The dashed band represents the effect of PDF uncertainties estimated by using the SHERPA prediction from the NNPDF3.0NNLO eigenvectors and the envelope of the differences between the CT18NNLO, MSHT20NNLO, NNPDF3.1NNLO and PDF4LHC15NNLO PDF sets. The MATRIX prediction displayed by the dashed-blue line is using the NNPDF3.1NNLO_AS_118_LUXQED PDF set.

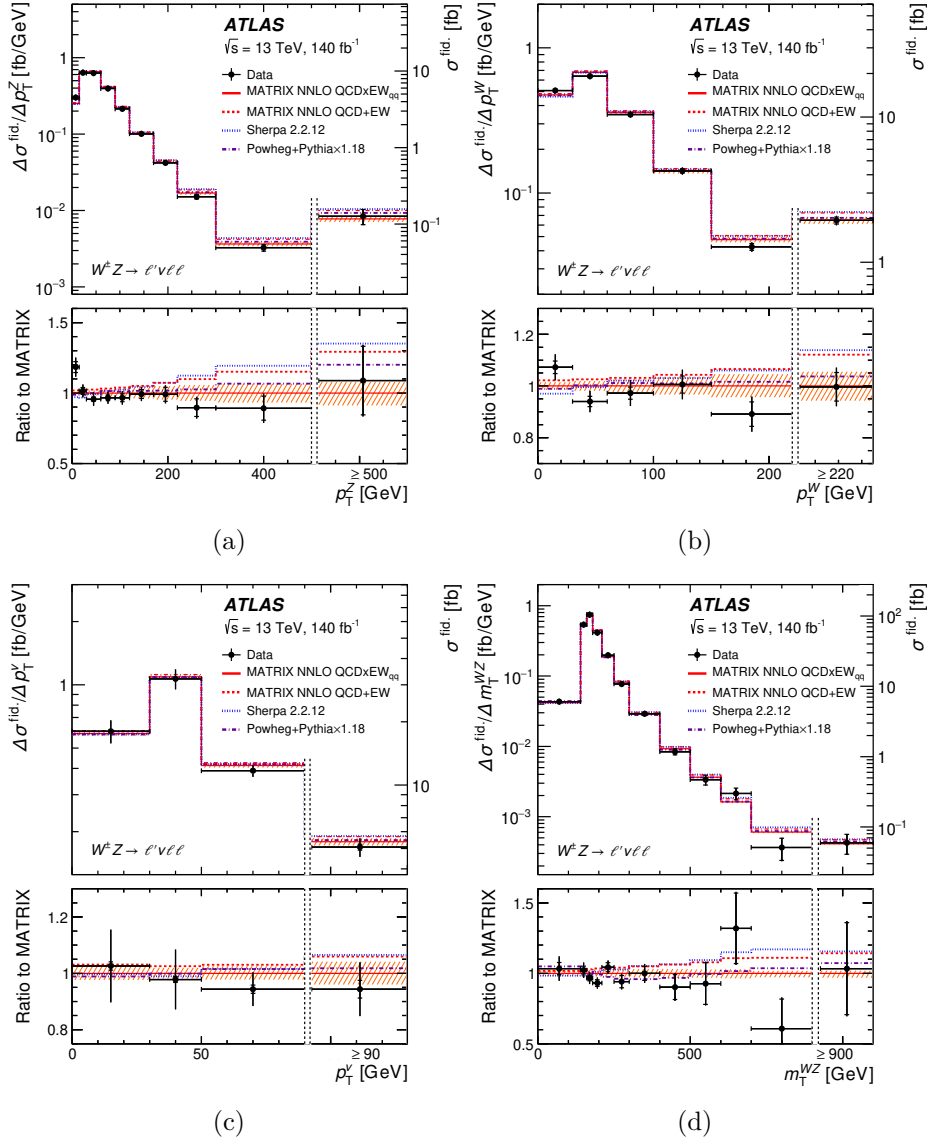


Figure 5. The measured $W^\pm Z$ differential cross-section in the fiducial phase space as a function of (a) p_T^Z , (b) p_T^W , (c) p_T^ν and (d) m_T^{WZ} . The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the prediction from MATRIX using either the NNLO QCD $\times$ EW_{qq} (red line) or the NNLO QCD + EW (dashed-red) line schemes. The shaded band shows how the QCD scale uncertainties affect the MATRIX predictions. The predictions from the SHERPA and POWHEG+PYTHIA MC generators are also indicated by dotted-blue and dotted-dashed violet lines, respectively. The right vertical axis refers to the last cross-section point, separated from the others by vertical dashed lines, as this last bin is integrated up to the maximum value reached in the phase space and the cross-section is not divided by the bin width.

8.3 Differential cross-section measurements

The $W^\pm Z$ production cross-section is measured as a function of several variables related to the energy of the $W^\pm Z$ system produced: the transverse momenta of the Z and W bosons, p_T^Z and p_T^W , the p_T of the neutrino associated with the decay of the W boson, p_T^ν

and the transverse mass of the $W^\pm Z$ system m_T^{WZ} , as presented in figure 5. The variable m_T^{WZ} is defined as follows:

$$m_T^{WZ} = \sqrt{\left(\sum_{\ell=1}^3 p_T^\ell + E_T^{\text{miss}}\right)^2 - \left[\left(\sum_{\ell=1}^3 p_x^\ell + E_x^{\text{miss}}\right)^2 + \left(\sum_{\ell=1}^3 p_y^\ell + E_y^{\text{miss}}\right)^2\right]}.$$

To derive p_T^W and p_T^Z from data events, it is assumed that the whole E_T^{miss} of each event arises from the neutrino of the W boson decay. The validity of this assumption was verified for SM WZ events using MC samples at the level of precision of the present results. The measured differential cross-sections in figure 5 are compared with the predictions from MATRIX. The predicted and measured cross-sections are in good agreement. The measurements are also compared with NLO MC predictions from POWHEG+PYTHIA, after a rescaling of its predicted integrated fiducial cross-section to the NNLO cross-section, and to SHERPA without rescaling its prediction. Good agreement of the shapes of the measured distributions with the predictions of POWHEG+PYTHIA and SHERPA is observed. As shown in previous publications, the high energy tails of the p_T^Z [11] and m_T^{WZ} [12] observables are sensitive to anomalous triple gauge couplings (aTGC), p_T^Z having the disadvantage of being more subject to higher-order perturbative effects in QCD [106] and electroweak theory [107]. This is also seen here with larger NNLO QCD scale uncertainties predicted by MATRIX for p_T^Z than for m_T^{WZ} . The difference between MATRIX predictions using the multiplicative or additive combination scheme for NLO EW corrections is also larger for p_T^Z than for m_T^{WZ} . No excess of data events in the tails of these distributions is observed. Deviations between data measurements and the theory predictions used are observed at low p_T^Z or p_T^W values. This is the manifestation in this kinematical regime of the domination of soft and collinear QCD radiations that cannot be described by the perturbative expansion in the strong coupling constant α_s . At low transverse momenta, a resummation of logarithmically-enhanced terms is required to obtain physical results [108, 109]. The description of resummation effects with PS algorithms depends on the set of tuned parameters used, as it can be observed in measurements of single Z or W production [110].

Differential cross-sections as a function of the transverse momenta of the harder boson, $p_T^{V_1}$, and of the softer boson, $p_T^{V_2}$, are presented in figure 6. The tail of the $p_T^{V_1}$ distribution is especially sensitive to effects of NLO EW corrections [30]. This is exemplified in figure 6(a) by the difference of 30% observed in the last bin of the differential $p_T^{V_1}$ cross-section between an additive combination of NNLO QCD and NLO EW correction, NNLO QCD + EW, and a factorised, NNLO QCD $\times$ EW_{qq}, combination prescription, as calculated using MATRIX [30]. The data measurements of both $p_T^{V_1}$ and $p_T^{V_2}$ have a slope falling more rapidly than predicted by SHERPA and MATRIX with the NNLO QCD + EW prescription, favouring therefore the NNLO QCD $\times$ EW_{qq} scheme. At very low p_T , the same mismodelling of data by present calculations as seen for p_T^Z and p_T^W observables is observed.

Angular observables sensitive to QCD higher-order perturbative effects are presented in figure 7: the absolute difference between the rapidities of the Z boson and the charged lepton from the decay of the W boson, $|y_Z - y_{\ell,W}|$, the difference between the azimuthal angle of the Z boson and the charged lepton from the decay of the W boson, $\Delta\phi(\ell^W, Z)$,

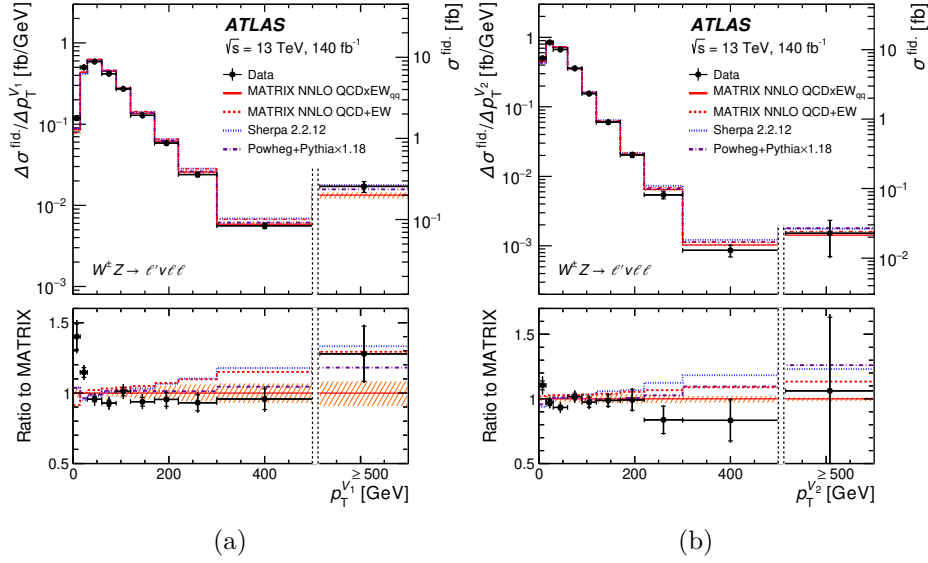


Figure 6. The measured $W^\pm Z$ differential cross-section in the fiducial phase space as a function of (a) p_T^{V1} and (b) p_T^{V2} . The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the prediction from MATRIX using either the NNLO QCD $\times$ EW_{qq} (red line) or the NNLO QCD + EW (dashed-red) line schemes. The shaded band shows how the QCD scale uncertainties affect the MATRIX predictions. The predictions from the SHERPA and POWHEG+PYTHIA MC generators are also indicated by dotted-blue and dotted-dashed violet lines, respectively. The right vertical axis refers to the last cross-section point, separated from the others by vertical dashed lines, as this last bin is integrated up to the maximum value reached in the phase space and the cross-section is not divided by the bin width.

and the azimuthal angle difference between the W and Z bosons, $\Delta\phi(W, Z)$. The rapidity correlations between the W and Z decay products have been found to be useful tools in searching for the approximately zero WZ helicity amplitudes expected at LO in the SM, or for aTGCs [111, 112]. These rapidity correlations are also sensitive to QCD corrections, PDF effects, and polarisation effects of the W and Z bosons. The rapidity difference between the W and Z bosons, $|y_Z - y_W|$, is a boost-invariant substitute for the centre-of-mass scattering angle θ of the W relative to the direction of the incoming quark. Since the rapidity of the W boson cannot be uniquely reconstructed due to the presence of the neutrino, the rapidity of the lepton from the W boson decay is used instead. The $\Delta\phi(\ell^W, Z)$ and $\Delta\phi(W, Z)$ observables are also sensitive to higher-order QCD scale corrections. An increase of the QCD scale uncertainties affecting the MATRIX prediction is observed at low values of $\Delta\phi(\ell^W, Z)$ and $\Delta\phi(W, Z)$. In this kinematical region, the prediction from SHERPA is seen to be very close to the MATRIX prediction, while the POWHEG prediction deviates more from MATRIX. Some difference between data and the prediction from MATRIX or SHERPA is observed. At low values of $|y_Z - y_{\ell, W}|$ and $\Delta\phi(W, Z)$ the predictions have a tendency to overestimate the measured cross-sections. The difference between data and predictions in these regions is not covered by QCD uncertainties alone, as estimated by using MATRIX. The difference observed could however arise from parton shower effects, as the difference of 3% between SHERPA and POWHEG MC predictions in the first bin in $|y_Z - y_{\ell, W}|$ seems to indicate. For

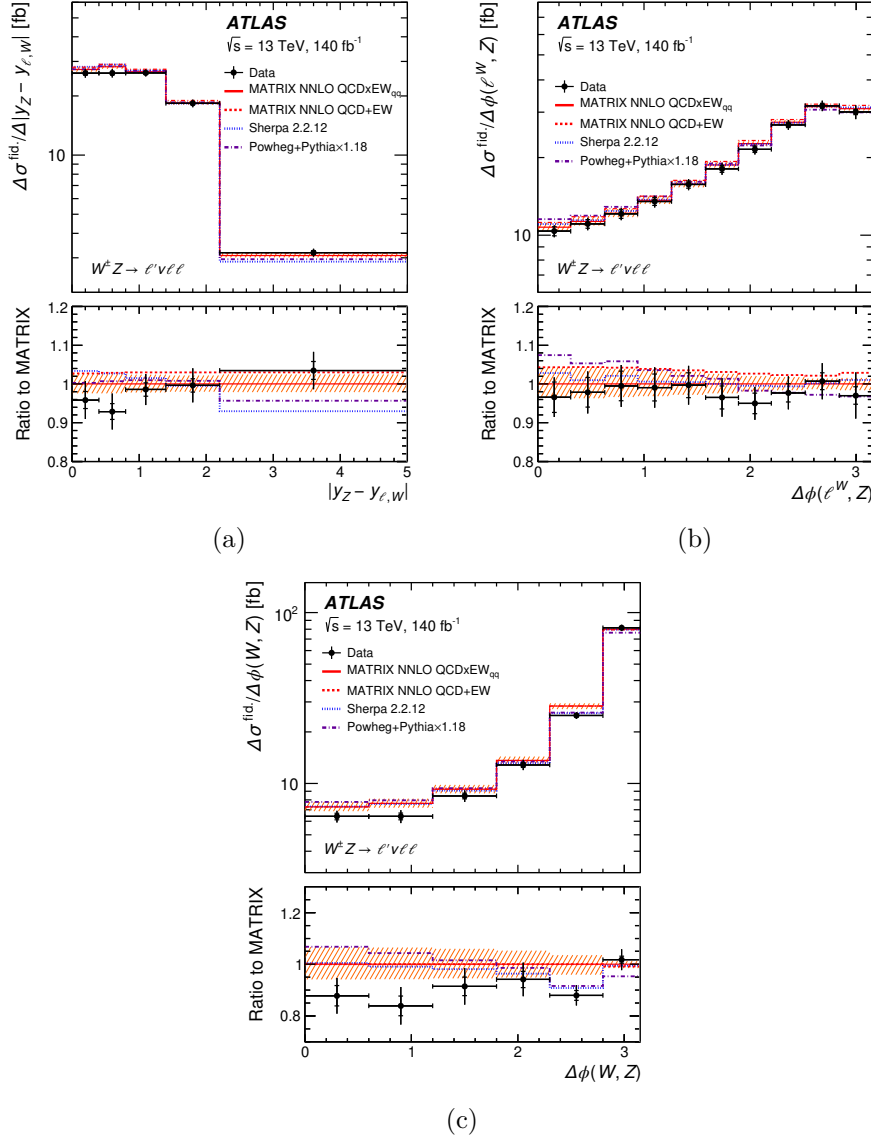


Figure 7. The measured $W^\pm Z$ differential cross-section in the fiducial phase space as a function of (a) $|y_Z - y_{\ell,W}|$, (b) $\Delta\phi(\ell^W, Z)$ and (c) $\Delta\phi(W, Z)$. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the prediction from MATRIX using either the NNLO QCD $\times$ EW $_{\text{qq}}$ (red line) or the NNLO QCD + EW (dashed-red) line schemes. The shaded band shows how the QCD scale uncertainties affect the MATRIX predictions. The predictions from the SHERPA and POWHEG+PYTHIA MC generators are also indicated by dotted-blue and dotted-dashed violet lines, respectively.

$\Delta\phi(\ell^W, Z)$ the difference at low values is covered by the QCD scale uncertainty derived for the MATRIX prediction. For these three observables, the difference in the treatment of NLO EW corrections is almost flat.

Differential cross-sections are also measured as functions of observables sensitive to possible CP-violation effects and presented in figure 8. These variables are also further used to look for effects that would arise from CP-odd EFT operators. The ϕ_W^* (ϕ_Z^*) angle

is defined following ref. [113] as the azimuthal angle of the charged (negatively charged) lepton resulting from the W (Z) boson decay between each boson decay plane and the $x - z$ plane in the centre-of-mass of the diboson system. The pseudorapidity of the W boson is reconstructed using an estimate of the longitudinal momentum of the neutrino obtained using the neural-network based method developed in ref. [16]. The triple product $p_{\perp}$ of three momenta, proposed in [114] for CP-violation studies, is defined as:

$$p_{\perp}(A, B, C) = \vec{p}_A \cdot \frac{\vec{p}_B \times \vec{p}_C}{|\vec{p}_B \times \vec{p}_C|}. \quad (8.1)$$

In all triple products the positively (negatively) charged lepton from the Z decay is denoted ℓ^+ (ℓ^-) while the lepton from the W decay is denoted ℓ^W regardless of its charge. The $\sum p^z$ notation represents the z components of the momenta resulting from the sum over the three final state leptons and the final state neutrino. Following this definition, two triple product observables are measured differentially: $p_{\perp}(\sum p^z, Z, \ell^W)$ and $p_{\perp}(\ell^{+,z}, \ell^-, \ell^W)$. Good agreement is observed between the measured cross-sections and the predictions for these four observables, as shown in figure 8. Any asymmetry observed around $\pi/2$ in the ϕ_W^* (ϕ_Z^*) distribution or around zero in the triple products distributions would be a hint for CP-violation effects in the weak-boson self-interactions.

The exclusive multiplicity of jets above a p_T threshold of 25 GeV unfolded at particle level is presented in figure 9(a). The measurements are compared with predictions from SHERPA, MADGRAPH+PYTHIA and POWHEG+PYTHIA. The SHERPA prediction provide a better description of the ratio of 0-jet to 1-jet event cross-sections than MADGRAPH+PYTHIA or POWHEG+PYTHIA. The MADGRAPH+PYTHIA prediction, which models up to two partons at NLO, tends to overestimate the cross-section of events with two or three jets, while SHERPA, which models only up to one parton at NLO, provides a slightly better description of data in these bins. Finally, the measured $W^{\pm}Z$ differential cross-section as a function of the invariant mass, m_{jj} , of the two leading jets with $p_T > 25$ GeV is presented in figure 9(b). All three MC predictions have difficulties in describing the data. A similar observation was made in the production of $W^{\pm}Zjj$ events in ref. [115].

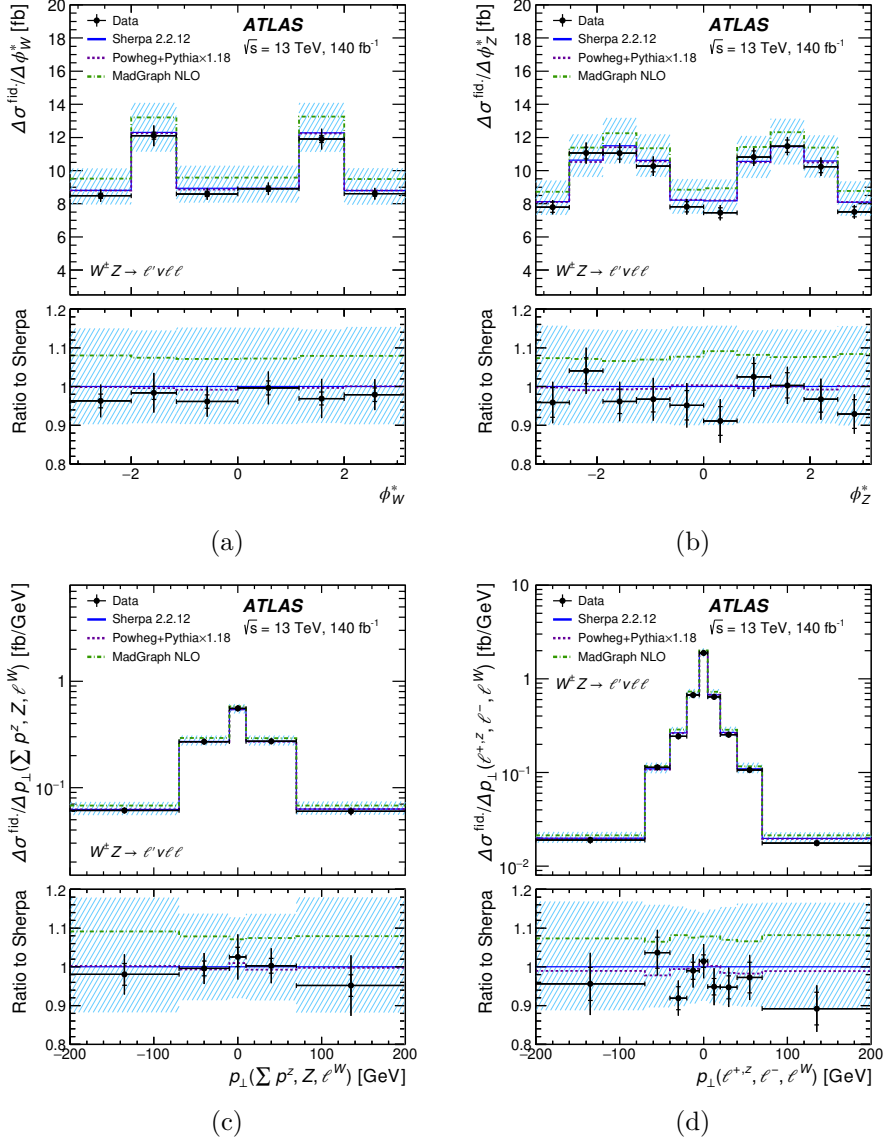


Figure 8. The measured $W^\pm Z$ differential cross-section in the fiducial phase space as a function of (a) ϕ_W^* , (b) ϕ_Z^* , (c) $p_\perp(\Sigma p^z, Z, \ell^W)$ and (d) $p_\perp(\ell^{+,z}, \ell^-, \ell^W)$. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the predictions from SHERPA (blue line), POWHEG+PYTHIA (dashed-violet line) and MADGRAPH+PYTHIA (dotted-dashed green line). The shaded band shows how the QCD scale uncertainties affect the SHERPA prediction.

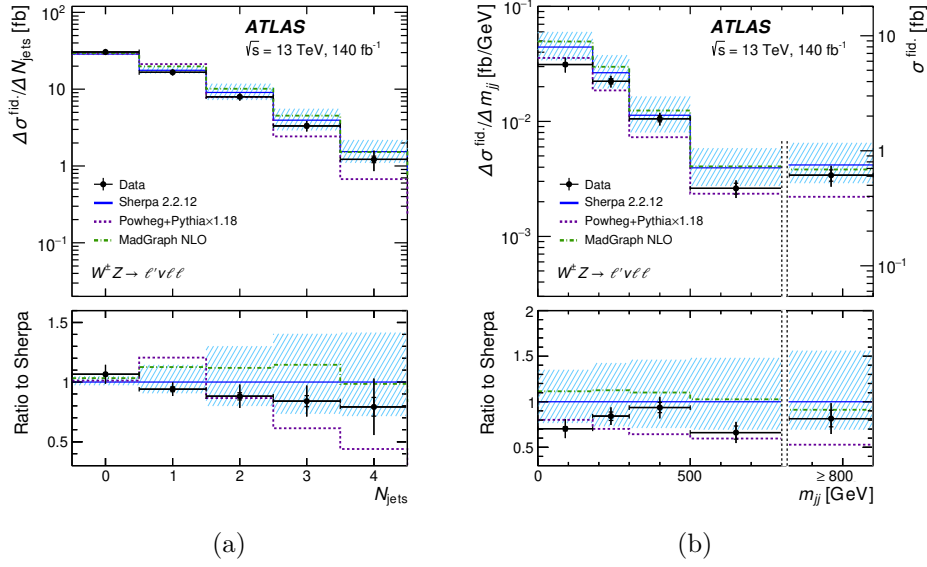


Figure 9. The measured $W^\pm Z$ differential cross-section in the fiducial phase space as a function of (a) the exclusive multiplicity of jets with $p_T > 25$ GeV and of (b) the invariant mass of the two leading jets with $p_T > 25$ GeV. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the predictions from SHERPA (blue line), POWHEG+PYTHIA (dashed-violet line) and MADGRAPH+PYTHIA (dotted-dashed green line). The shaded band shows how the QCD scale uncertainties affect the SHERPA prediction. In (b) the right vertical axis refers to the last cross-section point, separated from the others by vertical dashed lines, as this last bin is integrated up to the maximum value reached in the phase space and the cross-section is not divided by the bin width.

9 Constraints on anomalous interactions

9.1 SMEFT parameterisation

The measured detector-level distributions are used to constrain extensions to the SM that produce anomalous interactions. The anomalous interactions are introduced using an effective field theory (EFT) for which the Lagrangian is given by:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda_j^4} \mathcal{O}_j^{(8)} + \dots, \quad (9.1)$$

where $\mathcal{L}_{\text{SM}}$ contains the SM Lagrangian, extended with the addition of an effective Lagrangian $\mathcal{L}_{\text{EFT}}$. To comply with lepton and baryon number conservation, only operators of even dimensions are considered to construct $\mathcal{L}_{\text{EFT}}$. The terms $\mathcal{O}_i^{(6)}$ and $\mathcal{O}_j^{(8)}$ are dimension-6 and dimension-8 operators, respectively, involving only SM fields. The corresponding Wilson coefficients are denoted by $c_i^{(6)}/\Lambda_i^2$ and $c_j^{(8)}/\Lambda_j^4$. The analysis focuses on dimension-6 operators in the Warsaw basis [116], since anomalous effects from operators of higher dimensionality are more strongly suppressed by inverse powers of the new physics scale Λ .

Theoretical predictions are constructed using the Lagrangian in eq. (9.1). The amplitude for the $W^\pm Z$ process is split into an SM part and a dimension-6 part which contains the anomalous interactions. The squared amplitude which enters in the cross-section is:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \sum_i \frac{c_i}{\Lambda_i^2} 2\Re\{\mathcal{M}_{\text{SM}}^* \mathcal{M}_{i,6}\} + \sum_i \frac{c_i^2}{\Lambda_i^4} |\mathcal{M}_{i,6}|^2 + \sum_{i \neq j} \frac{c_i c_j}{\Lambda_i^2 \Lambda_j^2} 2\Re\{\mathcal{M}_{i,6}^* \mathcal{M}_{j,6}\}. \quad (9.2)$$

The first term in eq. (9.2) is the pure SM contribution. The second term, called the *linear term*, contains interferences between the SM and each considered SMEFT operator i , and is of order Λ^{-2} . The third term, of order Λ^{-4} , stands for the pure contributions of all single dimension-6 operators and is called the *quadratic term*. Finally, the fourth term represents interference terms between two different dimension-6 operators and are referenced as the *cross-term*.

Constraints are placed on the Wilson coefficients of three CP-conserving bosonic operators, O_W , O_{HWB} , O_{HD} and of two CP-violating bosonic operators, $O_{\tilde{W}}$ and $O_{H\tilde{W}B}$, as well as on the Wilson coefficients of operators, denoted $O_{Hq}^{(1)}$, $O_{Hq}^{(3)}$, describing fermion-boson interactions. The c_W/Λ^2 Wilson coefficient can only be measured in processes affected by modifications of the gauge-boson self couplings. Diboson measurements are therefore of particular interest to constrain it. Its effect increases rapidly with the centre-of-mass energy. However, in this regime, the SM amplitude and the anomalous amplitude are dominated by different helicity configurations, such that their interference is suppressed, reducing the impact of the operator on the measured cross-section [113, 117–119]. For CP-odd operators the interference with SM is expected to give no contribution to CP-even observables like m_T^{WZ} . The reduced sensitivity to the interference poses a problem for the truncation of the series at dimension-6 operators because contributions that depend on Λ^{-4} which are introduced by the interference between SM and dimension-8 operators, which are expected to be subdominant in the EFT expansion, cannot be safely neglected. Specific angular observables can be used to revive the interference [113, 114] and are exploited for CP-odd operators. For a more robust interpretation of the measurements, limits are therefore determined using parameterisations

that exclude or include the pure dimension-6 quadratic contributions, and are studied as a function of an upper energy cut-off on the SMEFT contributions [120].

The pure SM contribution to the $W^\pm Z$ differential cross-sections in eq. (9.2) is taken to be the prediction from SHERPA 2.2.12 described in section 3. The contributions arising from the interference and pure dimension-6 terms are generated at leading-order (LO) in perturbative QCD using MADGRAPH5_AMC@NLO 2.6.5, with the interactions from dimension-6 operators provided by the SMEFTSIM 3.0 package [121, 122]. A dynamic QCD scale is chosen, equal to the averaged sum of the two gauge-boson transverse masses and the m_W EW scheme is used. The `top` flavour scheme is chosen, implying that quarks from the third generation are described by independent fields with respect to the lighter quarks. The CKM matrix is considered diagonal and the only fermion assumed to be massive is the top quark. To account for the real part of NLO QCD corrections, these events are merged with events generated at LO in QCD using MADGRAPH5_AMC@NLO 2.6.5, containing three leptons, one neutrino and one jet in the final state. The merging procedure is done at the PS level using PYTHIA 8.240 in the CKKW-L scheme [123]. PYTHIA 8.240 is also used for the simulation of the hadronisation and underlying event. The NNPDF3.0NLO PDF set is used for the parton process generation. These MC sets are referred to as MADGRAPH 0,1j@LO samples in the following. They were passed through the ATLAS detector simulation and event reconstruction to be used in the determination of limits based on detector-level data.

For CP-even operators, the modelling of these samples is validated at particle-level against the predictions from SMEFTATNLO [124] interfaced with MADGRAPH5_AMC@NLO 2.9.9 which includes calculations up to next-to-leading-order in QCD for both SM and SMEFT contributions. The SMEFTATNLO simulation was used to verify that the difference between NLO and pure LO prediction, or between NLO and 0,1j@LO predictions, is not the same for the pure SM term and for the sum of the linear and quadratic EFT terms. The QCD corrections affecting the pure SM term are found to be larger than those related to the linear or quadratic terms. Therefore, any QCD correction derived from the pure SM simulation cannot be applied to the EFT contributions, in order to define a pseudo-NLO EFT MC simulation. Half of the difference between SMEFT MADGRAPH MC simulations at LO and at 0,1j@LO accuracy is used to define a modelling uncertainty affecting MC simulations of the linear and quadratic terms, accounting for missing higher-order QCD corrections. Using the SMEFTATNLO simulation, it is verified that this modelling uncertainty effectively covers the differences in shape and normalisation between the NLO and 0,1j@LO MC simulations for the sum of the linear and quadratic terms.

For CP-odd operators, such a validation procedure with SMEFTATNLO was not possible due to the lack of EFT models including CP-odd operators in SMEFTATNLO at that time. The model uncertainty affecting the simulation of CP-odd operators is thus defined in the same way as explained for CP-even operators.

9.2 Limits on CP-conserving operators

The effects of CP-conserving EFT operators are primarily expected to manifest themselves at high energies. A large range of kinematic observables was tested to enhance the sensitivity to CP-conserving EFT contributions in inclusive $W^\pm Z$ production, encompassing variables

	Expected [TeV ⁻²]		Observed [TeV ⁻²]	
	95% CL (lin.)	95% CL (lin.+quad.)	95% CL (lin.)	95% CL (lin.+quad.)
c_W/Λ^2	[-0.668, 0.733]	[-0.103, 0.095]	[-1.150, 0.181]	[-0.093, 0.079]
c_{HWB}/Λ^2	[-0.326, 0.412]	[-0.326, 0.413]	[-0.470, 1.440]	[-0.458, 1.520]
c_{HD}/Λ^2	[-8.107, 9.096]	[-4.494, 3.976]	[-18.0, 1.7]	[-5.840, 1.680]
$c_{Hq}^{(1)}/\Lambda^2$	[-1.994, 2.122]	[-2.923, 1.615]	[-0.367, 3.980]	[-0.503, 2.550]
$c_{Hq}^{(3)}/\Lambda^2$	[-0.097, 0.106]	[-0.145, 0.074]	[-0.146, 0.0275]	[-0.165, 0.015]

Table 5. Expected and observed 95% CL intervals on CP-even Wilson coefficients. Limits are presented using parameterisations excluding (“lin.”) and including (“lin.+quad.”) the pure dimension-6 contributions, respectively. Only one Wilson coefficient is permitted to vary from zero at a time.

related to the energy of the $W^\pm Z$ system, angular distributions of the final-state leptons, polarisation-related observables, as well as various multivariate combinations of them. Among all options investigated, the m_T^{WZ} observable is found to provide the best sensitivity to effects of CP-even EFT operators. Effects arising from higher-order QCD or EW corrections are also minimised in differential distributions of this observable. The distribution of observed events as a function of m_T^{WZ} , as represented in figure 10, is used to define an extended binned likelihood function consisting of a product of Poisson probability terms over bins of the m_T^{WZ} distribution [125]. The bin boundaries are optimised to obtain the best expected limits. Experimental and theory uncertainties, as discussed in section 7, are included as Gaussian-constrained nuisance parameters. Confidence intervals for a given c_i are determined using a profile-likelihood-ratio test statistic [126], which is assumed to be χ^2 -distributed according to Wilks’ theorem [127]. The validity of the χ^2 -approximation is confirmed using pseudo-experiments. For each individual c_i , or pair (c_i, c_j) for two-dimensional limits, a separate fit is performed, setting other coefficients to zero. Possible effects of the probed SMEFT operator on the background predictions are not considered. While detector-level distributions are expected to provide the highest sensitivity to BSM effects, the unfolded differential distribution of m_T^{WZ} was also used to derive limits. For all operators better or comparable limits are obtained using the detector-level distribution.

Expected and observed 95% confidence level (CL) intervals on CP-conserving Wilson coefficients are summarised in table 5. Limits are derived considering either only linear contributions, arising from the interference between SM and BSM amplitudes, or also including quadratic terms, i.e. including effects from pure BSM amplitudes. Considering cross-terms between SMEFT operators, two-dimensional limits at 95% CL on two pairs of operators, $(O_W, O_{Hq}^{(3)})$ and (O_W, O_{HWB}) , are also obtained and presented in figure 11.

All observed limits are compatible with the $c_i = 0$ assumption at 95% CL, indicating that no significant deviations from the SM are observed. Limits on c_{HWB}/Λ^2 , $c_{Hq}^{(3)}/\Lambda^2$, $c_{Hq}^{(1)}/\Lambda^2$, and, to a lower extent, on c_{HD}/Λ^2 , are driven by interference effects, as the expected sensitivity is not strongly affected by the inclusion of the quadratic term. Interference effects manifest at intermediate m_T^{WZ} values, between 500 GeV and 1 TeV. The deficit of observed data events in the region from 700 to 900 GeV induces, therefore, asymmetric observed

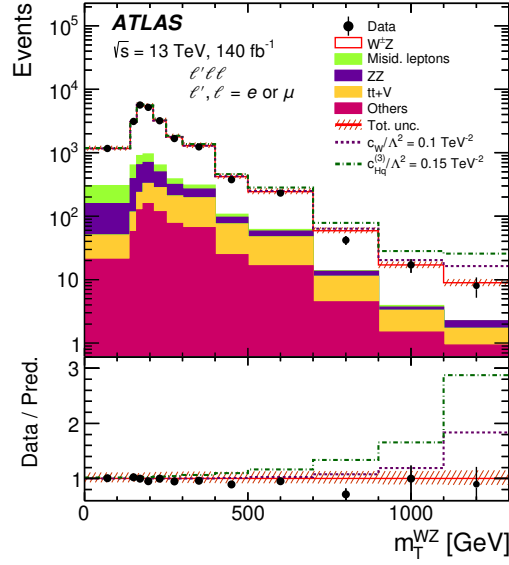


Figure 10. Detector-level distribution of m_T^{WZ} used to obtain limits on all CP-even EFT Wilson coefficients. The points correspond to the data with the error bars representing the statistical uncertainties, and the histograms correspond to the predictions of the various SM processes. The sum of the background processes with misidentified leptons is labelled “Misid. leptons”. The SHERPA MC prediction is used for the $W^\pm Z$ signal contribution. The open red histogram shows the total prediction; the shaded band is the total uncertainty of this prediction. The lower panel shows the ratio of the data points to the open red histogram with their respective uncertainties. For illustration purposes, the predicted contributions of the O_W and $O_{Hq}^{(3)}$ operators with values of the corresponding Wilson coefficients of 0.1 TeV^{-2} and 0.15 TeV^{-2} , respectively, are also represented. The parameterisation including the pure dimension-6 contribution is used.

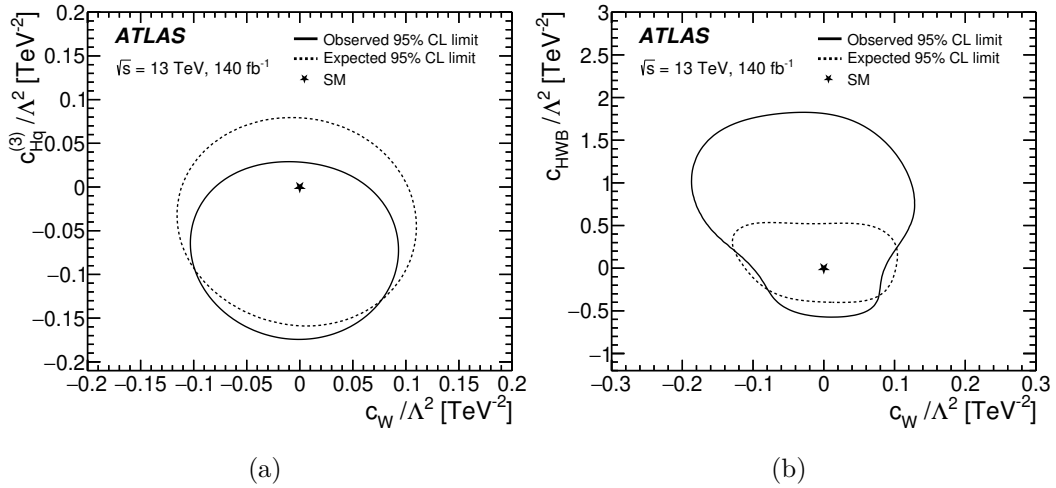


Figure 11. Two-dimensional expected (dashed line) and observed (solid line) 95% CL intervals on Wilson coefficients corresponding to the pairs of (a) $(O_W, O_{Hq}^{(3)})$ and (b) (O_W, O_{HWB}) operators. The parameterisation including the pure dimension-6 contribution is used.

Cut-off value on m_{WZ} [GeV]			
	1000	1500	no cut-off
c_W/Λ^2 [TeV ⁻²]	[-0.236, 0.208]	[-0.143, 0.130]	[-0.103, 0.095]
$c_{Hq}^{(3)}/\Lambda^2$ [TeV ⁻²]	[-0.286, 0.119]	[-0.195, 0.086]	[-0.145, 0.074]

Table 6. Evolution of the expected 95% CL intervals on CP-even c_W/Λ^2 and $c_{Hq}^{(3)}/\Lambda^2$ Wilson coefficients as a function of an upper energy cut-off on m_{WZ} in the SMEFT contribution. Limits are presented considering both the linear and quadratic contributions. Only one Wilson coefficient is permitted to vary from zero at a time.

limits for these Wilson coefficients. The limit on c_W/Λ^2 is predominantly determined by the quadratic contributions. The corresponding confidence intervals are therefore only valid for BSM models where contributions from dimension-8 operators are small with respect to the quadratic effects in dimension six. The range of validity of the EFT approach must be assessed, since arbitrary growth of dimension-6 contributions at high energies leads to nonphysical results and to violations of unitarity in the underlying quantum field theory. Following recommendations from the LHC EFT Working Group [120], confidence intervals are also derived as a function of an upper energy cut-off on the SMEFT contributions. The diboson invariant mass m_{WZ} , which represents to a good approximation the total energy of the interaction per event, is used to remove the SMEFT events at particle-level predicted above a certain threshold. Confidence intervals were derived for cut-off values of 1 TeV, 1.5 TeV and above. Only confidence intervals on c_W/Λ^2 and $c_{Hq}^{(3)}/\Lambda^2$ show a significant dependence on the cut-off value. The extracted limits on these two Wilson coefficients are presented in table 6. They are found to have only a mild dependence on the applied cut-off after a value of 1.5 TeV, degrading when lower cut-off values are applied. This result provides reassurance that the nominal limits, obtained without any cut-off procedure, do not suffer from issues related to the region of validity of the EFT model.

The sensitivity to $c_{Hq}^{(3)}/\Lambda^2$ and $c_{Hq}^{(1)}/\Lambda^2$ is nearly one order of magnitude worse than that achieved in direct Higgs boson production measurements [128–130] or in global fits combining Higgs, top-quark, and electroweak boson production [131, 132], where electroweak precision data is included [133]. A similar sensitivity as seen in W^+W^- production [134] is obtained for these Wilson coefficients. The limits extracted on the anomalous triple-gauge-coupling Wilson coefficient c_W surpass in sensitivity those obtained in global fits [131, 132], $H \rightarrow \gamma\gamma$ production [130], and in other diboson processes such as $W^\pm W^\mp$ [134] by roughly a factor of two, showing a similar level of sensitivity than measurements performed by the CMS collaboration in $W\gamma$ [135] and $W^\pm Z$ production [19].

Variable	S _p or S _n	S ₀
$p_T^{V_2}/p_T^{V_1}$	✓	
m_T^{WZ}	✓	✓
m_T^W		✓
p_T^{WZ}	✓	
E_T^{miss}	✓	
$p_\perp(\sum p^z, Z, \ell^W)$	✓	✓
$p_\perp(W, \ell^+, \ell^W)$	✓	✓
$p_\perp(W, \ell^-, \ell^W)$	✓	✓
$p_\perp(\ell^{-,z}, \ell^W, \ell^+)$		✓
$p_\perp(\ell^{+,z}, \ell^-, \ell^W)$		✓
ϕ_Z^*	✓	✓
ϕ_W^*		✓
$ \cos \theta_V $	✓	✓
$\cos \theta_{\ell^W}^*$	✓	✓
$\cos \theta_{\ell^Z}^*$		✓
$\cos \chi$		✓
$\Delta\phi(\ell^W, \ell^Z)^{ss}$	✓	
$\Delta\phi(\ell^W, Z)$		✓
$ y_Z - y_{\ell, W} $	✓	✓

Table 7. Input variables used for the three BDTs trained to separate effects of CP-odd EFT operators from the SM. The variables m_T^W , m_T^{WZ} , $|y_Z - y_{\ell, W}|$, $\Delta\phi(\ell^W, Z)$, ϕ_W^* , ϕ_Z^* and the triple products $p_\perp$ from three momenta are described in sections 8.1 and 8.3. The variables $\cos \theta_{\ell^W}^*$ and $\cos \theta_{\ell^Z}^*$ are the cosines of the decay angle of the charged lepton in the W or Z rest frame relative to the W or Z direction in the $W^\pm Z$ centre-of-mass frame [16]. The variable $|\cos \theta_V|$ is the cosine of the scattering angle of the W or Z boson in the WZ centre-of-mass frame, calculated relative to the beam axis [16]. The variable $\cos \chi$ is the cosine of the angle between the decay planes of both bosons taken in the WZ rest frame. The variable $\Delta\phi(\ell^W, \ell^Z)^{ss}$ is the difference in azimuthal angle between the two decay leptons of same sign from the W and Z bosons.

9.3 Limits on CP-violating operators

For CP-odd operators, the interference between the SM amplitude and the dimension-6 amplitude is also CP-odd. Therefore, interference effects cancel out entirely for CP-even observables, such as inclusive cross-sections or transverse momentum distributions. Interference effects however induce asymmetries in appropriately constructed CP-odd observables [114]. This asymmetry is a powerful tool to constrain the Wilson coefficients via a fit. It can be enhanced using multivariate techniques to construct a CP-odd observable resulting from the combination of different high-level variables.

The interference between SM and CP-violating EFT operators integrated over the total phase space brings a zero contribution to the total cross-section of the process. This means that the interference term can be modelled either as a positive or a negative contribution to the differential cross-section, depending on the region of the phase space. This is translated in the MC as events generated with a negative weight. Exploiting this sign difference of MC event weights, a multivariate approach is developed that combines angular and energy-dependent observables to construct an optimised CP-sensitive observable. Following ideas from refs. [136–138], MC event samples of the interference between the $O_{H\tilde{W}B}$ or $O_{\tilde{W}}$ EFT operators and the SM are used to train three different boosted decision trees (BDT), as implemented in the TMVA package [139]. Events from the EFT MC simulation are separated into two sets of positively and negatively-weighted events. A first BDT is trained to separate events generated with a positive weight from events generated with a negative weight. It combines single angular observables sensitive to CP-violation and outputs a score, called S_0 , which enhances the asymmetry specific to CP-violation already present in each input observable. Two other BDTs are trained to discriminate EFT events from pure SMs $W^\pm Z$ production. One BDT, with an output score S_p , separates positively-weighted EFT MC events from SM events, while the second BDT, with an output score S_n , is used for negatively-weighted EFT events. Input variables used in the training of each of the three BDTs are detailed in table 7. The same input variables are used for S_p and S_n BDTs. Detector-level distributions of S_0 for SM $W^\pm Z$ events and for interference contributions of the $O_{H\tilde{W}B}$ and $O_{\tilde{W}}$ EFT operators are compared in figure 12. The S_0 distribution of SM $W^\pm Z$ events is symmetric, with values peaking around zero, while the distribution of the interference contributions of EFT CP-odd operators is asymmetric around zero. This behaviour is further enhanced by combining the three BDT scores to form a combined observable S_{comb} as

$$S_{\text{comb}} = \frac{S_p + 1}{2} \times \frac{S_n + 1}{2} \times S_0.$$

As observed in figure 12, the asymmetry between SM and EFT interference events is enhanced by a factor of about eight in S_{comb} compared with S_0 . A specific training of the BDTs is used for each of the two different $O_{H\tilde{W}B}$ and $O_{\tilde{W}}$ operators, as the kinematic properties of their interference term distributions are different.

As non-zero EFT contributions also enhance the $W^\pm Z$ production at large diboson invariant masses, further sensitivity to EFT effects is gained by separating events in two different categories, with m_T^{WZ} smaller or greater than 600 GeV. Detector-level events distributed according to S_{comb} and m_T^{WZ} are thus used to look for EFT CP-odd effects.

Nine bins in the S_{comb} observable ($[-1, -0.4, -0.2, -0.1, -0.02, 0.02, 0.1, 0.2, 0.4, 1]$) are used. The bin boundaries are optimised to obtain the best expected limits. The nine bins in S_{comb} for the two categories in m_T^{WZ} are arranged in a one-dimensional histogram of 18 statistically independent bins, as represented in figure 13. The distribution is used to define an extended likelihood function. Similarly to section 9.2, a profile-likelihood-ratio test statistic is constructed to estimate the confidence intervals for a given c_i .

No deviation with respect to the SM predictions is observed and the expected and observed 95% CL lower and upper limits on the given Wilson coefficients are presented in table 8. The use of the S_{comb} observable improves the expected limits by factors of 2.5 and

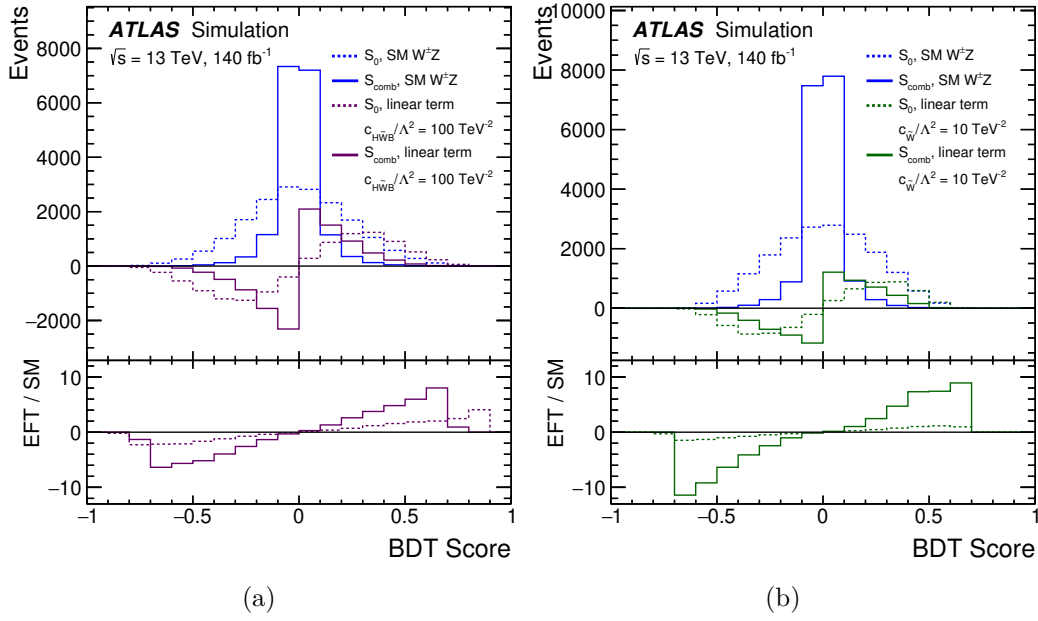


Figure 12. Comparison of the detector-level S_0 (dashed line) and S_{comb} (solid line) BDT score distributions for SM and interference events from the (a) $O_{H\tilde{W}B}$ and (b) $O_{\tilde{W}}$ operators. The lower panels in each figure show the ratio of the EFT contribution to the SM. For better visibility, large values of the Wilson coefficients are used to represent the interference distributions of $O_{H\tilde{W}B}$ and $O_{\tilde{W}}$ operators.

2.9 for $c_{H\tilde{W}B}/\Lambda^2$ and $c_{\tilde{W}}/\Lambda^2$, respectively, compared to using a single observable like m_T^{WZ} or a triple product. For the $c_{\tilde{W}}/\Lambda^2$ coefficient, the S_{comb} observable brings an important sensitivity to the linear term alone that is not possible to reach using a single observable. This makes the results less sensitive to missing higher-order operators in the EFT expansion. The $c_{H\tilde{W}B}/\Lambda^2$ coefficient is itself completely constrained by the contribution from the linear term.

Limits obtained on $c_{\tilde{W}}/\Lambda^2$ are comparable to those derived from VBF Z measurements [21]. The limit on $c_{H\tilde{W}B}$ is only slightly weaker by a factor of 1.5 to 2 than what is obtained in VBF Z or Higgs measurements [23, 24, 26]. However, the limit derived from $H \rightarrow WW^*$ measurements is completely dominated by effects of the quadratic term, while in VBF Z production and in the present result the limit purely results from effects of the linear term.

Confidence intervals on CP-conserving and CP-violating operators are summarised together in figure 14. Results for CP-conserving and CP-violating operators are also presented in figure 15 in terms of upper limits on the scale of new physics Λ assuming different input values of $c_i = 0.01, 1.0, (4\pi)^2$ and symmetrising the confidence intervals.

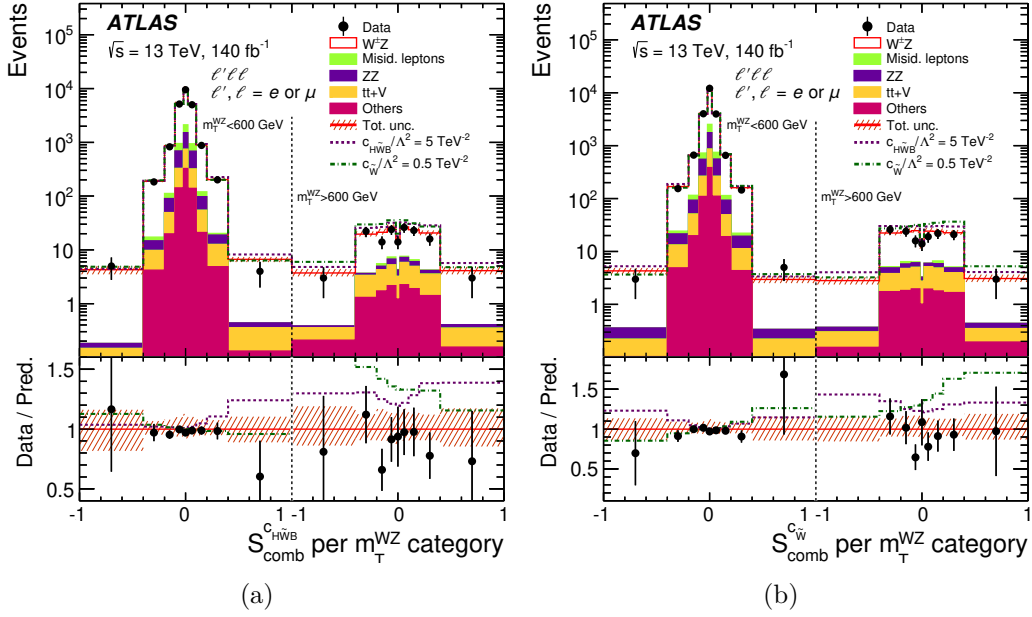


Figure 13. Detector-level one-dimensional distributions of the S_{comb} observable in two m_T^{WZ} categories used to obtain limits on (a) $c_{H\bar{W}B}$ and (b) $c_{\bar{W}}$ EFT Wilson coefficients. The points correspond to the data with the error bars representing the statistical uncertainties, and the histograms correspond to the predictions of the various SM processes. The sum of the background processes with misidentified leptons is labelled “Misid. leptons”. The SHERPA MC prediction is used for the $W^\pm Z$ signal contribution. The open red histogram shows the total prediction; the shaded band is the total uncertainty of this prediction. The lower panels in each figure show the ratio of the data points to the open red histogram with their respective uncertainties. For illustration purposes, contribution of the $O_{H\bar{W}B}$ and $O_{\bar{W}}$ operators with values of the corresponding Wilson coefficients of 5 TeV^{-2} and 0.5 TeV^{-2} , respectively, are also represented. The parameterisation including the pure dimension-6 contribution is used.

	Expected [TeV^{-2}]		Observed [TeV^{-2}]	
	95% CL (lin.)	95% CL (lin.+quad.)	95% CL (lin.)	95% CL (lin.+quad.)
$c_{H\bar{W}B}/\Lambda^2$	[-1.463, 1.456]	[-1.458, 1.459]	[-1.625, 1.332]	[-1.505, 1.263]
$c_{\bar{W}}/\Lambda^2$	[-0.162, 0.162]	[-0.127, 0.128]	[-0.186, 0.139]	[-0.109, 0.093]

Table 8. Expected and observed 95% CL intervals for CP-odd Wilson coefficients. Limits are presented using parameterisations excluding (“lin.”) and including (“lin.+quad.”) the pure dimension-6 contributions, respectively. Only one Wilson coefficient is constrained at a time.

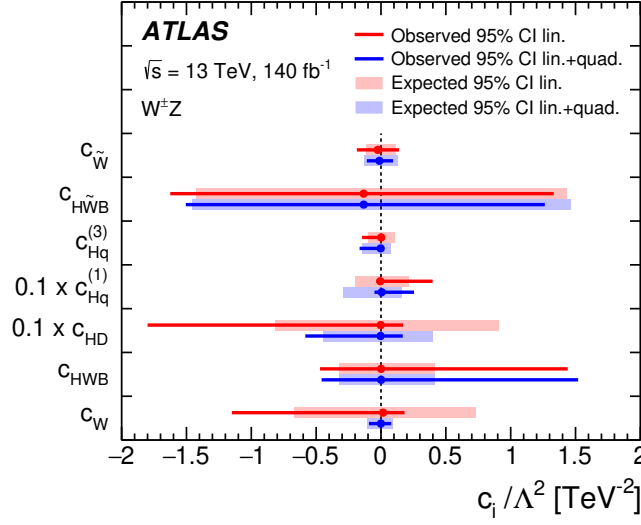


Figure 14. The observed and expected values of the Wilson coefficients from CP-even and CP-odd operators obtained with only one Wilson coefficient left floating at a time in the fit while all others are set to zero. The horizontal bands (bars) represent the expected (observed) intervals at 95% CL using the parameterisations excluding (“lin.”) and including (“lin.+quad.”) the pure dimension-6 contributions, respectively. For the observed intervals, the point represent the best-fit values. The values of c_{HD}/Λ^2 and $c_{Hq}^{(1)}/\Lambda^2$ are scaled by a factor of 0.1.

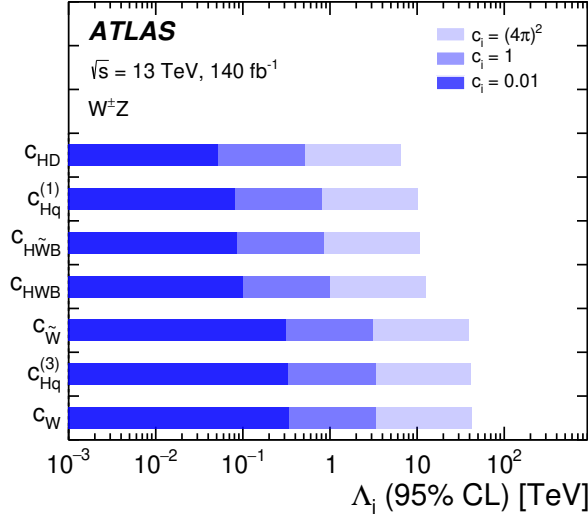


Figure 15. Observed exclusion limits at 95% CL on the scale of new physics Λ for different values of the anomalous coupling strength c_i . The parameterisation including the pure dimension-6 contribution is used.

10 Conclusion

Measurements of $W^\pm Z$ production cross-sections in $\sqrt{s} = 13$ TeV pp collisions at the LHC are presented. The data analysed were collected with the ATLAS detector from 2015 to 2018 and correspond to an integrated luminosity of 140 fb^{-1} . The measurements use leptonic decay modes of the gauge bosons into electrons or muons and are performed in a fiducial phase space closely matching the detector acceptance. The measured inclusive cross-section in the fiducial region for leptonic decay modes (electrons or muons) is measured with a relative precision of 4% and yields $\sigma_{W^\pm Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}} = 60.7 \pm 0.5 \text{ (stat.)} \pm 2.3 \text{ (syst.)} \pm 0.6 \text{ (lumi.) fb}$, in agreement with the Standard Model MATRIX prediction of $61.4 \pm 1.3 \text{ (scale) fb}$ at NNLO QCD $\times$ EW_{qq}. The ratio of the cross-sections for $W^+ Z$ and $W^- Z$ production is also measured. Differential $W^\pm Z$ production cross-sections are measured as functions of several kinematic variables and compared with SM predictions at NNLO QCD and NLO EW precision from the MATRIX calculation and from the SHERPA and POWHEG+PYTHIA MC event generators. The differential cross-section distributions are fairly well described by the theory predictions, except at low transverse momenta of the bosons where resummed calculations would be needed to describe data. Measurements from the tail of the transverse momentum of the harder boson, $p_T^{V_1}$, tend to favour the multiplicative NNLO QCD $\times$ EW_{qq} scheme for the combination of NNLO QCD corrections with NLO EW corrections instead of the additive one.

New observables sensitive to CP-violation effects are also measured for the first time in $W^\pm Z$ production. An effective field theory interpretation of the measurements is performed, considering a set of both CP-conserving and CP-violating dimension-6 operators impacting the $W^\pm Z$ production. Limits are extracted on CP-conserving Wilson coefficients using the transverse mass of the $W^\pm Z$ system. For CP-violating coefficients a novel machine learning approach is used to design an observable with enhanced sensitivity to CP-violation effects, allowing a significant improvement in sensitivity compared to the use of a single kinematic variable. The limit obtained on the CP-even bosonic coupling operator is comparable to previously existing limits from single measurements. Limits reached on CP-odd operators have the same sensitivity as the best existing limits derived from other final states, and therefore bring new complementary information.

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