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Measurements of electroweak $W^{\pm}Z$ boson pair production in association with two jets 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 electroweak $W^{\pm}Z$ production in association with two jets ($W^{\pm}Zjj$) 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 $W^{\pm}Zjj$ candidate events are reconstructed using leptonic decay modes of the gauge bosons. Events containing three identified leptons, either electrons or muons, and two jets are selected. Processes involving pure electroweak $W^{\pm}Zjj$ production at Born level are separated from $W^{\pm}Zjj$ production involving a strong coupling. The measured integrated fiducial cross-section of electroweak $W^{\pm}Zjj$ production per lepton flavour is $\sigma_{WZjj-\mathrm{EW}\to\ell'\nu\ell\ell jj} = 0.368 \pm 0.037\,(\text{stat.}) \pm 0.059\,(\text{syst.}) \pm 0.003\,(\text{lumi.})$ fb, where ℓ and ℓ' are either an electron or a muon. Respective cross-sections of electroweak and strong $W^{\pm}Zjj$ production are measured separately for events with exactly two jets or with more than two jets, and in three bins of the invariant mass of the two jets. The inclusive $W^{\pm}Zjj$ production cross-section, without separating electroweak and strong production, is also measured to be $\sigma_{WZjj\to\ell'\nu\ell\ell jj} = 1.462 \pm 0.063\,(\text{stat.}) \pm 0.118\,(\text{syst.}) \pm 0.012\,(\text{lumi.})$ fb, per lepton flavour. The inclusive $W^{\pm}Zjj$ production cross-section is measured differentially for several kinematic observables. Finally, the measurements are used to constrain anomalous quartic gauge couplings by extracting 95% confidence level intervals on dimension-8 operators.

Keywords: Beyond Standard Model, Hadron-Hadron Scattering, Proton-Proton Scattering, Vector Boson Production

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Contents

1 Introduction

Vector boson scattering (VBS), $VV \to VV$ with $V = W/Z/\gamma$, is a key process with which to probe the $\mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$ gauge symmetry of the electroweak (EW) theory that determines the self-couplings of the vector bosons. New phenomena beyond the Standard Model (SM) can alter the couplings of vector bosons, generating additional contributions to quartic gauge couplings compared with the SM predictions [1–3].

In proton-proton collisions, VBS is initiated by an interaction of two vector bosons radiated from the initial-state quarks, yielding a final state with two bosons and two jets, $VVjj$, in a purely electroweak process [4]. VBS diagrams are not independently gauge invariant and cannot be studied separately from other processes leading to the same $VVjj$ final state [5]. Two categories of processes give rise to $VVjj$ final states. The first category, which includes VBS contributions, involves exclusively weak interactions at Born level of order

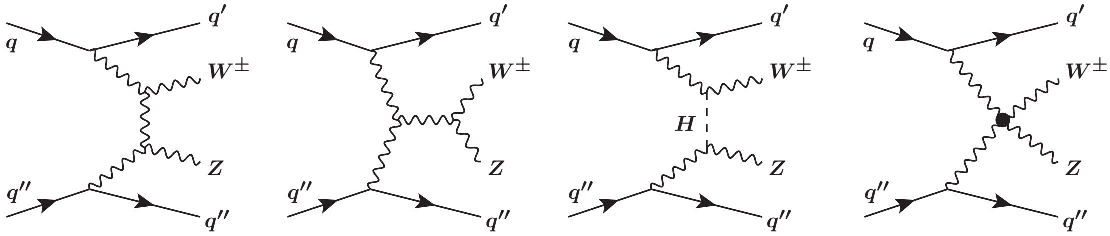

Figure 1. Representative diagrams at LO of the $WZjj$−EW production in pp collisions.

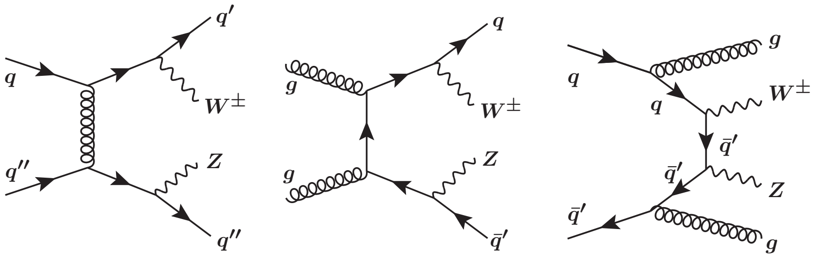

Figure 2. Representative diagrams at LO of the $WZjj$−QCD production in pp collisions.

$\alpha_{\rm EW}^6$ including the boson decays, where $\alpha_{\rm EW}$ is the electroweak coupling constant. It is referred to as EW production. The second category involves both the quantum chromodynamics (QCD) and electroweak interactions at Born level of order $\alpha_{\rm s}^2\alpha_{\rm EW}^4$, where $\alpha_{\rm s}$ is the strong interaction coupling constant. It is referred to as QCD production. According to the SM a small interference occurs between electroweak and QCD production that also involves both the strong and electroweak interactions at Born level of orders $\alpha_{\rm s}\,\alpha_{\rm EW}^5$. The sum of QCD and interference contributions are referred to as strong production, as opposite to the pure EW production. Representative diagrams at LO of $WZjj$−EW and $WZjj$−QCD production are presented in figures 1 and 2, respectively.

A first observation of $W^{\pm}Zjj$ electroweak production was reported by the ATLAS Collaboration [6] using an integrated luminosity of 36 fb^{-1} of pp collision data collected at a centre-of-mass energy of 13 TeV. The observation was then confirmed by the CMS Collaboration using data corresponding to an integrated luminosity of 137 fb^{-1} [7]. In these two results only integrated measurements of the electroweak $W^{\pm}Zjj$ production cross-section were made, without further attempts to verify the modelling of key kinematic observables of the electroweak $W^{\pm}Zjj$ processes by theory predictions. The CMS and ATLAS Collaborations also used the measured $W^{\pm}Zjj$ events to obtain constraints on the structure of quartic vector boson interactions in an Effective Field Theory (EFT) framework [7, 8].

This paper presents measurements of integrated and differential cross-sections for electroweak and inclusive $W^{\pm}Zjj$ production, exploiting the fully leptonic decays of the Z and W bosons where final state charged leptons are electrons or muons. The pp collision data were collected with the ATLAS detector from 2015 to 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV and correspond to an integrated luminosity of 140 fb^{-1}. A multivariate discriminant constructed from a boosted decision tree (BDT) is used to separate electroweak and strong $W^{\pm}Zjj$ production modes. Their respective cross-sections are measured integrated over a fiducial phase space. They are also measured differentially in three bins of the invariant mass of the two tagging jets, m_{jj}, and separately for events with exactly two jets or with more than two jets. The cross-section of inclusive $W^{\pm}Zjj$ production is also measured differentially as a function of various kinematic observables sensitive to the modelling from Monte Carlo (MC) event generators or to new physics effects. The distributions of the transverse mass of the $W^{\pm}Z$ system, m_{T}^{WZ}, and of the BDT score are used in an EFT interpretation to constrain dimension-8 operators.

2 ATLAS detector

The ATLAS experiment [9] at the Large Hadron Collider (LHC) [10] 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 is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. 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 1 kHz on average depending on the data-taking conditions. An extensive software suite [11] 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 Phase space for cross-section measurements

The $W^{\pm}Zjj$ cross-sections are measured in a fiducial phase space that is defined by the kinematics of the final-state leptons, electrons or muons, associated with the $W^{\pm}$ and Z boson decays. Leptons produced in the decay of a hadron, a τ-lepton, or their descendants are not considered in the definition of the fiducial phase space and are treated as background. At particle level, the kinematics of the charged leptons after quantum electrodynamics final-state radiation are 'dressed' by including contributions from photons with an angular distance

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

$\Delta R < 0.1$ from the lepton. Dressed charged leptons, and final-state neutrinos that do not originate from hadron or τ-lepton decays, are matched to the $W^\pm$ and Z boson decay products using a MC generator-independent algorithmic approach, called the 'resonant shape' algorithm [12]. This algorithm is based on the value of an estimator expressing the product of the nominal line-shapes of the W and Z resonances,

$$P = \left| \frac{1}{m^2_{(\ell^+,\ell^-)} - \left(m_Z^{\mathrm{PDG}}\right)^2 + \mathrm{i}\,\Gamma_Z^{\mathrm{PDG}}\; m_Z^{\mathrm{PDG}}} \right|^2 \times \left| \frac{1}{m^2_{(\ell',\nu_{\ell'})} - \left(m_W^{\mathrm{PDG}}\right)^2 + \mathrm{i}\,\Gamma_W^{\mathrm{PDG}}\; m_W^{\mathrm{PDG}}} \right|^2 ,$$

where m_Z^{PDG} (m_W^{PDG}) and Γ_Z^{PDG} (Γ_W^{PDG}) are the world average mass and total width of the Z (W) boson, respectively, as reported by the Particle Data Group [13]. The input to the estimator is the invariant mass m of all possible pairs (ℓ^+,ℓ^-) and $(\ell',\nu_{\ell'})$ satisfying the fiducial selection requirements defined in the next paragraph. The final choice of which leptons are assigned to the W or Z bosons corresponds to the configuration exhibiting the largest value of the estimator. Using this association algorithm, the gauge boson kinematics can be computed using the kinematics of the associated leptons independently of any internal MC generator details.

The fiducial phase space of the measurement is the same as used in ref. [6]. It is defined at particle level by the following requirements: the charged leptons from the Z boson decay are required to have transverse momentum $p_{\mathrm{T}} > 15$ GeV, the charged lepton from the $W^\pm$ decay is required to have transverse momentum $p_{\mathrm{T}}^{\ell} > 20$ GeV, the charged leptons from the $W^\pm$ and Z bosons are required to have $|\eta| < 2.5$ and the invariant mass of the two leptons from the Z boson decay must be within 10 GeV of the nominal Z boson mass, taken from the world average value, $m_Z^{\mathrm{PDG}} = 91.1876$ GeV [13]. The W boson transverse mass, defined as $m_{\mathrm{T}}^{W} = \sqrt{2 \cdot p_{\mathrm{T}}^{\nu} \cdot p_{\mathrm{T}}^{\ell} \cdot [1 - \cos\Delta\phi(\ell,\nu)]}$, where $\Delta\phi(\ell,\nu)$ is the angle between the lepton and the neutrino in the transverse plane and p_{T}^{ν} is the transverse momentum of the neutrino, is required to be $m_{\mathrm{T}}^{W} > 30$ GeV. The angular distance between the charged lepton from the $W^\pm$ decay and each of the charged leptons from the Z decay is required to be $\Delta R > 0.3$, and the angular distance between the two leptons from the Z decay is required to be $\Delta R > 0.2$.

In addition to these requirements that define an inclusive phase space, at least two jets with $p_{\mathrm{T}} > 40$ GeV and $|\eta_j| < 4.5$ are required. These particle-level jets are reconstructed from stable particles with a lifetime of $\tau > 30$ ps in the simulation after parton showering, hadronisation, and decay of particles with $\tau < 30$ ps. Muons, electrons, neutrinos and photons associated with W and Z decays are excluded. The particle-level jets are reconstructed using the anti-k_t [14, 15] algorithm with a radius parameter $R = 0.4$. 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. The invariant mass, m_{jj}, of the two highest-p_{T} jets in opposite hemispheres, $\eta_{j1} \cdot \eta_{j2} < 0$, is required to be $m_{jj} > 500$ GeV to enhance the sensitivity to VBS processes. These two jets are referred to as tagging jets. Finally, hard processes with a b-quark in the initial or final states at the matrix-element level, such as tZj production, are not considered as part of the $WZjj$−EW events. The production of tZj results from a t-channel exchange of a W boson between a b- and a u-quark giving a final state with a t-quark, a Z boson and a light-quark jet, but does not include diagrams with gauge boson couplings.

4 Signal and background simulation

The MadGraph5_aMC@NLO 2.6.5 [16] MC event generator, interfaced with Pythia 8.240 [17] using the A14 tune [18] for the modelling of the parton shower (PS), hadronisation and underlying event, was used to model $W^{\pm}Zjj$ events. The NNPDF3.0nlo [19] parton distribution function (PDF) set was used for the hard-scattering process, while the NNPDF2.3lo [19] PDF set was used for the PS. The dipole recoil scheme [20] is used for the PS. The default dynamic renormalisation and factorisation scales set by MadGraph5_aMC@NLO [21] were used. A first MC event sample, referred to as $WZjj$−EW, includes processes of order six (zero) in α_{EW} (α_{s}). In this sample, which includes VBS diagrams, two additional jets originating from electroweak vertices from matrix-element partons are included in the final state. Diagrams with a b-quark in either the initial or final state, i.e. b-quarks in the matrix-element calculation, are not considered. This sample provides a LO prediction for the $WZjj$−EW signal process. A second MC event sample, referred to as $WZjj$−QCD, includes processes of order four in α_{EW} in the matrix-element. Matrix elements containing three leptons, one neutrino and up to two jets in the final state were calculated at NLO QCD and merged with the PS from Pythia 8.210 using the FxFx scheme [22]. This $WZjj$−QCD sample includes matrix-element b-quarks. Interferences between the $WZjj$−EW and $WZjj$−QCD processes, labelled $WZjj$−INT, include only contributions to the squared matrix-element of order one in α_{s}. Their contribution is simulated at LO in a third MC sample using MadGraph5_aMC@NLO 2.6.5 [16] and the same parameters as used for $WZjj$−EW events. The contribution of interferences is found to be positive and approximately 6% of the $WZjj$−EW cross-section in the fiducial phase space at particle level and maximaly 12% of the $WZjj$−EW cross-section for events with three or more jets of $p_{\mathrm{T}} > 25$ GeV.

For the estimate of the PS uncertainties in the simulation of the $WZjj$−EW process, an alternative MC sample was simulated using MadGraph5_aMC@NLO 2.6.5 interfaced with Herwig 7.1 [23, 24]. For the estimate of modelling uncertainties and comparisons to data, alternative MC samples of $WZjj$−QCD and $WZjj$−EW processes were generated with the Sherpa 2.2.12 [25] MC event generator. For $WZjj$−QCD processes, the matrix elements contain all diagrams with four electroweak vertices. They were calculated for up to one parton at next-to-leading-order (NLO) in QCD and up to three partons at leading-order (LO) using Comix [26] and OpenLoops [27], and merged with the Sherpa PS [28] according to the ME+PS@NLO prescription [29]. The NNPDF3.0nnlo PDF set was used along with the associated set of tuned parton-shower parameters developed by the Sherpa authors. For $WZjj$−EW production, processes of order six (zero) in α_{EW} (α_{s}) are included. Two additional jets originating from electroweak vertices from matrix-element partons are included in the final state. Diagrams with a b-quark in either the initial or final state are not considered. The LO-accurate matrix elements for up to one additional parton were matched to a PS based on Catani-Seymour dipole factorisation [26, 28] using the MEPS@LO prescription [29–32]. The contribution of interferences is not simulated using Sherpa 2.2.12 but the $WZjj$−INT prediction from MadGraph5_aMC@NLO 2.6.5 is added to the $WZjj$−EW and $WZjj$−QCD Sherpa 2.2.12 predictions to form the $W^{\pm}Zjj$ Sherpa 2.2.12 prediction.

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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 $Z\gamma$). MC simulation is used to estimate the contribution from background processes with three or more prompt leptons. 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 processes, including $H \to ZZ$ production, using the NNPDF3.0NNLO PDF set. It provides a matrix element calculation accurate to NLO in α_s for 0- and 1-jet final states, and LO accuracy for 2- and 3-jet final states. 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 tune and the NNPDF2.3LO PDF set.

The production of $t\bar{t} + V$ events was modelled using the MADGRAPH5_AMC@NLO 2.3.3 [16] generator at NLO with the NNPDF3.0NLO PDF. The events were interfaced to PYTHIA 8.210 using the A14 tune and the NNPDF2.3LO PDF set. The tZj process was modelled using the MADGRAPH5_AMC@NLO 2.3.3 [16] generator at NLO with the NNPDF3.0NLO PDF. The events were interfaced with PYTHIA 8.230 using the A14 tune and the NNPDF2.3LO PDF set. Finally, the on-shell production of triboson events with fully leptonic decays were 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 decays of bottom and charm hadrons were simulated using the EVTGEN 1.2.0 program [33], except for processes modelled using SHERPA.

All generated MC events were passed through the ATLAS detector simulation [34], based on GEANT4 [35], and processed using the same reconstruction software as used for the data. The event samples include the simulation of additional pp interactions (pile-up) generated with PYTHIA 8.186 using the NNPDF2.3LO PDF set and the A3 [36] set of tuned parameters. Simulated events were reweighted to match the pile-up conditions observed in the data. 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.

5 Event selection

Only data recorded with stable beam conditions and with all relevant detector subsystems operational are considered. Candidate events are selected using triggers requiring at least one electron or muon [37–39]. 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 $W^{\pm}Zjj$ 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

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defined as the reconstructed vertex with at least two charged-particle tracks that has the largest sum of the p_T^2 for the 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 [40, 41]. 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 [42]. 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 [42], 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 [41].

Jets of hadrons are reconstructed using a particle-flow algorithm based on noise-suppressed positive-energy topological clusters in the calorimeters [43]. 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 with a radius parameter $R = 0.4$. They are calibrated according to in situ measurements of the jet energy scale [44]. 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 [45] and forward jet vertex [46] tagging algorithms, respectively. Jets with $|\eta| < 2.5$ containing a b-hadron are identified with a deep-learning neural network (NN) [47] which uses distinctive features of b-hadron decays in terms of the impact parameters of the tracks and the displaced vertices reconstructed in the inner detector. Jets initiated by b-quarks are selected by setting the algorithm's output threshold such that an 70% b-jet selection efficiency is achieved in simulated $t\bar{t}$ events, with a rejection factor of 40 against light-flavour jets. Corrections to the flavour-tagging efficiencies are based on data-driven calibration analyses [47].

The transverse momentum of the neutrino is estimated from the missing transverse momentum in the event, $E_{\mathrm{T}}^{\mathrm{miss}}$, 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 [48].

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 $p_{\mathrm{T}} > 25$ GeV for 2015 and $p_{\mathrm{T}} > 27$ GeV for 2016–2018 data, as well as being geometrically matched to a lepton that was selected by the trigger. This detector-level requirement that the transverse momentum of the leading lepton be above 27 GeV is not present in the definition of the fiducial phase space. It would reduce the acceptance of the fiducial phase space by only 0.02%.

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 $p_{\mathrm{T}} > 5$ GeV, electrons are allowed to be reconstructed in the region $1.37 < |\eta| < 1.52$ and 'loose' identification requirements [41, 42] 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. 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 m_Z^{PDG} is taken as the Z boson candidate. The remaining third lepton is assigned to the W boson decay.[2] The transverse mass of the W candidate, computed using $E_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of the associated lepton, is required to be greater than 30 GeV.

Backgrounds originating from 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 and isolation requirements [41, 42], which results in an efficiency between 90% and 98% depending on p_{T} for muons and an overall efficiency of 85% for electrons.

To select $W^{\pm}Zjj$ candidates, events are further required to be associated with at least two 'tagging' jets. The leading tagging jet is selected as the highest-p_{T} jet in the event with $p_{\mathrm{T}} > 40$ GeV. The second tagging jet is selected as the one with the highest p_{T} among the remaining jets that have a pseudorapidity of opposite sign to the first tagging jet and a $p_{\mathrm{T}} > 40$ GeV. These two jets are required to satisfy $m_{jj} > 150$ GeV, in order to minimise the contamination from triboson processes.

[2]For true $W^{\pm}Zjj$ events with same flavour decays, the probability to mis-assign a lepton with its mother boson is of 2.5%.

The final signal region (SR) for VBS processes is defined by requiring that the invariant mass of the two tagging jets, m_{jj}, be greater than 500 GeV and that no b-jet be present in the event.

6 Background estimation

The background sources are classified into two groups: events where all candidates are prompt leptons or are produced in the decay of a τ-lepton (irreducible background) and events where at least one of the candidate leptons is not a prompt lepton (reducible background). Candidates that are not prompt leptons are also called 'misidentified' or 'fake' leptons.

The main sources of irreducible background arise from ZZ and $t\bar{t}+V$ (where $V = Z$ or W). These irreducible backgrounds are modelled using MC simulations. Data in two dedicated control regions (CR), referred to as ZZ-CR and b-CR, respectively, are used to constrain the normalisations of the $ZZjj-$QCD and $t\bar{t}+V$ backgrounds. The control region ZZ-CR, enriched in ZZ events, is defined by applying the $W^{\pm}Zjj$ event selection defined in section 5, but instead of vetoing a fourth lepton, events must have at least a fourth lepton candidate with looser identification requirements. This region is dominated by $ZZjj-$QCD events with a small contribution of $ZZjj-$EW events. The control region b-CR, enriched in $t\bar{t}+V$ and tZj events, is defined by selecting $W^{\pm}Zjj$ candidate events having at least one reconstructed b-jet. The remaining sources of irreducible background are $ZZjj-$EW and VVV events. Their contributions in the control and signal regions are estimated from MC simulations.

The reducible backgrounds originate from $Z+j$, $Z\gamma$, $t\bar{t}$, Wt and WW production processes. These backgrounds are estimated by using a data-driven method based on the inversion of a global matrix containing the efficiencies and the misidentification probabilities for prompt and fake leptons [12, 49–51]. The method exploits the classification of the leptons as loose or tight candidates and the probability that a fake lepton is misidentified as a loose or tight lepton candidate. Tight lepton candidates are signal lepton candidates as defined in section 5. Loose lepton candidates are leptons that do not meet the isolation and identification criteria of signal lepton candidates but satisfy only looser criteria. The misidentification probabilities for misidentified 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. [40–42]. The lepton efficiencies and misidentification probabilities are parameterised as a function of the p_{T} and η of leptons and combined with event rates in data samples of $W^{\pm}Zjj$ candidate events where at least one and up to three of the leptons are 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 $W^{\pm}Zjj$ sample. 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 the data-to-MC comparison in dedicated control regions. Agreement within 20% with the matrix method estimate is obtained in both yield and shape of the distributions of irreducible

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	SR, $N_{\text{jets}} = 2$	SR, $N_{\text{jets}} \geq 3$	b-CR	ZZ-CR
Data	169	477	666	210
Total pred.	231 ± 12	550 ± 50	660 ± 40	205 ± 11
$WZjj$-EW	65.0 ± 3.5	60 ± 6	4.82 ± 0.28	0.725 ± 0.014
$WZjj$-QCD	125 ± 9	380 ± 50	77 ± 18	6.2 ± 0.7
$WZjj$-INT	1.3 ± 0.6	5.3 ± 2.6	0.58 ± 0.29	0.22 ± 0.11
$t\bar{t} + V$	0.66 ± 0.04	20.2 ± 0.7	289 ± 10	9.89 ± 0.28
tZj	8.78 ± 0.34	19.7 ± 1.2	134 ± 4	0.432 ± 0.005
ZZ-QCD	9.6 ± 0.4	32.0 ± 2.5	10.1 ± 0.6	159 ± 9
ZZ-EW	2.2 ± 0.6	4.4 ± 1.1	0.25 ± 0.06	23 ± 6
VVV	0.41 ± 0.10	2.0 ± 0.5	0.39 ± 0.10	4.1 ± 1.1
Misid. leptons	18 ± 4	28 ± 7	150 ± 40	1.7 ± 0.5

Table 1. Expected and observed numbers of events in the $W^{\pm}Zjj$ signal region and in the two control regions, before the fit described in section 7.1. The expected number of $WZjj$−EW, $WZjj$−QCD and $WZjj$−INT events and the estimated number of background events from the other processes are shown. The sum of the backgrounds containing misidentified leptons is labelled 'Misid. leptons'. The total systematic uncertainties are quoted.

background events. This level of agreement is compatible with the systematic uncertainties determined for the matrix method estimate.

The number of events expected from MC simulation and data-driven background estimates are summarised in table 1 and compared to the number of observed data events, for the signal region and the two control regions. All sources of uncertainties, as described in section 8, are included. The expected contribution of $WZjj$−EW events in the $W^{\pm}Zjj$ signal region is about 16% while 64% of the events are expected to arise from $WZjj$−QCD production. The contributions of $W^{\pm}Zjj$ events with τ-lepton decays, amounting to 5.3% of all $W^{\pm}Zjj$ events, are included in the $WZjj$−EW, $WZjj$−QCD and $WZjj$−INT contributions.

7 Measurements methodology

7.1 $WZjj$−EW and $WZjj$−strong integrated measurements

Events associated to $WZjj$−EW production are separated from other $W^{\pm}Zjj$ events originating from $WZjj$−QCD production and from the interference $WZjj$−INT, based on their kinematic properties as modelled by MC predictions. The production cross-section of the two populations of events, $\sigma_{WZjj-\text{EW}}$ and $\sigma_{WZjj-\text{strong}}$, are then measured simultaneously.

Given the small contribution to the signal region of $WZjj$−EW processes, a multivariate discriminant is used to separate the signal from the backgrounds. A BDT, as implemented in the TMVA package [52], is used to exploit the kinematic differences between the $WZjj$−EW signal and the $WZjj$−QCD and other backgrounds. The BDT is trained and optimised on simulated events from the SR to separate $WZjj$−EW events from all other processes.

Similarly to ref. [6], 15 variables are used as inputs to the BDT discriminant. The variables can be classified into three categories: jet-kinematics variables, vector-bosons-kinematics variables, and variables related to both jets and leptons kinematics. The variables related

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to the kinematic properties of the two tagging jets are the invariant mass of the two jets, m_{jj}, the transverse momenta of the jets, $p_{\mathrm{T}^{j1}}$ and $p_{\mathrm{T}^{j2}}$, the difference in pseudorapidity and azimuthal angle between the two jets, $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$, the rapidity of the leading jet and the jet multiplicity. The variables related to the kinematic properties of the vector bosons are the transverse momenta of the W and Z bosons, the pseudorapidity of the W boson, the absolute difference between the rapidities of the Z boson and the lepton from the decay of the W boson, $|y_Z - y_{\ell,W}|$, and the transverse mass of the $W^{\pm}Z$ system m_{T}^{WZ}. 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. [50]. The m_{T}^{WZ} observable is reconstructed following ref. [12]. The variables that relate the kinematic properties of jets and leptons are the distance in the pseudorapidity-azimuth plane between the Z boson and the leading jet, $\Delta R(j_1, Z)$, the event balance $R_{p_{\mathrm{T}}}^{\mathrm{hard}}$, defined as the transverse component of the vector sum of the WZ bosons and tagging jets momenta, normalised to their scalar p_{T} sum, and, finally the centrality of the WZ system relative to the tagging jets, defined as $\zeta_{\mathrm{lep.}} = \min(\Delta\eta_-, \Delta\eta_+)$, with $\Delta\eta_- = \min(\eta_\ell^W, \eta_{\ell_2}^Z, \eta_{\ell_1}^Z) - \min(\eta_{j_1}, \eta_{j_2})$ and $\Delta\eta_+ = \max(\eta_{j_1}, \eta_{j_2}) - \max(\eta_\ell^W, \eta_{\ell_2}^Z, \eta_{\ell_1}^Z)$, where $\eta_{\ell_1}^Z$ and $\eta_{\ell_2}^Z$ are the pseudorapidity of the leading and sub-leading leptons associated to the Z boson. The good modelling by MC simulations of the distribution shapes and the correlations of all input variables to the BDT is verified in a validation region defined by requiring $150 < m_{jj} < 500$ GeV. The modelling of input variables to the BDT, and in particular of the m_{jj} distribution, is also verified in a sub-signal region enriched in $WZjj-$QCD events. This sub-signal region is constructed using an Adversarial Neural Network (ANN) developed to separate $WZjj-$QCD from $WZjj-$EW events in the SR, without introducing a bias in the shape of the m_{jj} distribution. The output score of this ANN is used to select a sub-sample of events in the SR enriched in $WZjj-$QCD production. For these events, a good modelling of the shapes of the m_{jj} distribution and of the other BDT input observables is observed. Finally the good modelling by MC simulations of the kinematic of $W^{\pm}Zjj$ events is verified independently by the measurement of differential cross-sections of key observables as presented in section 7.3 and whose results are shown in section 9.3.

To better separate the $t\bar{t}+V$ and tZj events in the b-CR and to constrain the normalisation of both contributions using data in this CR, a second BDT discriminant, labelled b-CR BDT, is built using 16 input variables. The input variables used are related to the kinematics of tagging jets: $p_{\mathrm{T}^{j1}}$, η_{j1}, ϕ_{j1}, $p_{\mathrm{T}^{j2}}$, $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$; to the kinematics of vector bosons: p_{T}^{Z}, η_Z, ϕ_Z, p_{T}^{W}, m_{WZ}, $\Delta\eta(W,Z)$ and $\Delta\phi(W,Z)$; to the jet mutiplicites: N_{jets}, $N_{\mathrm{b-jets}}$; and to the invariant mass of final state particles: $m(3\ell, \mathrm{jets})$, defined as the invariant mass of the three charged leptons and all jets with a $p_{\mathrm{T}} > 25$ GeV. The b-CR BDT is trained and optimised on simulated events to separate tZj from $t\bar{t}+V$ events. Its discriminant output is labelled b-CR BDT score.

In the $W^{\pm}Zjj$ signal region, the distribution of the BDT score is used in a maximum-likelihood fit to separate $WZjj-$EW events from $WZjj-$strong events and to measure their respective fiducial cross-sections. To minimise the dependency of the measurement on possible mis-modelling of $WZjj-$QCD and $WZjj-$EW events by the MC generators, the $W^{\pm}Zjj$ SR is divided in two categories corresponding to events with exactly two jets of $p_{\mathrm{T}} > 25$ GeV or with three or more jets. An extended likelihood is built from the product of four likelihoods corresponding to the BDT score distributions in the two event categories of the $W^{\pm}Zjj$ SR, the b-CR BDT distribution in the b-CR and the m_{jj} distribution in the ZZ-CR. The inclusion of the two control regions in the fit allows the yields of the $t\bar{t}+V$, tZj and $ZZjj$−QCD backgrounds to be constrained by data. The shapes of these backgrounds are taken from MC predictions and can vary within the uncertainties affecting the measurement as described in section 8. The normalisations of these backgrounds are introduced in the likelihood as parameters, labelled μ_{ttV}, μ_{tZj} and μ_{ZZ} for $t\bar{t}+V$, tZj and $ZZjj$−QCD backgrounds, respectively. They are treated as unconstrained nuisance parameters that are determined mainly by the data in the respective control region. The normalisation and shape of the other irreducible backgrounds are taken from MC simulations and are allowed to vary within their respective uncertainties. The distribution of the reducible background is estimated from data using the matrix method presented in section 6 and is allowed to vary within its uncertainty. Each source of systematic uncertainty is implemented in the likelihood function as a nuisance parameter with a Gaussian constraint.

The fiducial cross-sections $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ integrated over the two event categories in N_{jets} are determined as parameters of a binned fit to data. The fit parameters are directly linked to normalisation factors of the $WZjj$−EW, $WZjj$−QCD and $WZjj$−INT MC templates as

$$
\begin{aligned}
\sigma_{WZjj-\mathrm{EW}} &= \sum_{i=1}^{2} \mu^{i}_{WZjj-\mathrm{EW}} \cdot \sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{EW}}\,, \\
\sigma_{WZjj-\mathrm{strong}} &= \sum_{i=1}^{2} \left(\mu^{i}_{WZjj-\mathrm{QCD}} \cdot \sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{QCD}} + \mu^{i}_{WZjj-\mathrm{INT}} \cdot \sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{INT}} \right), \\
&= \sum_{i=1}^{2} \left(\mu^{i}_{WZjj-\mathrm{QCD}} \cdot \sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{QCD}} + \sqrt{\mu^{i}_{WZjj-\mathrm{EW}}} \cdot \sqrt{\mu^{i}_{WZjj-\mathrm{QCD}}} \cdot \sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{INT}} \right),
\end{aligned}
\tag{7.1}
$$

where i runs over the two categories of the SR with exactly two jets of $p_{\mathrm{T}} > 25$ GeV or with three or more jets, $\sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{EW}}$, $\sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{QCD}}$ and $\sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{INT}}$ are the theoretical cross-sections predicted by the MC for the respective processes in each category, and $\mu^{i}_{WZjj-\mathrm{EW}}$ and $\mu^{i}_{WZjj-\mathrm{QCD}}$ are the normalisation factors of the $WZjj$−EW and $WZjj$−QCD MC templates in each category. The contributions from τ-decay leptons are included in the $WZjj$−EW, $WZjj$−QCD and $WZjj$−INT MC templates, assuming that measured cross-sections are flavour independent. By convention, the measured fiducial cross-sections correspond to a given decay channel $W^{\pm}Z \to \ell'^{\pm}\nu\ell^{+}\ell^{-}$, where ℓ and ℓ' are either an electron or a muon. The contribution of the interference between $WZjj$−EW and $WZjj$−QCD production processes, $WZjj$−INT, is introduced in the fit using a separate MC template. Its contribution is estimated to be very low at detector level, of the order of 5.3% of the $WZjj$−EW contribution as predicted by MadGraph+Pythia8. The kinematics and shape of the BDT score distribution of $WZjj$−INT events is very close to the one of $WZjj$−QCD events. Therefore, with the statistical sensitivity of the present data sample, this contribution can not be extracted alone from data. The normalisation of the interference contribution, $\mu^{i}_{WZjj-\mathrm{INT}}$, is not fixed in the fit to the predicted MadGraph+Pythia8 cross-section but is linked to the measured $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ cross-section as $\mu^{i}_{WZjj-\mathrm{INT}} = \sqrt{\mu^{i}_{WZjj-\mathrm{EW}}}\,\cdot$

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$\sqrt{\mu^i_{WZjj-\mathrm{QCD}}}$, and the $WZjj$−INT contribution is included into the measured $\sigma_{WZjj-\mathrm{strong}}$ cross-section.

7.2 $WZjj$−EW and $WZjj$−strong differential measurements

Events in the SR are separated in bins as a function of N_{jets}, the exclusive multiplicity of jets with a $p_{\mathrm{T}} > 25$ GeV or as a function of m_{jj}, the invariant mass of the two tagging jets. Two bins in N_{jets}, separating events with $N_{\mathrm{jets}} = 2$ and $N_{\mathrm{jets}} \geq 3$ and three bins in m_{jj} are used. In each of the bins, the BDT score distribution is used to separate $WZjj$−EW events and $WZjj$−strong events and therefore measure differentially the separate $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ production cross-sections. A simultaneous fit to data of the BDT score distributions of events in each bin is performed to measure the fiducial cross-section in each bin. For e.g. $WZjj$−EW events, the fiducial cross-section is defined in each bin i as

$$\sigma^i_{WZjj-\mathrm{EW}} = \mu^i_{WZjj-\mathrm{EW}} \cdot \sigma^{i,\,\mathrm{th.\,MC}}_{WZjj-\mathrm{EW}} = \frac{N^i_{\mathrm{fit}}}{\mathcal{L} \cdot C_i}, \quad C_i = \frac{N^i_{\mathrm{MC,\,det.}}}{N^i_{\mathrm{MC,\,part.}}}, \tag{7.2}$$

where $\mu^i_{WZjj-\mathrm{EW}}$ is the normalisation factor of the $WZjj$−EW MC template in bin i, N^i_{fit} is the number of extracted $WZjj$−EW events in data, $\mathcal{L}$ is the integrated luminosity of data and C_i is a bin-by-bin correction factor for detector inefficiency, resolution and bin-to-bin migrations. The term $N^i_{\mathrm{MC,\,det.}}$ is the number of $WZjj$−EW events predicted by the MC at detector level and $N^i_{\mathrm{MC,\,part.}}$ is the corresponding number of MC events predicted at particle level in the fiducial phase space. Correction factors are calculated using the MadGraph+Pythia8 MC simulations. The same control regions, without any N_{jets} or m_{jj} splitting, and a similar parameterisation of the fit as described in section 7.1 are used. Correlations between bins of experimental and background systematic uncertainties detailed in section 8 are taken into account in the simultaneous fit.

7.3 $W^{\pm}Zjj$ differential measurements

Events in the SR are also used to measure the $W^{\pm}Zjj$ differential production cross-section in the VBS fiducial phase space. The differential detector-level distributions are corrected for detector efficiency and resolution effects using an iterative Bayesian unfolding method [53], as implemented in the RooUnfold toolkit [54]. The number of iterations was tuned in order to obtain the best trade-off in minimising both the unfolding bias and the unfolding statistical uncertainty. Three iterations were used for the unfolding of each 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 that bin. The fraction of signal MC events reconstructed in the same bin as generated is always greater than 40% and around 70% on average.

For each distribution, simulated $W^{\pm}Zjj$ events are used to obtain a response matrix that accounts for bin-to-bin migration effects between the reconstruction-level and particle-level distributions. The MadGraph+Pythia8 MC samples for $WZjj$−EW, $WZjj$−INT and $WZjj$−QCD production are added together to model $W^{\pm}Zjj$ production. Because of differences in event kinematics, the response matrix for separate $WZjj$−EW and $WZjj$−QCD processes are close but not similar. To better model the data and to minimise

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unfolding uncertainties, their predicted cross-sections are rescaled by the signal strengths of 1 and 0.71 for the $WZjj-$EW and $WZjj-$strong contributions, respectively, as measured by the maximum-likelihood fit described in section 7.1 applied to data in section 9.1. The background contributions from $ZZjj-$QCD, $t\bar{t}+V$ and tZj are also rescaled according to the result of the maximum-likelihood fit of section 7.1, following constraints from data in the CRs.

8 Systematic uncertainties

Systematic uncertainties in the signal and control regions affecting the shape and normalisation of the BDT score, m_{jj} and b-CR BDT distributions for the individual backgrounds, as well as the acceptance of the $WZjj-$EW, $WZjj-$QCD and $WZjj-$INT events and the shape of their templates are considered. Shape and normalisation uncertainties affecting $WZjj-$EW, $WZjj-$QCD and $WZjj-$INT contributions in control regions are also considered. A bootstrapping procedure [55] is used to ensure statistically significant variations as a function of considered distributions.

Systematic uncertainties due to the theoretical modelling in the event generator used to evaluate the $WZjj-$QCD and $WZjj-$EW templates are considered. Uncertainties due to higher order QCD corrections are evaluated by varying the renormalisation, μ_{R}, and factorisation, μ_{F}, scales independently by factors of two and one-half, removing combinations where the variations differ by a factor of four. For the $WZjj-$EW process, simulated only at LO in QCD, changes in the definition of μ_{F} are also considered: dedicated MC studies show that depending on the definition of μ_{F} the shape of the BDT score distribution is subject to changes not covered by the scaling of μ_{F} by factors half or one-half. In the SR, these uncertainties are of up to $\pm 5\%$ and of $\pm 20\%$ on the shape of the BDT score distribution for $WZjj-$QCD and $WZjj-$EW events, respectively. The uncertainties due to the PDF and the α_{s} value used in the PDF determination are evaluated using the `PDF4LHC` prescription [56] and are of the order of 1% to 2% in shape. A global modelling uncertainty in the $WZjj-$QCD background template that includes effects of the parton shower model is estimated by comparing predictions of the BDT score distribution in the signal region from the MadGraph+Pythia8 and Sherpa MC event generators. The difference between the predicted shapes of the BDT score distribution from the two generators is considered as an uncertainty and affects the shape of the BDT score distribution of $WZjj-$QCD events by up to 30% at larger values of the BDT score. A parton-shower uncertainty in the $WZjj-$EW signal template is estimated by comparing predictions of the BDT score distribution in the signal region from MC simulations from MadGraph interfaced to Pythia or Herwig. This parton-shower uncertainty affects the shape of the BDT score distribution of $WZjj-$EW events by at most 10% at lower values of the BDT score. For the $WZjj-$INT template, uncertainties due to variations of the renormalisation and factorisation scales and due to the PDF and to the α_{s} value used in the PDF determination are considered. They affect the shape of the template by approximately 3%.

For the measurement of integrated and differential $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ cross-sections using a combined maximum-likelihood fit, all the uncertainties related to higher order QCD corrections, parton shower and modelling are considered as uncorrelated between bins in N_{jets} or m_{jj} in the SR and between the SR and the control regions. This leads to the most conservative fit approach for these uncertainties.

For the measurements of $\sigma_{WZjj-\text{EW}}$, $\sigma_{WZjj-\text{strong}}$ and σ_{WZjj} differential cross-sections, uncertainties in the unfolding due to imperfect modelling of the data by the MC simulation are evaluated using a data-driven method [57], where the MC differential distribution is corrected to match the data distribution and the resulting weighted MC distribution at reconstruction level is unfolded with the response matrix used in the data unfolding. The new unfolded distribution is compared with the weighted MC distribution at generator level and the difference is taken as the systematic uncertainty. For $\sigma_{WZjj-\text{EW}}$ and $\sigma_{WZjj-\text{strong}}$ cross-sections, the uncertainties obtained range from 4% to 9%. For σ_{WZjj} cross-sections, the uncertainties range from 0.1% to 16% depending on the resolution of the unfolded observables and on the quality of its description by MadGraph+Pythia8. They cover residual modelling uncertainties in the unfolded observables, which could still be present after the adjustment to data of the normalisation of $WZjj$−QCD and $WZjj$−EW contributions. It is also verified that, by construction, these uncertainties cover for possible EFT contributions being present in the data. An additional uncertainty is derived to account for more subtle differences between the MadGraph+Pythia8 and Sherpa generators (e.g. hadronisation models, additional soft objects, mis-modelling in other kinematic variables). The Sherpa generator is used to unfold the data and deviation from the nominal result is taken as the uncertainty. To remove effects already accounted for in the data-driven method, the Sherpa distributions were first reweighed to match MadGraph+Pythia8 distributions at particle level.

Systematic uncertainties affecting the reconstruction and energy calibration of jets, electrons and muons are propagated through the analysis. The dominant sources of uncertainties are the jet energy scale calibration, including the modelling of pile-up. The uncertainties in the jet energy scale are obtained from $\sqrt{s} = 13$ TeV simulations and *in situ* measurements [58]. The uncertainties in the jet energy resolution [58], in the suppression of jets originating from pile-up [45], in the b-tagging efficiency and in the mistag rate [47] are also considered. The uncertainty in the $E_{\text{T}}^{\text{miss}}$ measurement is estimated by propagating the uncertainties in the transverse momenta of hard physics objects and by applying momentum scale and resolution uncertainties to the track-based soft term [48]. A variation in the pile-up reweighting of MC events is included in order to cover the uncertainty in the ratio of the predicted and measured pp inelastic cross-sections [59].

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 $Z \to \ell\ell$ events [40–42].

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.

The uncertainty due to irreducible background sources that are not constraint by data in the dedicated CRs is evaluated by propagating the uncertainty in their MC cross-sections. These are 20% for VVV [60] and 25% for $ZZjj$−EW to account for the potentially large impact of scale variations.

Source	$\frac{\Delta\sigma_{WZjj-\text{EW}}}{\sigma_{WZjj-\text{EW}}}$ [%]	$\frac{\Delta\sigma_{WZjj-\text{strong}}}{\sigma_{WZjj-\text{strong}}}$ [%]
$WZjj-$EW theory modelling	7	1.8
$WZjj-$QCD theory modelling	2.8	8
$WZjj-$EW and $WZjj-$QCD interference	0.35	0.6
PDFs	1.0	0.06
Jets	2.3	5
Pile-up	1.1	0.6
Electrons	0.8	0.8
Muons	0.9	0.9
b-tagging	0.10	0.11
MC statistics	1.9	1.2
Misid. lepton background	2.3	2.3
Other backgrounds	0.9	0.23
Luminosity	0.7	0.9
All systematics	16	12
Statistics	10	6
Total	19	13

Table 2. Grouped impact of systematic uncertainties in the measured integrated fiducial cross-sections $\sigma_{WZjj-\text{EW}}$ and $\sigma_{WZjj-\text{strong}}$. The uncertainties are reported as percentages. The total systematic uncertainty does not correspond directly to the sum in quadrature of the distinct sources due to correlations introduced by the fit, in particular between $\sigma_{WZjj-\text{EW}}$ and $\sigma_{WZjj-\text{strong}}$.

The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [61], obtained using the LUCID-2 detector [62] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters.

The effect of the systematic uncertainties on the final results after the maximum-likelihood fit is shown in table 2 where the breakdown of the contributions to the uncertainties in the measured fiducial cross-section $\sigma_{WZjj-\text{EW}}$ and $\sigma_{WZjj-\text{strong}}$ is presented. The individual sources of systematic uncertainty are combined into theory modelling and experimental categories. As shown in the table, the systematic uncertainties in the modelling of the $WZjj-$EW and $WZjj-$QCD processes play a dominant role, followed by the uncertainties in the jet reconstruction and calibration. Systematic uncertainties in the missing transverse momentum computation arise directly from the momentum and energy calibration of jets, electrons and muons and are included in the respective lines of table 2. Systematic uncertainties in the modelling of the other backgrounds are also considered.

9 Results

9.1 $WZjj-$EW and $WZjj-$strong integrated measurements

The post-fit distributions of the BDT score in the signal region for events with $N_{\text{jets}} = 2$ and $N_{\text{jets}} \geq 3$ are presented in figures 3(a) and (b), respectively. The background normalisations, signal normalisation and nuisance parameters are adjusted by the profile-likelihood fit. The

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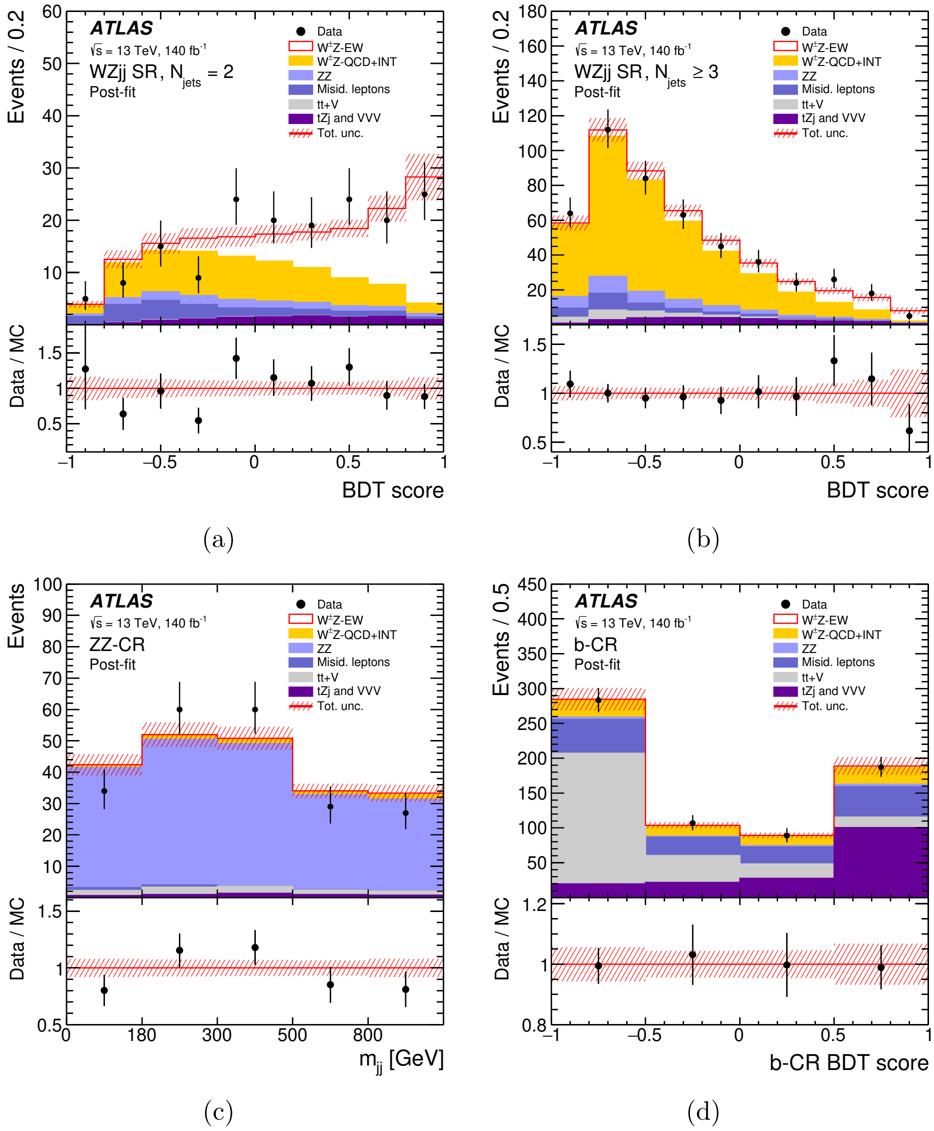

Figure 3. Post-fit distributions of (a) the BDT score distribution in the signal region, for $N_{\text{jets}} = 2$ and (b) $N_{\text{jets}} \geq 3$ categories, (c) m_{jj} in the ZZ-CR control region, (d) the b-CR BDT score in the b-CR. Signal and backgrounds are normalised to the expected number of events after the fit. The uncertainty band around the MC expectation includes all systematic uncertainties as obtained from the fit.

post-fit distributions of m_{jj} and of the b-CR BDT score in the ZZ-CR and b-CR, respectively, are also presented in figures 3(c) and (d). The corresponding post-fit event yields are detailed in table 3. The normalisation parameters of the $t\bar{t}+V$ and ZZ backgrounds constrained by data in the control and signal regions are measured to be $\mu_{ttV} = 0.91 \pm 0.13$, $\mu_{tZj} = 1.26 \pm 0.22$ and $\mu_{ZZ} = 1.07 \pm 0.11$. No pull of nuisance parameters by more than 0.5σ is observed.

The integrated fiducial cross-sections $\sigma_{WZjj\text{–EW}}$ and $\sigma_{WZjj\text{–strong}}$, for a given decay channel $W^{\pm}Z \to \ell'^{\pm}\nu\ell^{+}\ell^{-}$, where ℓ and ℓ' are either an electron or a muon, are measured to be

$$\begin{aligned}\sigma_{WZjj\text{–EW}} &= 0.368\ \pm 0.037\,(\text{stat.})\ \pm 0.059\,(\text{syst.})\ \pm 0.003\,(\text{lumi.})\ \text{fb}\\ &= 0.37\ \pm 0.07\ \text{fb},\end{aligned}$$

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	SR, $N_{\text{jets}} = 2$	SR, $N_{\text{jets}} \geq 3$	b-CR	ZZ-CR
Data	169	477	666	210
Total pred.	170 $\pm$ 13	476 $\pm$ 22	667 $\pm$ 26	212 $\pm$ 14
$WZjj$-EW	68 $\pm$ 14	55 $\pm$ 18	4.84 $\pm$ 0.27	0.724 $\pm$ 0.014
$WZjj$-QCD	58 $\pm$ 16	307 $\pm$ 27	77 $\pm$ 18	6.3 $\pm$ 0.7
$WZjj$-INT	0.9 $\pm$ 0.4	4.4 $\pm$ 2.3	0.57 $\pm$ 0.29	0.22 $\pm$ 0.11
$t\bar{t}+V$	0.59 $\pm$ 0.10	18.3 $\pm$ 2.4	262 $\pm$ 34	9.0 $\pm$ 1.3
tZj	11.0 $\pm$ 1.9	25 $\pm$ 5	169 $\pm$ 30	0.54 $\pm$ 0.09
ZZ-QCD	10.3 $\pm$ 1.0	34.6 $\pm$ 3.2	10.1 $\pm$ 0.5	171 $\pm$ 15
ZZ-EW	1.9 $\pm$ 0.4	3.7 $\pm$ 0.9	0.21 $\pm$ 0.05	19 $\pm$ 5
VVV	0.41 $\pm$ 0.10	2.0 $\pm$ 0.5	0.39 $\pm$ 0.10	4.2 $\pm$ 1.0
Misid. leptons	18 $\pm$ 4	27 $\pm$ 6	143 $\pm$ 35	1.7 $\pm$ 0.5

Table 3. Observed and expected numbers of events in the $W^{\pm}Zjj$ signal region and in the two control regions, after the fit. The expected number of $WZjj$−EW, $WZjj$−QCD and $WZjj$−INT events and the estimated number of background events from the other processes are shown. The sum of the backgrounds containing misidentified leptons is labelled 'Misid. leptons'. The total correlated post-fit systematic uncertainties are quoted.

$$\begin{aligned}\sigma_{WZjj-\text{strong}} &= 1.093 \pm 0.066\,(\text{stat.}) \pm 0.131\,(\text{syst.}) \pm 0.009\,(\text{lumi.})\ \text{fb}\\ &= 1.09 \pm 0.14\ \text{fb},\end{aligned}$$

where the uncertainties correspond to statistical, systematic, and luminosity uncertainties, respectively. Table 2 shows the main sources of uncertainty in the measured cross-sections. The precision of the measurements is limited by the systematic uncertainties, and in particular by the model uncertainties of the MC event generators. The total systematic uncertainties are also increased by existing correlations between the $\sigma_{WZjj-\text{EW}}$ and $\sigma_{WZjj-\text{strong}}$ measured cross-sections, which are of the order of 36%. The corresponding predictions from MadGraph+Pythia8 are

$$\begin{aligned}\sigma^{\text{MadGraph+Pythia8}}_{WZjj-\text{EW}} &= 0.370 \pm 0.001\,(\text{stat.}) \pm 0.006\,(\text{PDF})\ ^{+0.030}_{-0.026}\,(\text{scale})\ \text{fb}\,,\\ \sigma^{\text{MadGraph+Pythia8}}_{WZjj-\text{strong}} &= 1.537 \pm 0.009\,(\text{stat.}) \pm 0.016\,(\text{PDF})\ ^{+0.087}_{-0.149}\,(\text{scale})\ \text{fb}\,,\end{aligned}$$

where the uncertainties correspond to statistical, PDF and QCD scale uncertainties, respectively, calculated as detailed in section 8. The measured values of $\sigma_{WZjj-\text{EW}}$ and $\sigma_{WZjj-\text{strong}}$ are also compared to the predictions from MadGraph+Pythia8 and Sherpa 2.2.12 in figure 4. A good agreement of the MC predictions with the measured $WZjj$−EW integrated cross-section is observed, while the $WZjj$−QCD integrated cross-section is measured to be lower than the prediction from both MC event generators by a factor of 0.7. Considering the theory uncertainty in the MadGraph+Pythia8 prediction, the present measurement and the MadGraph+Pythia8 prediction agree within 1.8σ. A similar observation regarding the modelling of $WZjj$−QCD production was also made by the ATLAS Collaboration using a different measurement phase space [63]. It is also consistent with measurements done in previous ATLAS publications dedicated to $W^{\pm}Zjj$ and $W^{\pm}Z$ final states [6, 50].

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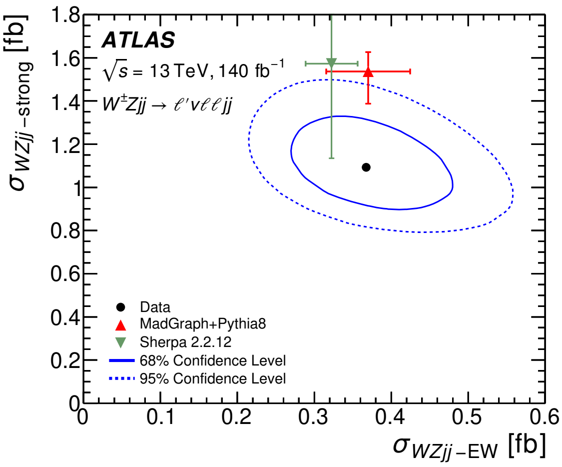

Figure 4. The measured $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ integrated cross-sections compared with predictions from MadGraph+Pythia8 (upward pointing triangle) and Sherpa 2.2.12 (downward pointing triangle). The full and dashed contours around the data points correspond to 68% and 95% CL, respectively.

The $W^{\pm}Zjj$ integrated cross-section in the fiducial phase space is also measured from the fit to be $\sigma_{WZjj} = 1.462 \pm 0.133\,\mathrm{fb} = 1.462 \pm 0.063\,(\mathrm{stat.}) \pm 0.118\,(\mathrm{sys.}) \pm 0.012\,(\mathrm{lumi.})\,\mathrm{fb}$. The corresponding prediction from MadGraph+Pythia8 for strong and electroweak production and including interference effects is $1.907 \pm 0.009\,(\mathrm{stat.}) \pm 0.022\,(\mathrm{PDF})^{+0.117}_{-0.175}\,(\mathrm{scale})$ fb.

9.2 $WZjj$−EW and $WZjj$−strong differential measurements

Dividing the SR in events with $N_{\mathrm{jets}} = 2$ and $N_{\mathrm{jets}} \geq 3$ the $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ production cross-sections of these two categories of events are measured. The measurements are compared in figure 5 to the prediction from MadGraph+Pythia8 and Sherpa 2.2.12. For $N_{\mathrm{jets}} \geq 3$, the predicted $\sigma_{WZjj-\mathrm{EW}}$ cross-sections are in good agreement with the measured value while the predicted $\sigma_{WZjj-\mathrm{strong}}$ cross-section lie within about 2σ of the measurement. However, for $N_{\mathrm{jets}} = 2$ the measured $\sigma_{WZjj-\mathrm{strong}}$ cross-section is lower by a factor of two than the value predicted by both MadGraph+Pythia8 and Sherpa. The predicted values of $\sigma_{WZjj-\mathrm{EW}}$ are found to be in agreement within 1σ of the measured value. The ratio $R_{2/3}$ of the number of events with $N_{\mathrm{jets}} = 2$ to the number of events with $N_{\mathrm{jets}} \geq 3$ is also extracted from data by the simultaneous fit of the two categories to be $R^{\mathrm{EW}}_{2/3} = 1.70 \pm 0.71$ and $R^{\mathrm{QCD}}_{2/3} = 0.21 \pm 0.06$ for $WZjj$−EW and $WZjj$−QCD events, respectively. In comparison, the values predicted by MadGraph+Pythia8 (Sherpa) are $R^{\mathrm{EW}}_{2/3} = 1.43^{+0.06}_{-0.02}\,(1.67 \pm 0.13)$ and $R^{\mathrm{QCD}}_{2/3} = 0.36^{+0.02}_{-0.04}\,(0.38 \pm 0.03)$, respectively.

The $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ production cross-sections are measured differentially in three bins of m_{jj}. The measurements are compared in figure 6 to the prediction from MadGraph+Pythia8 and Sherpa 2.2.12. For $500 < m_{jj} < 1300$ GeV, the MC predictions are found to overestimate the measured $\sigma_{WZjj-\mathrm{strong}}$ value by a factor 1.4. For m_{jj} values above 1300 GeV, the MC predictions agree within approximately 2σ with the measurements, for both $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$.

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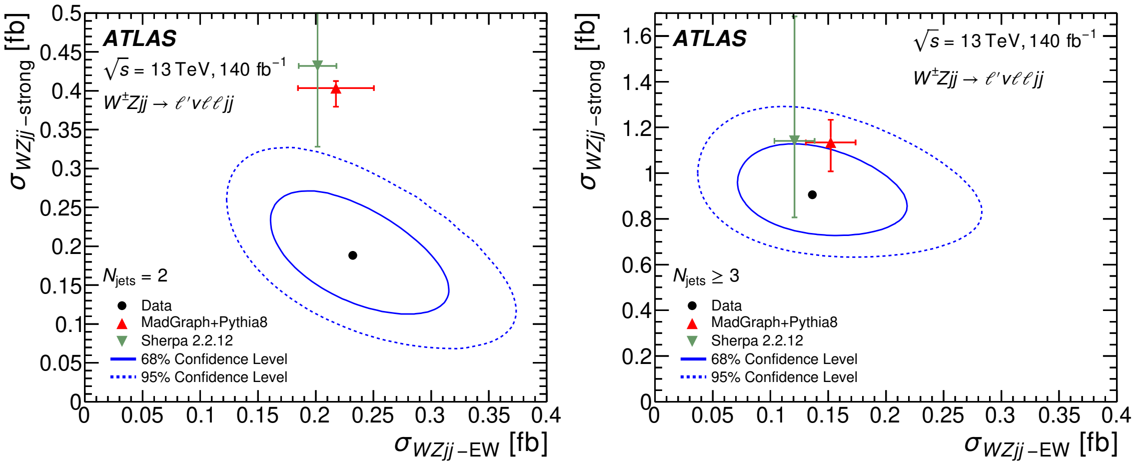

(a) (b)

Figure 5. The measured $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ cross-sections (a) for $N_{\mathrm{jets}} = 2$ and (b) $N_{\mathrm{jets}} \geq 3$ compared with predictions from MadGraph+Pythia8 (upward pointing triangle) and Sherpa 2.2.12 (downward pointing triangle). The full and dashed contours around the data points correspond to 68% and 95% CL, respectively.

9.3 $W^\pm Zjj$ differential measurements

Differential measurements of $W^\pm Zjj$ production cross-section are performed as a function of three variables sensitive to anomalies in the quartic gauge coupling in $W^\pm Zjj$ events [12], namely the scalar sum of the transverse momenta of the three charged leptons associated with the W and Z bosons $\sum p_{\mathrm{T}}^{\ell}$, the difference in azimuthal angle $\Delta\phi(W,Z)$ between the W and Z bosons' directions, and the transverse mass of the $W^\pm Z$ system m_{T}^{WZ}, defined following ref. [12]. These are presented in figure 7.

Measurements are also performed as a function of variables related to the kinematics of jets. The exclusive multiplicity of jets with $p_{\mathrm{T}} > 40$ GeV, $N_{\mathrm{jets}}^{p_{\mathrm{T}}>40\mathrm{GeV}}$, the absolute difference in rapidity between the two tagging jets Δy_{jj}, the invariant mass of the tagging jets m_{jj}, the exclusive multiplicity $N_{\mathrm{jets}}^{\mathrm{gap}}$ of jets with $p_{\mathrm{T}} > 25$ GeV in the gap in η between the two tagging jets, and the azimuthal angle between the two tagging jets $\Delta\phi_{jj}$ are shown in figure 8.

Measurements related to the jet activity in the gap between the two tagging jets are also performed using the subset of events in the SR where a third jet with $p_{\mathrm{T}} > 25$ GeV is present. The exclusive multiplicity $N_{\mathrm{jets}}^{\mathrm{gap}}$ of jets with $p_{\mathrm{T}} > 25$ GeV in the gap in η between the two tagging jets and the Zeppenfeld variable [64], z_{j_3}, for the third jet with $p_{\mathrm{T}} > 25$ GeV are presented in figure 9. The z_{j_3} variable is defined as

$$z_{j_3} = \left| \frac{y_{j_3} - \frac{1}{2}(y_{j_1} + y_{j_2})}{y_{j_1} - y_{j_2}} \right| , \tag{9.1}$$

where y_{j_i} is the rapidity of the jet i.

Finally, a differential measurement of $W^\pm Zjj$ production cross-section is performed as a function of the BDT score and is presented in figure 10. The particle-level BDT score

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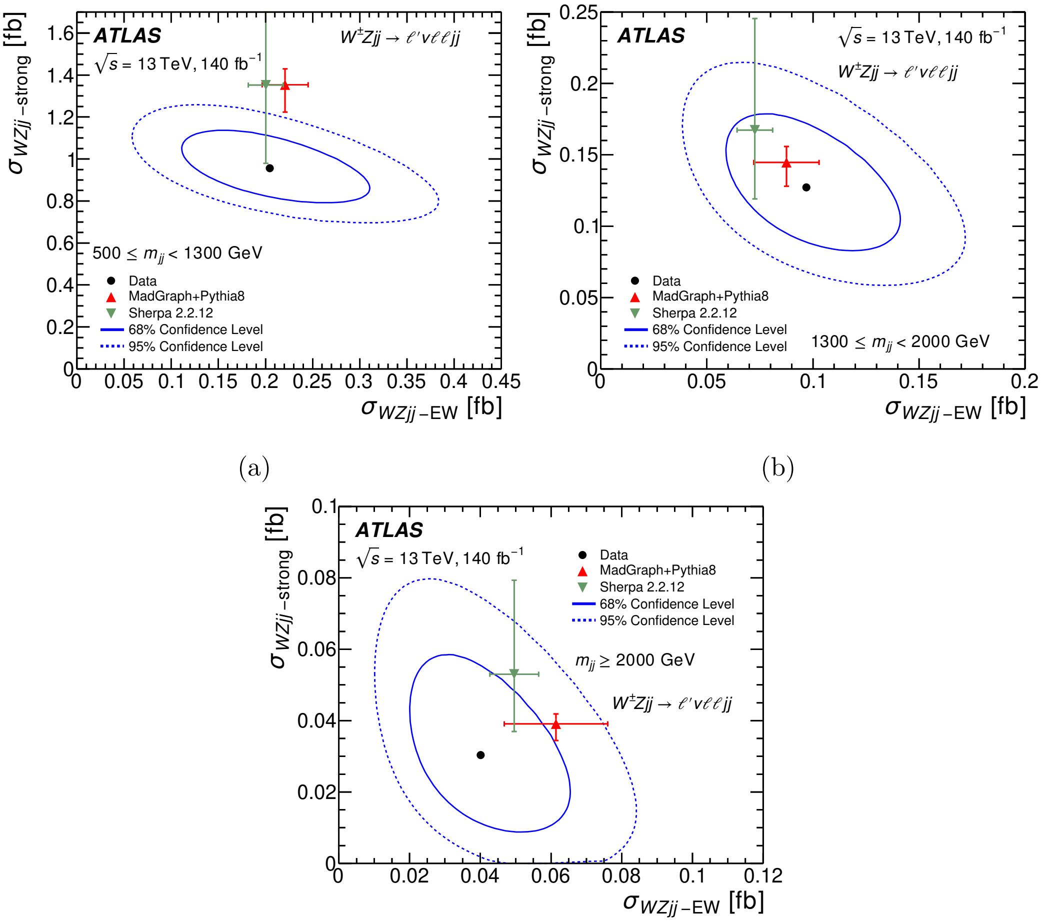

Figure 6. The measured $\sigma_{WZjj-\mathrm{EW}}$ and $\sigma_{WZjj-\mathrm{strong}}$ cross-sections per m_{jj} bin, (a) $500 \leq m_{jj} < 1300$ GeV, (b) $1300 \leq m_{jj} < 2000$ GeV, (c) $m_{jj} \geq 2000$ GeV, compared with predictions from MadGraph+Pythia8 (upward pointing triangle) and Sherpa 2.2.12 (downward pointing triangle). The full and dashed contours around the data points correspond to 68% and 95% CL, respectively.

prediction is evaluated using the same BDT as trained at detector level and evaluated using particle-level input observables.

Total uncertainties in the measurements are dominated by statistical uncertainties. The differential measurements are compared with the prediction from MadGraph+Pythia8, after having rescaled the separate $WZjj$−QCD and $WZjj$−EW components respectively to the inclusive $\sigma_{WZjj-\mathrm{strong}}$ and $\sigma_{WZjj-\mathrm{EW}}$ cross-sections obtained from the profile-likelihood fit to data. Interference effects between the $WZjj$−QCD and $WZjj$−EW processes are incorporated in the $WZjj$−QCD prediction. The measurements are also compared with the predictions from Sherpa 2.2.12.

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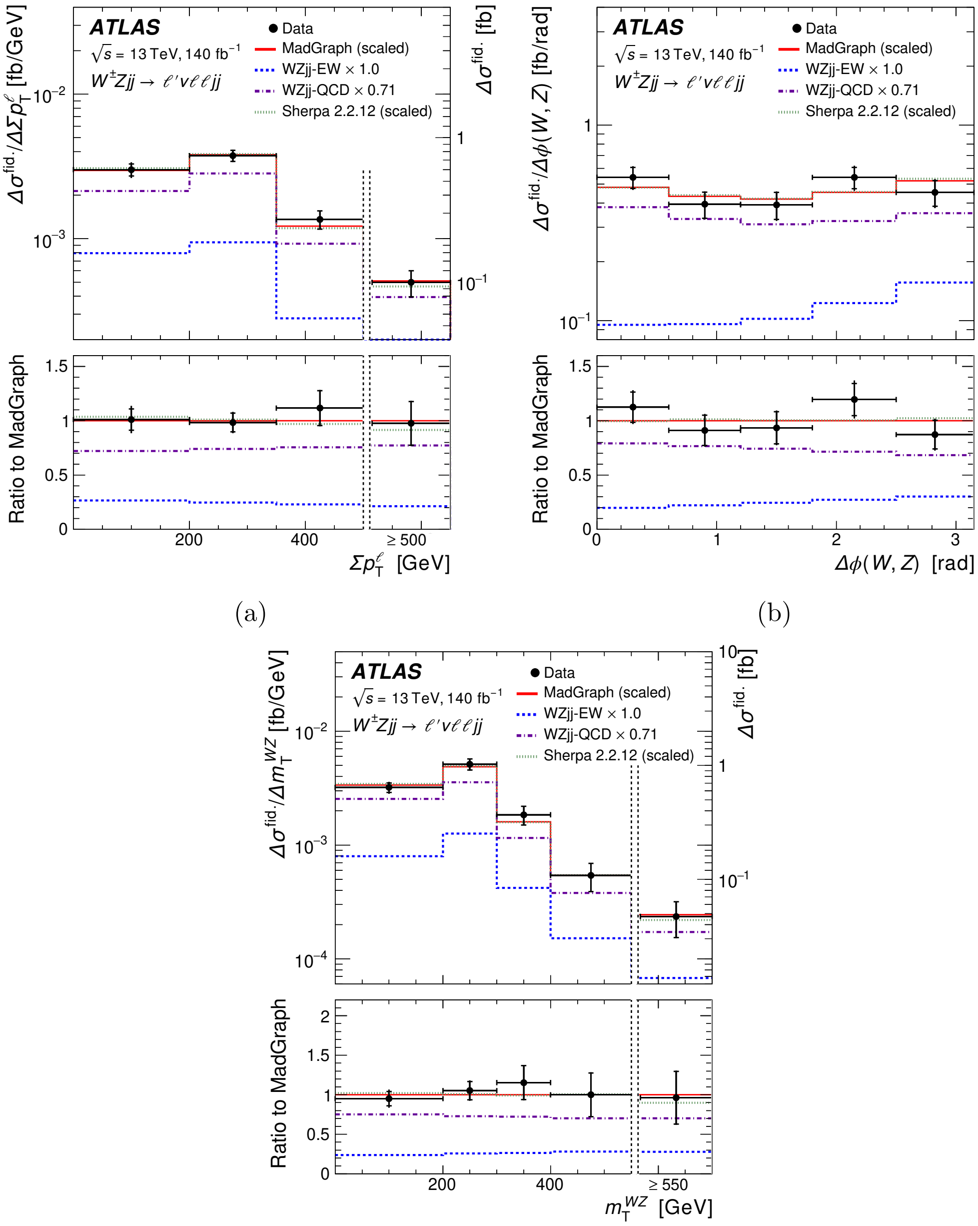

Figure 7. The measured $W^{\pm}Zjj$ differential cross-section in the VBS fiducial phase space as a function of (a) $\sum p_{\mathrm{T}}^{\ell}$, (b) $\Delta\phi(W,Z)$ and (c) m_{T}^{WZ}. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the sum of the rescaled $WZjj$−QCD and $WZjj$−EW predictions from MadGraph+Pythia8 (solid line) and Sherpa 2.2.12 (dotted line). The $WZjj$−EW and $WZjj$−QCD contributions are also represented by dashed and dashed-dotted lines, respectively. In (a) and (c), the right y-axis refers to the last cross-section point, separated from the others by a vertical dashed line, as this last bin is integrated up to the maximum value reached in the phase space. The lower panels show the ratios of the data to the predictions from MadGraph+Pythia8.

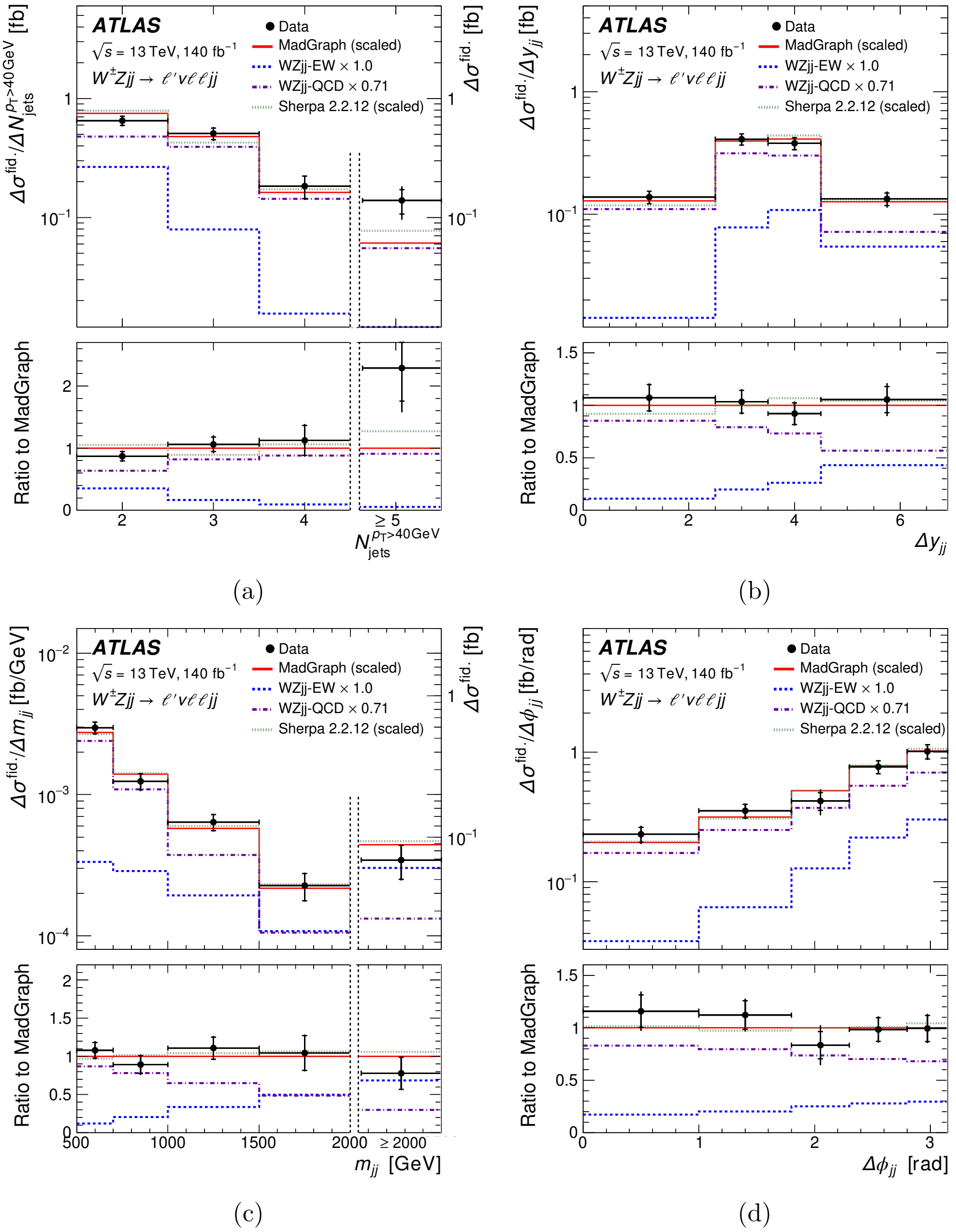

Figure 8. The measured $W^{\pm}Zjj$ differential cross-section in the VBS fiducial phase space as a function of (a) the exclusive jet multiplicity of jets with $p_{\text{T}} > 40$ GeV, $N_{\text{jets}}^{p_{\text{T}}>40\text{GeV}}$, (b) the absolute difference in rapidity between the two tagging jets Δy_{jj}, (c) the invariant mass of the tagging jets m_{jj}, and (d) the azimuthal angle between the two tagging jets $\Delta\phi_{jj}$. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the sum of the rescaled $WZjj$–QCD and $WZjj$–EW predictions from MadGraph+Pythia8 (solid line) and Sherpa 2.2.12 (dotted line). The $WZjj$–EW and $WZjj$–QCD contributions are also represented by dashed and dashed-dotted lines, respectively. In (a) and (c), the right y-axis refers to the last cross-section point, separated from the others by a vertical dashed line, as this last bin is integrated up to the maximum value reached in the phase space. The lower panels show the ratios of the data to the predictions from MadGraph+Pythia8.

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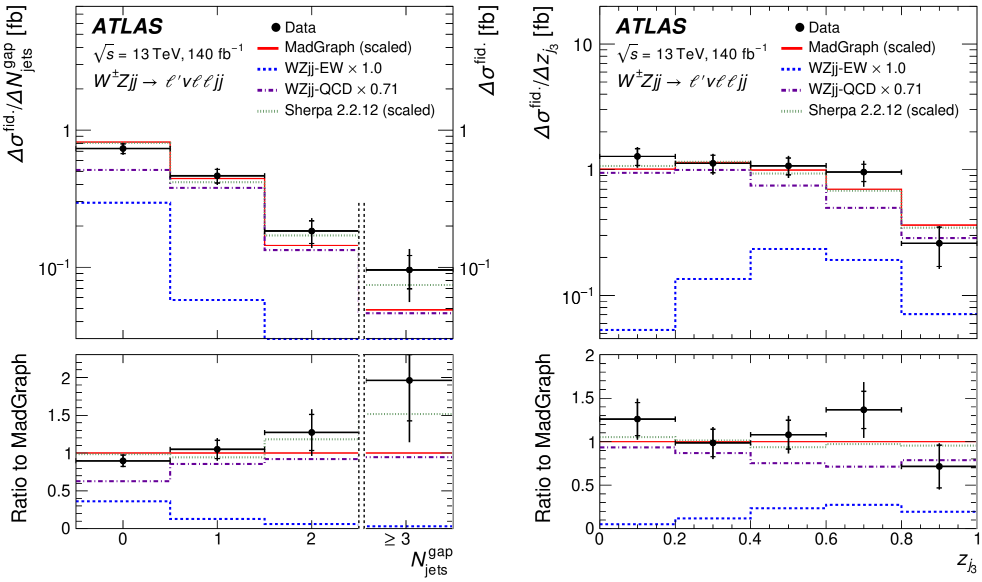


(a) (b)

Figure 9. The measured $W^{\pm}Zjj$ differential cross-section in the VBS fiducial phase space as a function of (a) $N_{\text{jets}}^{\text{gap}}$ the exclusive jet multiplicity of jets with $p_{\text{T}} > 25$ GeV in the gap between the two tagging jets, and (b) z_{j_3} the Zeppenfeld variable. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the sum of the rescaled $WZjj-$QCD and $WZjj-$EW predictions from MadGraph+Pythia8 (solid line) and Sherpa 2.2.12 (dotted line). The $WZjj-$EW and $WZjj-$QCD contributions from MadGraph+Pythia8 are also represented separately by dashed and dashed-dotted lines, respectively. In (a) the right y-axis refers to the last cross-section point, separated from the others by a vertical dashed line, as this last bin is integrated up to the maximum value reached in the phase space. The lower panels show the ratios of the data to the predictions from MadGraph+Pythia8.

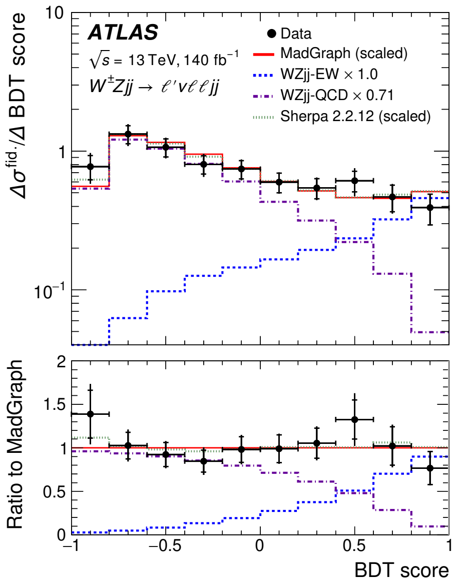


Figure 10. The measured $W^{\pm}Zjj$ differential cross-section in the VBS fiducial phase space as a function of the BDT score. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The measurements are compared with the sum of the rescaled $WZjj$–QCD and $WZjj$–EW predictions from MadGraph+Pythia8 (solid line) and Sherpa 2.2.12 (dotted line). The $WZjj$–EW and $WZjj$–QCD contributions from MadGraph+Pythia8 are also represented separately by dashed and dashed-dotted lines, respectively. The lower panels show the ratios of the data to the predictions from MadGraph+Pythia8.

10 Limits on anomalous quartic gauge couplings

The $WZjj$−EW production can be sensitive to effects beyond the SM affecting the quartic interactions of weak bosons. The measured $W^{\pm}Zjj$ events are therefore used to search for anomalous quartic gauge couplings (aQGC) using an EFT framework [2, 65]. In this model the SM Lagrangian $\mathcal{L}_{\rm SM}$ is extended in an effective Lagrangian $\mathcal{L}_{\rm eff}$ adding higher order operators and their respective Wilson coefficients as:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{f_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \sum_j \frac{f_i^{(8)}}{\Lambda_i^4} O_j^{(8)} + \dots\,, \tag{10.1}$$

where $O_{i,j}^{(6),(8)}$ are dimension-6 and dimension-8 operators, respectively, and involve SM fields with respective dimensionless couplings $f_i^{(6)}$ and $f_j^{(8)}$, and Λ is the energy scale of the new processes. In this study only dimension-8 operators are considered and all dimension-6 couplings, affecting triple gauge boson couplings, are assumed to be equal to zero. Dimension-6 couplings are indeed already constrained by other processes, and especially by inclusive diboson production [66, 67]. The effect of dimension-6 operators in VBS processes is of interest on its own [68, 69], but is not studied here. Nine independent charge-conjugate and parity conserving dimension-8 operators are considered [2]. The $O_{\rm S0,\,1,\,2}$ operators are constructed from the covariant derivative of the Higgs doublet. The $O_{\rm T0,\,1,\,2}$ operators are constructed from the $\rm SU_L(2)$ gauge fields. The mixed operators $O_{\rm M0,\,1,\,7}$ involve the $\rm SU_L(2)$ gauge fields and the Higgs doublet. Because the operators $O_{\rm S0}$ and $O_{\rm S2}$ are Hermitian conjugates of each other, they are varied simultaneously, with equal coefficient values $f_{\rm S0} = f_{\rm S2} = f_{\rm S02}$.

The squared scattering amplitude of the effective field theory prediction for $W^{\pm}Zjj$ production can be written as:

$$\left| A_{\rm SM} + \sum_i c_i A_i \right|^2 = |A_{\rm SM}|^2 + \sum_i c_i\, 2\,{\rm Re}(A_{\rm SM}^* A_i) + \sum_i c_i^2 |A_i|^2 + \sum_{ij, i\neq j} c_i c_j\, 2\,{\rm Re}(A_i A_j^*)\,, \tag{10.2}$$

where $c_i = f_j^{(8)}/\Lambda^4$, $A_{\rm SM}$ is the SM scattering amplitude, $\sum_i c_i\, 2\,{\rm Re}(A_{\rm SM}^* A_i)$ is the amplitude of the interference term between the SM and the dimension-8 operators, $\sum_i {c_i}^2 |A_i|^2$ is the pure dimension-8 contribution, and $\sum_{ij,i\neq j} c_i c_j 2\,{\rm Re}(A_i A_j^*)$ is the amplitude of interferences between two dimension-8 operators, called cross terms. The different terms are simulated separately using MadGraph5_aMC@NLO 2.6.5 interfaced with Pythia 8.240, providing individual MC samples. The same PDF sets and PS modelling as for $W^{\pm}Zjj$ SM events and detailed in section 4 are used. Generated events corresponding to a given value of the EFT coefficient c_i, or c_i and c_j for cross terms, are obtained by multiplying the respective MC samples by the coefficient value and adding them together.

As non-zero aQGC contributions will enhance the production cross-section of $WZjj$−EW events at large diboson invariant masses, a two-dimensional combination of the BDT score, separating $WZjj$−EW from $WZjj$−QCD events, and $m_{\rm T}^{WZ}$ observables is used to look for dimension-8 EFT contributions. Four bins in BDT score ($[-1, -0.25, 0.17, 0.72, 1]$) and five bins in $m_{\rm T}^{WZ}$ ($[0, 400, 750, 1050, 1350, \infty]$ GeV) are used and arranged in a one-dimensional histogram of 20 statistically independent bins, as represented in figure 11. The bin boundaries

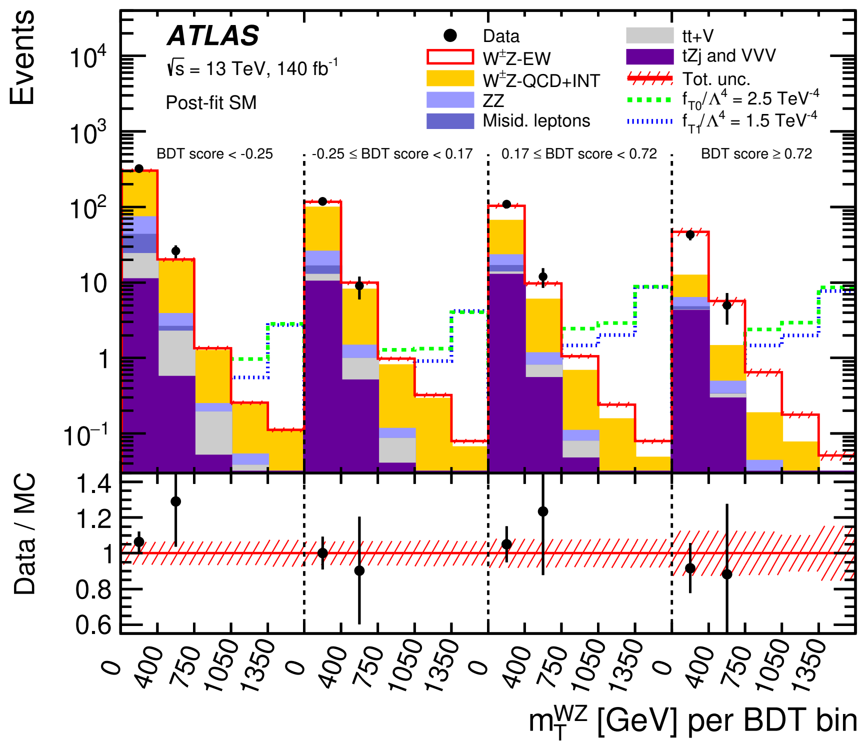


Figure 11. Detector-level one-dimension distribution of the two-dimensional combination of BDT score and m_{T}^{WZ} observables used to obtain limits on EFT coefficients. The SM predicted event yields resulting from the SM-only fit to data are shown. The uncertainty band around the MC expectation includes all systematic uncertainties as obtained from the fit. The contribution of the O_{T0} and O_{T1} operators with illustrative values of the corresponding Wilson coefficients are also represented.

are optimised to obtain the best expected limits when no unitarisation cut-off are applied. The distribution is used to define an extended likelihood function, adding the same control regions as defined in section 7.1. Experimental and theory uncertainties, as discussed in section 8, are included as Gaussian-constrained nuisance parameters. A profile-likelihood ratio test statistic is constructed to estimate the confidence intervals for a given c_i. For each individual c_i, or pair (c_i, c_j) for two-dimensional limits, a maximum-likelihood fit to data is performed by setting other coefficients to zero. The same fit parameterisation as described in section 7.1 is used.

No deviation with respect to the SM predictions is observed and the expected and observed 95% confidence level (CL) lower and upper limits on the given Wilson coefficients are presented in table 4. Coefficients associated to the O_{T0} and O_{T1} operators are the most tightly constraint. The limits are dominated by the pure dimension-8 contribution in eq. (10.2). These limits are similar to those obtained by the CMS experiment also using leptonic decay modes of $W^{\pm}Zjj$ events [7]. Two-dimensional limits at 95% CL on the pair of O_{T0} and O_{T1} operators are also obtained and presented in figure 12. No unitarisation procedure is applied to obtain these results.

The EFT is not a complete model and the presence of non-zero dimension-8 operators violates tree-level unitarity at sufficiently high energy. More physical limits are obtained by

	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	[-1.6, 1.4]	[-1.2, 1.0]
f_{M0}/Λ^4	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	[-16.2, 16.2]	[-11.3, 11.3]
f_{S02}/Λ^4	[-14.2, 14.2]	[-10.4, 10.4]
f_{S1}/Λ^4	[-42, 41]	[-30, 30]

Table 4. Expected and observed 95% CL intervals on the Wilson coefficients of the different dimension-8 operators, with no unitarisation procedure. The notation S02 is used to indicate that the coefficients corresponding to operators O_{S0} and O_{S2} are assigned the same value.

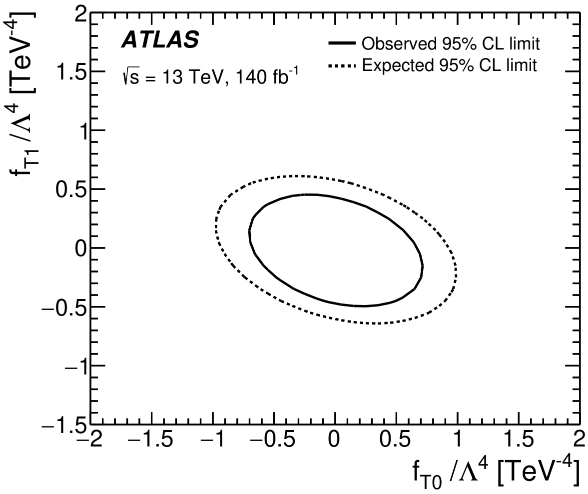
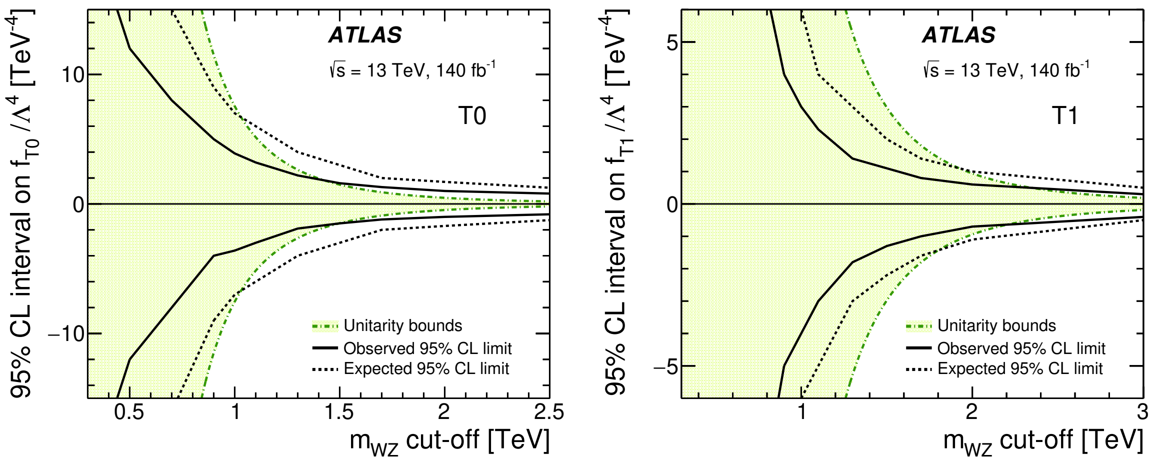


Figure 12. Two-dimensional expected (dashed line) and observed (solid line) 95% CL intervals on Wilson coefficients corresponding to the pair of O_{T0} and O_{T1} operators. No unitarisation procedure is used.

removing the EFT contribution above the unitarity limit and keeping the SM prediction for all WZ invariant masses, even above the unitarity limit. The unitarity limits from ref. [70] are used with only one non-zero Wilson coefficient. These unitarity limits are presented in figure 13 for the Wilson coefficients f_{T0} and f_{T1}, together with the evolution of the expected and observed 95% CL intervals as a function of the cut-off scale m_{WZ} used in the unitarisation procedure.

Table 5 shows the individual 95% CL intervals of each Wilson coefficients obtained when applying a unitarisation cut-off at the unitarity bound. For the O_{S1} operator no crossing with the unitarity bound was found in the scanned region above 600 GeV and therefore no limits are reported.



(a) (b)

Figure 13. Evolution as a function of the cut-off scale of the individual expected (dashed lines) and observed (solid lines) limits at 95% CL on the Wilson coefficients corresponding to the operators (a) O_{T0} and (b) O_{T1}. The shaded area represents the unitarity allowed region. The unitarity bounds (dotted-dashed line) for each operator are defined for one non-zero Wilson coefficient following ref. [70].

	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
$f_{\mathrm{T0}}/\Lambda^4$	[-7.0, 7.0]	[-1.5, 1.6]
$f_{\mathrm{T1}}/\Lambda^4$	[-1.1, 1.0]	[-0.7, 0.6]
$f_{\mathrm{T2}}/\Lambda^4$	[-12, 6]	[-2.4, 1.8]
$f_{\mathrm{M0}}/\Lambda^4$	[-60, 60]	[-12, 12]
$f_{\mathrm{M1}}/\Lambda^4$	[-32, 32]	[-15, 15]
$f_{\mathrm{M7}}/\Lambda^4$	[-30, 30]	[-15, 15]
$f_{\mathrm{S02}}/\Lambda^4$	[-41, 41]	[-18, 18]
$f_{\mathrm{S1}}/\Lambda^4$	—	—

Table 5. Expected and observed 95% CL intervals on the Wilson coefficients of the different dimension-8 operators, with a unitarisation cut-off set at the unitary bound, ie. where the unitary bound and the experimental bound cross. The notation S02 is used to indicate that the coefficients corresponding to operators O_{S0} and O_{S2} are assigned the same value.

11 Conclusion

Measurements of integrated and differential cross-sections of electroweak production of a $W^{\pm}Z$ pair in association with two jets and measurements of its production cross-section in $\sqrt{s} = 13$ TeV pp collisions at the LHC are presented. The data were collected with the ATLAS detector and correspond to an integrated luminosity of 140 fb^{-1}. The measurements use leptonic decays of the gauge bosons into electrons or muons and are performed in a fiducial phase space approximating the detector acceptance that increases the sensitivity to $W^{\pm}Zjj$ electroweak production modes.

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The measured integrated fiducial cross-sections for a single leptonic decay mode of electroweak and inclusive $W^{\pm}Zjj$ production are $\sigma_{WZjj-\mathrm{EW}\rightarrow\ell'\nu\ell\ell jj} = 0.368 \pm 0.037\,(\mathrm{stat.}) \pm 0.059\,(\mathrm{syst.}) \pm 0.003\,(\mathrm{lumi.})$ fb and $\sigma_{WZjj\rightarrow\ell'\nu\ell\ell jj} = 1.462 \pm 0.063\,(\mathrm{stat.}) \pm 0.118\,(\mathrm{syst.}) \pm 0.012\,(\mathrm{lumi.})$ fb, respectively. This is the most precise measurement to date of the $WZjj$−EW production cross-section. The electroweak $W^{\pm}Zjj$ production cross-section is found to agree with the LO SM prediction of 0.37 ± 0.03 fb as calculated with the MadGraph+Pythia8 MC event generator. However, the inclusive $W^{\pm}Zjj$ production cross-section is found to be smaller than the SM prediction from the MadGraph+Pythia8 generator of 1.91 ± 0.17 fb. The reason for this is that the $WZjj$−QCD integrated cross-section is measured to be lower than the prediction from MadGraph+Pythia8 by a factor of 0.7, with a compatibility of 1.8σ between the measurement and the prediction.

Differential cross-sections of electroweak and strong $W^{\pm}Zjj$ production are measured for the first time separately for events with exactly two jets or with more than two jets, as well as in three bins of the invariant mass of the two tagging jets. For electroweak $W^{\pm}Zjj$ production, MC predictions from both MadGraph+Pythia8 or Sherpa 2.2.12 are found to agree with the measured cross-sections within two standard deviations in all sub-categories of signal region events. The strong $W^{\pm}Zjj$ production cross-section is however found to be largely mis-modelled by MC predictions from both MadGraph+Pythia8 or Sherpa 2.2.12 for events with exactly two jets of $p_{\mathrm{T}} > 25$ GeV or with $500 < m_{jj} < 1300$ GeV. Differential cross-sections of $W^{\pm}Zjj$ production, including both the strong and electroweak processes, are also measured in the same fiducial phase space as a function of several kinematic observables.

Finally, the measured $W^{\pm}Zjj$ events are also used to constrain anomalous quartic gauge couplings by extracting 95% confidence level intervals on the dimension-8 operators T0, T1, T2, M0, M1, M7, S02 and S1, with and without consideration of tree-level unitarity violation. These constraints are similar to those obtained by the CMS Collaboration using the $W^{\pm}Zjj$ final state.

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