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Evidence for the production of three massive vector bosons with the ATLAS detector

The ATLAS Collaboration

A search for the production of three massive vector bosons in proton–proton collisions is performed using data at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider in the years 2015–2017, corresponding to an integrated luminosity of 79.8 fb^{-1}. Events with two same-sign leptons ℓ (electrons or muons) and at least two reconstructed jets are selected to search for $WWW \to \ell\nu\ell\nu qq$. Events with three leptons without any same-flavour opposite-sign lepton pairs are used to search for $WWW \to \ell\nu\ell\nu\ell\nu$, while events with three leptons and at least one same-flavour opposite-sign lepton pair and one or more reconstructed jets are used to search for $WWZ \to \ell\nu qq\ell\ell$. Finally, events with four leptons are analysed to search for $WWZ \to \ell\nu\ell\nu\ell\ell$ and $WZZ \to qq\ell\ell\ell\ell$. Evidence for the joint production of three massive vector bosons is observed with a significance of 4.1 standard deviations, where the expectation is 3.1 standard deviations.

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1 Introduction

The joint production of three vector bosons is a rare process in the Standard Model (SM). Studies of triboson production can test the non-Abelian gauge structure of the SM theory and any deviations from the SM prediction would provide hints of new physics at higher energy scales [1–4]. Triboson production has been studied at the Large Hadron Collider (LHC) using proton–proton (pp) collision data taken at $\sqrt{s} = 8$ TeV for processes such as $\gamma\gamma\gamma$ [5], $W\gamma\gamma$ [6, 7], $Z\gamma\gamma$ [7, 8], $WW\gamma$ and $WZ\gamma$ [9, 10], and WWW [11].

This letter presents the first evidence for the joint production of three massive vector bosons in pp collisions using the dataset collected with the ATLAS detector between 2015 and 2017 at $\sqrt{s} = 13$ TeV. At leading order (LO) in quantum chromodynamics (QCD), the production of three massive vector bosons (VVV, with $V = W, Z$) can proceed via the radiation of each vector boson from a fermion, from an associated boson production with an intermediate boson (W, Z/γ^* or H) decaying into two vector bosons, or from a quartic gauge coupling vertex. Representative Feynman diagrams are shown in Figure 1.

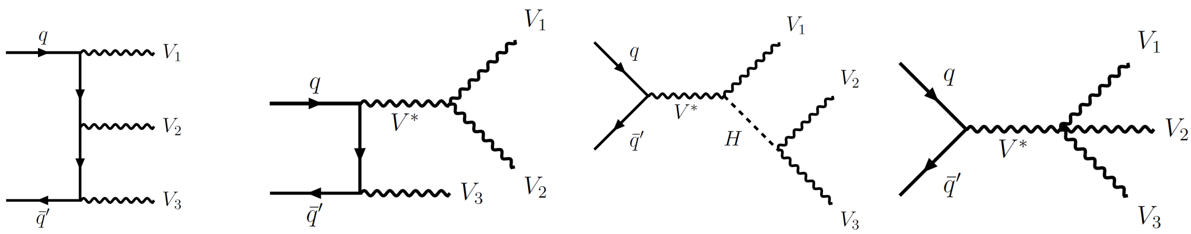


Figure 1: Representative Feynman diagrams at LO for the production of three massive vector bosons, including diagrams sensitive to triple and quartic gauge couplings.

Two dedicated searches are performed, one for the $W^{\pm}W^{\pm}W^{\mp}$ (denoted as WWW) process and one for the $W^{\pm}W^{\mp}Z$ (denoted as WWZ) and $W^{\pm}ZZ$ (denoted as WZZ) processes. To search for the WWW process, events with two same-sign leptons with at least two jets resulting from $WWW \to \ell\nu\ell\nu qq$ ($\ell = e, \mu$, including $\tau \to \ell\nu\nu$) or three leptons resulting from $WWW \to \ell\nu\ell\nu\ell\nu$ are considered and are hereafter referred to as the $\ell\nu\ell\nu qq$ and $\ell\nu\ell\nu\ell\nu$ channels, respectively. To search for the WWZ and WZZ (denoted as WVZ) processes, events with three or four leptons resulting from $WVZ \to \ell\nu qq\ell\ell$, $WWZ \to \ell\nu\ell\nu\ell\ell$, and $WZZ \to qq\ell\ell\ell\ell$ are used. Selection criteria are chosen in order to ensure there is no overlap between different channels. A discriminant that separates the WWW or WVZ signal from the background is defined in each channel. The discriminants are combined using a binned maximum-likelihood fit, which allows the signal yield and the background normalisations to be extracted. The combined observable is the signal strength parameter μ defined as the ratio of the measured WVV cross section to its SM expectation, where one common ratio is assumed for WWW and WVZ.

2 The ATLAS detector, data and simulation samples

The ATLAS detector [12–14] is a multi-purpose particle detector comprised of an inner detector (ID) surrounded by a 2 T superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS) with one barrel and two endcap air-core toroids. The ID consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker, and covers $|\eta| < 2.5$ in pseudorapidity.[1] The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. The MS provides muon triggering capability for $|\eta| < 2.4$ and muon identification and measurement for $|\eta| < 2.7$. A two-level trigger system [15], using custom hardware followed by a software-based trigger level, is used to reduce the event rate to an average of around 1 kHz for offline storage.

The data used were collected between 2015 and 2017 in pp collisions at $\sqrt{s} = 13$ TeV. Only events recorded with a fully operational detector and stable beams are included. Candidate events are selected by single isolated-lepton (e or μ) triggers with transverse momentum thresholds varying from $p_{\mathrm{T}} = 20$ GeV to 26 GeV (depending on the lepton flavour and run period) or single-lepton triggers with thresholds of $p_{\mathrm{T}} = 50$ GeV for muons and $p_{\mathrm{T}} = 60$ GeV for electrons. Due to the presence of two, three or four leptons in the final state, these single-lepton triggers are fully efficient for the triboson signals in the signal regions defined in Sections 4 and 5. The resulting total integrated luminosity is 79.8 fb^{-1}.

Signal and background processes were simulated with several Monte Carlo (MC) event generators, while the ATLAS detector response was modelled [16] with Geant4 [17]. The effect of multiple pp interactions in the same and neighbouring bunch crossings (pile-up) was included by overlaying minimum-bias events simulated with Pythia 8.186 [18] interfaced to EvtGen 1.2.0 [19], referred to as Pythia 8.1 in the following, and using the A3 [20] set of tuned MC parameters, on each generated event in all samples. Triboson signal events [21] were generated using Sherpa 2.2.2 [22–24] with the NNPDF3.0NNLO [25] parton distribution function (PDF) set, where all three bosons are on-mass-shell, using a factorised approach [26]. Events with an off-mass-shell boson through $WH \rightarrow WVV^*$ and $ZH \rightarrow ZVV^*$ were generated using Powheg-Box 2 [27–32] interfaced to Pythia 8.1 for the WWW analysis, while for the WVZ analysis only Pythia 8.1 was used. The generator was interfaced to the CT10 [33] (NNPDF2.3LO [34]) PDF and the AZNLO [35] (A14 [36]) set of tuned MC parameters for the WWW (WVZ) analysis. Both on-mass-shell and off-mass-shell processes were generated at next-to-leading order (NLO) QCD accuracy [37–40] and are included in the signal definition. The expected cross sections for WWW and WWZ production are 0.50 pb and 0.29 pb, respectively, with an uncertainty of ~ 10 %, evaluated by varying parameters in the simulation related to the renormalisation and factorisation scales, parton shower and PDF sets.

Diboson (WW, WZ, ZZ) [26], $W/Z + \gamma$ [21] and single boson (W/Z+jets) [41] production, as well as electroweak production of $W^{\pm}W^{\pm} + 2$ jets, $WZ + 2$ jets, and $ZZ + 2$ jets, were modelled using Sherpa 2.2.2 with the NNPDF3.0NNLO PDF set. In order to improve the agreement between the simulated and observed jet multiplicity distributions for the $WZ \rightarrow \ell\nu\ell\ell$ and $ZZ \rightarrow \ell\ell\ell\ell$ events, a jet-multiplicity based reweighting was applied to the simulated WZ and ZZ samples. Top-quark pair events ($t\bar{t}$) were generated using Powheg-Box 2 [42] interfaced to Pythia 8.230 [43] interfaced to EvtGen 1.6.0. The NNPDF3.0NLO PDF set was used for the matrix-element calculation, while the NNPDF2.3LO PDF set was used for the showering with the A14 set of tuned parameters. Other background processes containing top quarks were generated with MadGraph5_aMC@NLO [44] interfaced to Pythia 8, at LO ($t\bar{t}\gamma$, tZ, $t\bar{t}WW$, and $t\bar{t}t\bar{t}$) or at NLO ($t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$), with MadGraph5_aMC@NLO interfaced to Herwig [45] (tWZ and tWH) or with Powheg-Box 2 [46] interfaced to Pythia 6 (tW).

[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 upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

3 Object definitions and selection criteria

Selected events are required to contain at least one reconstructed primary vertex. If more than one vertex is found, the vertex with the largest p_{T}^2 sum of associated ID tracks is selected as the primary vertex.

Electrons are reconstructed as energy clusters in the EM calorimeter that are matched to tracks found in the ID. Muons are reconstructed by combining tracks reconstructed in the ID with tracks or track segments found in the MS. Leptons need to satisfy $p_{\mathrm{T}} > 15$ GeV and have $|\eta| < 2.47$ for electrons (electrons within the transition region between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.52$, are excluded) and $|\eta| < 2.5$ for muons. Leptons are required to be consistent with originating from the primary vertex by imposing requirements on the transverse impact parameter, d_0, its uncertainty, σ_{d_0}, the longitudinal impact parameter, z_0, and the polar angle θ. These requirements are $|d_0|/\sigma_{d_0} < 5$ and $|z_0 \times \sin\theta| < 0.5$ mm for electrons, and $|d_0|/\sigma_{d_0} < 3$ and $|z_0 \times \sin\theta| < 0.5$ mm for muons. Leptons are required to pass certain identification quality requirements and to be isolated from other particles in both the calorimeters and the ID. The lepton isolation cone size is at most $\Delta R = 0.2$, except for the muon isolation in the ID, where it is at most $\Delta R = 0.3$. Electrons have to satisfy the likelihood-based "Tight" quality definition and pass the "Fix (Loose)" isolation requirement [47]. For the WWW (WVZ) analysis, muons are required to pass the "Medium" ("Loose") identification criteria and the "Gradient" ("FixedCutLoose") isolation requirement [48]. These requirements are more restrictive in the WWW analysis because a larger contamination from jets misidentified as leptons or leptons from hadron decays (including b- and c-hadron decays), referred to as "non-prompt" leptons in the following, is expected.

A dedicated boosted decision tree (BDT), termed "non-prompt lepton BDT" [49], is used to reject leptons likely to originate from heavy-flavour decays. In addition, electrons have to pass the "charge misidentification suppression BDT" [47] to reject electrons likely to have the electric charge wrongly measured.

The non-prompt lepton BDT uses isolation and b-tagging information derived from energy deposits and tracks in a cone around the lepton direction. The charge misidentification suppression BDT uses the electron track impact parameter, the track curvature significance, the cluster width and the quality of the matching between the cluster and its associated track. Leptons passing all requirements listed above are referred to as "nominal" leptons.

Jets are reconstructed from calibrated topological clusters built from energy deposits in the calorimeter [50] using the anti-k_t algorithm with a radius parameter of 0.4 [51, 52] and calibrated using the techniques described in Ref. [53]. Jet candidates are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$. To reject jets likely to be arising from pile-up collisions, an additional criterion using the jet vertex tagger [54] discriminant is applied for jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$. Jets containing b-hadrons (b-jets) are identified by a multivariate discriminant combining information from algorithms using secondary vertices reconstructed within the jet and track impact parameters [55, 56], with an efficiency of 85% (70%) for the WWW (WVZ) analysis.

The missing transverse momentum, whose magnitude is denoted $E_{\mathrm{T}}^{\mathrm{miss}}$, is defined as the negative vector sum of the p_{T} of all reconstructed and calibrated objects in the event. This sum includes a term to account for the energy from low-momentum particles that are not associated with any of the selected objects, and is calculated from ID tracks matched to the reconstructed primary vertex in the event [57]. The sum also includes jets with $|\eta| > 2.5$ and $p_{\mathrm{T}} > 30$ GeV.

The object reconstruction and identification algorithms do not always result in unambiguous identifications. An overlap removal algorithm is therefore applied. Electrons sharing a track with any muons are removed. Any jet within $\Delta R < 0.2$ of an electron is removed and electrons within $\Delta R < 0.4$ of any remaining jets are removed. Jets with less than three associated tracks and within $\Delta R < 0.2$ of a muon are removed, and muons within $\Delta R < 0.4$ of any of the remaining jets are removed.

At least one reconstructed "trigger" lepton with a minimum p_{T} is required to match within $\Delta R < 0.15$ a lepton with the same flavour reconstructed by the trigger algorithm. The thresholds for the trigger (other) leptons are 27 GeV (20 GeV) for the WWW analysis, and from 21 GeV to 27 GeV (15 GeV), depending on the run period and lepton flavour, for the WVZ analysis.

4 Analysis targeting WWW

The experimental signature of the $\ell\nu\ell\nu qq$ process is the presence of two same-sign leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$, and two jets. The signature of the $\ell\nu\ell\nu\ell\nu$ process is the presence of three leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$. To reduce the background contributions from processes that have more than two (three) leptons in the $\ell\nu\ell\nu qq$ ($\ell\nu\ell\nu\ell\nu$) channel a "veto lepton" definition is introduced. Compared with the nominal lepton selection criteria described in Section 3, the veto lepton p_{T} threshold is lowered to 7 GeV, and the isolation, non-prompt lepton BDT, charge misidentification suppression BDT, and impact parameter requirements are removed. For veto electrons, the likelihood-based Loose identification definition [47] is used. For veto muons, the Loose identification definition [48] is used, and the pseudorapidity range is extended to $|\eta| < 2.7$.

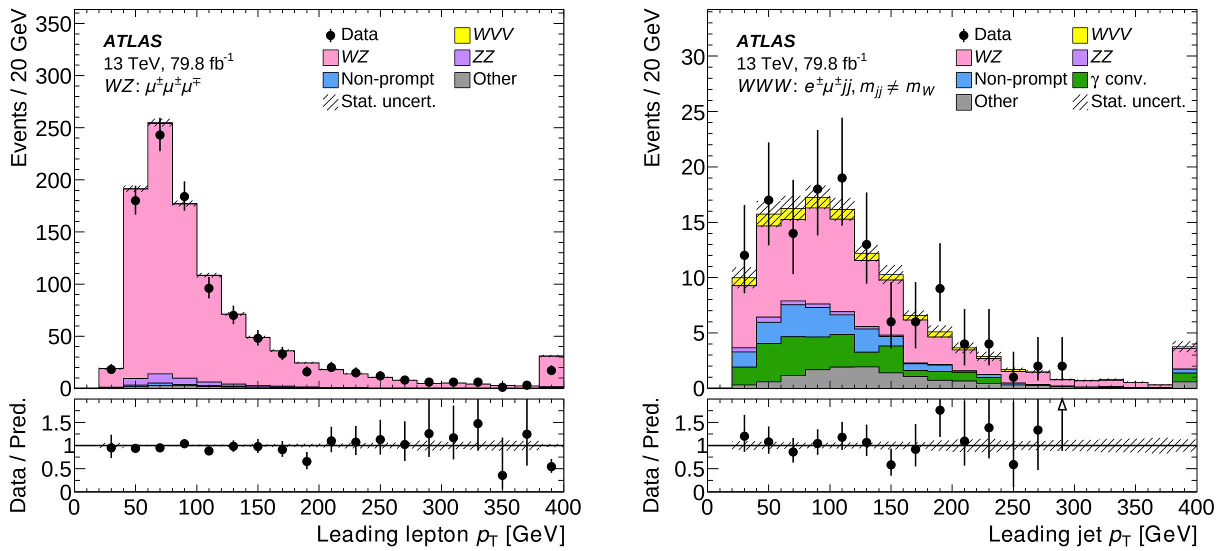
To select $\ell\nu\ell\nu qq$ candidates, events are required to have exactly two nominal leptons with $p_{\mathrm{T}} > 20$ GeV and the same electric charge, at least two jets, and no identified b-jets. Four regions are considered, based on the lepton flavour, namely ee, $e\mu$, μe, and $\mu\mu$, where $e\mu$ denotes the highest-p_{T} (leading) lepton being an electron, while μe denotes the leading lepton being a muon. Events with an additional veto lepton are removed. The invariant mass of the dilepton system is required to be in the range $40 < m_{\ell\ell} < 400$ GeV. The upper mass limit reduces the contribution from the WZ+jets process. The leading (sub-leading) jet must have $p_{\mathrm{T}} > 30\,(20)$ GeV and $|\eta| < 2.5$. A dijet system, formed by the two jets with the largest p_{T}, is required to have $m_{jj} < 300$ GeV and $|\Delta\eta_{jj}| < 1.5$, where m_{jj} is the dijet invariant mass and $\Delta\eta_{jj}$ is the pseudorapidity separation between the two jets. The cuts applied on the dijet system mainly reduce the contributions from the same-sign WW vector boson scattering process. Additionally, in the ee final state, $E_{\mathrm{T}}^{\mathrm{miss}}$ is required to be above 55 GeV and $m_{\ell\ell}$ must satisfy $m_{\ell\ell} < 80$ GeV or $m_{\ell\ell} > 100$ GeV, to reduce contamination from $Z \to ee$ where the charge of one electron is misidentified. The $m_{\ell\ell}$ cut is not applied in the $\mu\mu$ final state, since the muon charge misidentification rate is found to be negligible, nor is it applied in the $e\mu$ and μe final states, where the contamination from Z events is small.

To select $\ell\nu\ell\nu\ell\nu$ candidates, events are required to have exactly three nominal leptons with $p_{\mathrm{T}} > 20$ GeV and no identified b-jets. Events with an additional veto lepton are removed. To reduce the contribution from the $WZ \to \ell\nu\ell\ell$ process, events are required to have no same-flavour opposite-sign (SFOS) lepton pairs, and thus only $\mu^{\pm}e^{\mp}e^{\mp}$ and $e^{\pm}\mu^{\mp}\mu^{\mp}$ events are selected.

A major background originates from the WZ+jets $\to \ell\nu\ell\ell$+jets process, contributing to the $\ell\nu\ell\nu qq$ channel when one lepton is not reconstructed or identified, or to the $\ell\nu\ell\nu\ell\nu$ channel, when a Z boson decays into a pair of τ leptons both of which decay to an electron or muon.

Simulation is used to estimate this background. The WZ+jets modelling is tested in a WZ-dominated validation region defined by selecting events with exactly three nominal leptons with one SFOS lepton pair.

In addition, events are required to have no b-jets reconstructed, $E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV and the trilepton invariant mass $m_{\ell\ell\ell} > 110$ GeV. Data and simulation agree in this validation region, as shown in Figure 2(a) for the leading lepton p_{T} distribution.



(a) (b)

Figure 2: Comparison between data and prediction of (a) the leading lepton p_{T} distribution in the WZ validation region and (b) the leading jet p_{T} distribution in the W sideband region. The contribution denoted "Other" is dominated by the $W^{\pm}W^{\pm} + 2$ jets process for the W sideband region. The contribution denoted "γ-conv." is described in the text. Predictions from simulation are scaled to the integrated luminosity of the data using the theoretical cross sections of each sample. The hatched area represents the statistical uncertainty in the prediction due to the limited number of simulated events. The last bin contains the overflow. The bottom panel displays the ratio of data to the total prediction.

Contributions from SM processes that produce at least one non-prompt lepton are estimated using a data-driven method as described in Ref. [58] by introducing "fake" leptons. The definitions of nominal and fake leptons are mutually exclusive. Fake electrons have to satisfy the likelihood-based Medium [47] but fail the Tight identification, and the isolation, non-prompt lepton BDT and charge misidentification suppression BDT requirements are removed. Fake muons have the impact parameter requirements loosened to $|d_0|/\sigma_{d_0} < 10$, and both isolation and non-prompt lepton BDT requirements are removed. Additionally, they have to fail the nominal muon definition. Simulation shows that the $t\bar{t}$ process is the dominant contributor of events with fake leptons, with more than 90% in the $\ell\nu\ell\nu qq$ channel and more than 95% in the $\ell\nu\ell\nu\ell\nu$ channel originating from this process. Events containing one (two) nominal lepton(s) and one fake lepton with $p_{\mathrm{T}} > 20$ GeV are scaled by a "fake factor" to predict the non-prompt lepton background contribution in the $\ell\nu\ell\nu qq$ ($\ell\nu\ell\nu\ell\nu$) channel. The fake factor is the ratio of the number of non-prompt leptons passing the nominal lepton criteria over the number passing the fake lepton criteria. Its value is derived from two $t\bar{t}$-enriched regions selected with two or three leptons (no SFOS lepton pairs) and exactly one b-jet. One of the same-sign leptons passes either nominal or fake lepton criteria, while the other lepton(s) must pass the nominal lepton criteria. The fake factor is found to be 0.017 ± 0.010 for electrons and 0.035 ± 0.005 for muons.

Events resulting from the $V\gamma jj$ production can pass the ee, $e\mu$ and μe signal selection criteria if the photon is misreconstructed as an electron. This contribution (referred to as "γ conv.") is evaluated using a data-driven method similar to the non-prompt lepton background evaluation by introducing "photon-like" electrons. A photon-like electron is an object reconstructed like a nominal electron except that the track has no hit in the innermost layer of the pixel detector and the non-prompt lepton BDT and charge misidentification suppression BDT requirements are not applied. The photon fake factor is determined in two regions selected with two nominal muons, no b-jets, and one nominal or photon-like electron. The trilepton invariant mass is required to satisfy $80\,\text{GeV} < m_{e\mu\mu} < 100\,\text{GeV}$. Most of these events contain a $Z \to \mu\mu$ decay, where one muon radiates a photon, which is misreconstructed as an electron.

The charge misidentification background originates from processes that produce oppositely-charged prompt leptons, where one lepton's charge is misidentified and results in final states with two same-sign leptons. The background is estimated using a data-driven technique as described in Ref. [11].

All $\ell\nu\ell\nu qq$ candidates with $m_{jj} < 50\,\text{GeV}$ or $m_{jj} > 120\,\text{GeV}$ (denoted as the "W sideband" region) are used to validate the modelling of different backgrounds described above. Data and prediction agree, as shown in Figure 2(b) for the leading jet p_{T} distribution. Events with $m_{jj} < 300\,\text{GeV}$ are used in the fit to extract the signal.

5 Analysis targeting WWZ and WZZ

The experimental signature of the $WVZ \to \ell\nu qq\ell\ell$, $WWZ \to \ell\nu\ell\nu\ell\ell$, and $WZZ \to qq\ell\ell\ell\ell$ processes is the presence of three or four charged leptons. In order to increase the signal acceptance, "loose" leptons are defined in addition to nominal leptons, the latter being a subset of the former. Loose leptons have both the isolation and non-prompt lepton BDT requirements removed. In addition, loose electrons are required to pass the likelihood-based Loose identification definition and the charge misidentification suppression BDT requirement is removed.

Six regions are defined with either three or four loose leptons, sensitive to triboson final states containing Z bosons. Among all possible SFOS lepton pairs, the one with $m_{\ell\ell}$ closest to the Z boson mass is defined as the best Z candidate. In all regions, the presence of such a best Z candidate with $|m_{\ell\ell} - 91.2\,\text{GeV}| < 10\,\text{GeV}$, is required. Furthermore, any SFOS lepton pair combination is required to have a minimum invariant mass of $m_{\ell\ell} > 12\,\text{GeV}$. Events with b-tagged jets are vetoed.

For the three-lepton channel, the lepton which is not part of the best Z candidate is required to be a nominal lepton. The scalar sum of the transverse momenta of all leptons and jets (H_{T}) is required to be larger than 200 GeV. This significantly reduces the contribution of the $Z \to \ell\ell$ processes with one additional non-prompt lepton. Three regions are defined according to the number of jets in the event: one jet (3ℓ-1j), two jets (3ℓ-2j), and at least three jets (3ℓ-3j).

For the four-lepton channel, the third and fourth leading leptons are required to be nominal leptons. The two leptons which are not part of the best Z candidate definition are required to have opposite charges. These "other leptons" are used to define three regions, depending on whether they are different-flavour (4ℓ-DF), or same-flavour and their mass lies within a window of 10 GeV around the Z boson mass (4ℓ-SF-Z) or their mass is outside this window (4ℓ-SF-noZ).

In each of the six regions the distribution of a dedicated boosted-decision-tree discriminant, separating the WVZ signal from the dominating diboson background, is fed as input to the binned maximum-likelihood fit to extract the signal. For the three-lepton channels, 13, 15, and 12 input variables are used for the 3ℓ-1j,

3ℓ-2j, and 3ℓ-3j final states, respectively, while for the four-lepton channels, six input variables are used for each of the 4ℓ-DF, 4ℓ-SF-Z and 4ℓ-SF-noZ final states. These input variables are listed in Table 1.

Due to the required presence of nominal leptons in the three- and four-lepton channels, backgrounds with a Z boson and non-prompt leptons are reduced. The remaining backgrounds are dominated by processes with prompt leptons and thus all backgrounds are estimated using simulation. The WZ+jets and Z+jets backgrounds are validated in a region defined in the same way as the 3ℓ-1j region, with the exception that no requirement on H_T is applied, the third-highest-p_T lepton is required to have a small transverse momentum ($10\,\text{GeV} < p_T < 15\,\text{GeV}$), and the invariant mass of the three leptons has to be smaller than 150 GeV. Data and expectation agree in the 3ℓ-1j validation region, as shown in Figure 3(a) for the transverse momentum distribution of the third-highest-p_T lepton.

The $t\bar{t}Z$ background is determined in a region defined like the 3ℓ-3j region with the exception that no requirement on H_T is applied, and at least four jets are required, of which at least two are b-tagged. This region is included as a single-bin control region (CR) in the fit model, outlined in Section 6. Data and expectation agree, as shown in Figure 3(b) for the $t\bar{t}Z$ control region.

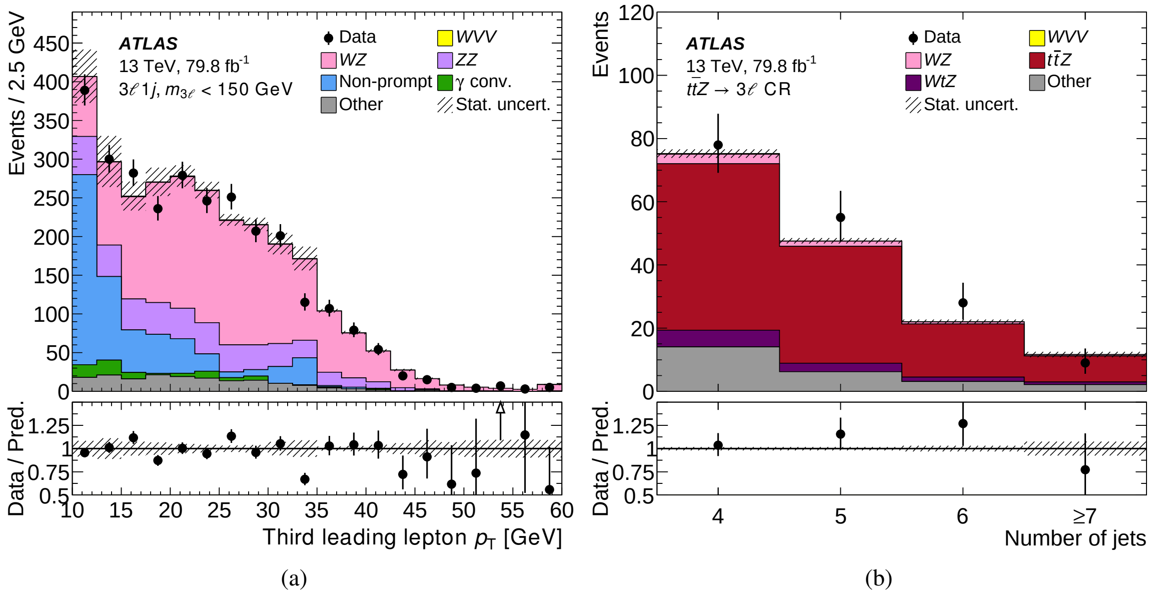


Figure 3: Data compared with expectations for (a) the transverse momentum of the third-highest-p_T lepton in the 3ℓ-1j region with the additional requirement $m_{\ell\ell\ell} < 150\,\text{GeV}$, no requirement on H_T, and including the $10\,\text{GeV} < p_T < 15\,\text{GeV}$ validation region and (b) the number of jets in the $t\bar{t}Z$ control region. The contributions denoted "Other" are dominated by (a) the tZ and VH processes, where the Higgs boson does not decay to two massive bosons, and (b) the tZ process. Predictions from simulation are scaled to the integrated luminosity of the data using the theoretical cross sections of each sample. The hatched area represents the statistical uncertainty in the prediction due to the limited number of simulated events. The last bin contains the overflow. The bottom panel displays the ratio of data to the total prediction.

Table 1: List of input variables used in the multivariate analysis for each of the WVZ channels, denoted by $\times$. The subscripts 1, 2 and 3 refer to the leading, subleading and third leading lepton or jet. The definitions of "best Z" and "other leptons" are given in the text. The variable $m_{\mathrm{T}}(W)$ is the W-boson transverse mass of the leptonically decaying W-boson candidate. Among the invariant masses formed by all possible jet pairs, the one closest to the W-boson mass defines the "m_{jj} of best W" and the smallest one defines the "smallest m_{jj}". Finally, the leptonic and hadronic H_{T} are calculated as the scalar sum of the p_{T} of all leptons or all jets, respectively.

Variable	3ℓ-1j	3ℓ-2j	3ℓ-3j	4ℓ DF	4ℓ SF on-shell	4ℓ SF off-shell
$p_{\mathrm{T}}(\ell_1)$	$\times$	$\times$				
$p_{\mathrm{T}}(\ell_2)$	$\times$	$\times$	$\times$			
$p_{\mathrm{T}}(\ell_3)$	$\times$	$\times$	$\times$			
Sum of $p_{\mathrm{T}}(\ell)$	$\times$	$\times$	$\times$			
$m_{\ell_1\ell_2}$	$\times$	$\times$				
$m_{\ell_1\ell_3}$	$\times$	$\times$				
$m_{\ell_2\ell_3}$	$\times$	$\times$				
$m_{\ell\ell}$ of best Z					$\times$	$\times$
$m_{\ell\ell}$ of other leptons				$\times$	$\times$	$\times$
$m_{3\ell}$	$\times$	$\times$	$\times$			
$m_{4\ell}$				$\times$	$\times$	$\times$
Sum of lepton charges	$\times$	$\times$	$\times$			
$p_{\mathrm{T}}(j_1)$	$\times$	$\times$				
$p_{\mathrm{T}}(j_2)$		$\times$	$\times$			
Sum of $p_{\mathrm{T}}(j)$			$\times$			
Number of jets			$\times$	$\times$	$\times$	$\times$
$m_{j_1j_2}$		$\times$				
$m_{\mathrm{T}}(W_\ell)$		$\times$				
m_{jj} of best W			$\times$			
Smallest m_{jj}			$\times$			
$E_{\mathrm{T}}^{\mathrm{miss}}$		$\times$	$\times$	$\times$	$\times$	$\times$
H_{T}	$\times$	$\times$			$\times$	$\times$
Leptonic H_{T}				$\times$		
Hadronic H_{T}				$\times$		
Invariant mass of all leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$		$\times$			
Invariant mass of the best Z leptons and j_1	$\times$					

6 Signal extraction and combination

The WWW, WWZ and WZZ regions are combined using the profile likelihood method described in Ref. [59] based on a simultaneous fit to distributions in the signal and background control regions. A total of eleven signal regions are considered: four regions (ee, $e\mu$, μe, and $\mu\mu$) for the $\ell\nu\ell\nu qq$ channel, one region (μee and $e\mu\mu$ combined) for the $\ell\nu\ell\nu\ell\nu$ channel, three regions (3ℓ-1j, 3ℓ-2j, and 3ℓ-3j) for the WVZ three-lepton channel, and three regions (4ℓ-DF, 4ℓ-SF-Z, and 4ℓ-SF-noZ) for the WVZ four-lepton channel. One control region is considered: the $t\bar{t}Z$ control region described in Section 5. The distributions used in the fit are the m_{jj} distributions for the $\ell\nu\ell\nu qq$ channel and the BDT distributions for the WVZ three-lepton and four-lepton channels. The number of selected events in the $\ell\nu\ell\nu\ell\nu$ channel and the $t\bar{t}Z$ control region are each included as a single bin in the fit. In total, 186 bins are used in the combined fit.

A binned likelihood function $\mathcal{L}(\mu, \boldsymbol{\theta})$ is constructed as a product of Poisson probability terms over all bins considered. This likelihood function depends on the signal-strength parameter μ, a multiplicative factor that scales the number of expected signal events, and $\boldsymbol{\theta}$, a set of nuisance parameters that encode the effect of systematic uncertainties of the signal and background expectations. The nuisance parameters are implemented in the likelihood function as Gaussian, log-normal or Poisson constraints. The same value for $\mu = \mu_{WVV}$ is assumed for the on- and off-mass-shell WWW, WWZ and WZZ processes. Correlations of systematic uncertainties arising from common sources are maintained across processes and channels.

Experimental uncertainties are related to the lepton trigger, reconstruction and identification efficiencies [47, 48], lepton isolation criteria [60], lepton energy (momentum) scale and resolution [48, 61], jet energy scale and resolution [53], jet vertex tagging [54, 62], b-tagging [56], modelling of pile-up and missing transverse momentum [57], and integrated luminosity [63, 64]. Nuisance parameters related to these uncertainties are treated as correlated between all channels. The time-dependence of the efficiencies, scales and resolutions across the various run periods is taken into account.

For each of the background processes evaluated using simulation, a nuisance parameter representing its normalisation uncertainty is included. The following prior uncertainties in the normalisations are assumed: 20% for WZ and ZZ; 40% for Z+jets, 10% [65] for WtZ, 30% [66, 67] for tZ, 11% [68] for $t\bar{t}Z$, and 30% for VH not producing three massive bosons. For dominant backgrounds from the WZ and ZZ processes, the simultaneous fit model has the power to constrain their normalisations at the ~5% level, independently of the assumed prior. In addition, shape-only variations for backgrounds from the WZ and ZZ processes are derived from alternative samples, generated using Powheg [69] with Pythia 8 for the parton shower to account for differences in the modelling of diboson production and showering. Shape variations due to renormalisation and factorisation scales are also considered for these two processes. The prior uncertainties assumed for Z+jets and VH cover the observed data/simulation agreement in validation regions, and the calculations in Ref. [68], respectively. The impact of these uncertainties on the measurement is small.

Uncertainties in data-driven background evaluations mainly come from statistical and systematic uncertainties in the charge misidentification rate, lepton fake factor, and photon-like electron scale factor. Additional uncertainties come from the statistical uncertainties of the subsamples used to extrapolate the background evaluations to the signal region. Nuisance parameters are treated as correlated for backgrounds evaluated using the same method and from the same systematic sources.

Shape-only variations of the signal distributions due to QCD renormalisation and factorisation scales, PDF, and parton-shower matching scales are considered in the simultaneous fit. The corresponding nuisance parameters are treated as correlated between the $\ell\nu\ell\nu qq$ and $\ell\nu\ell\nu\ell\nu$ channels in the WWW analysis and between three-lepton and four-lepton channels in the WVZ analysis. These parameters are treated as uncorrelated between the WWW and WVZ analyses.

Tables 2 and 3 show the post-fit background, signal and observed yields for the signal regions and the background control region. The contribution to the WVV signal from VH associated production is $\sim 40\%$ in the WWW fiducial regions and $\sim 30\%$ in the WVZ fiducial regions. Contributions from SM processes producing the same detector signature as events in these signal regions (or the $t\bar{t}Z$ control region) besides those listed are combined into "Other". The uncertainties shown include both statistical and systematic uncertainties. Data and predictions agree in all channels.

Table 2: Post-fit background, signal and observed yields for the $\ell\nu\ell\nu qq$ and $\ell\nu\ell\nu\ell\nu$ channels. Uncertainties of the predictions include both statistical and systematic uncertainties added in quadrature; correlations among systematic uncertainties are taken into account in the calculation of the total.

	ee	$e\mu$	μe	$\mu\mu$	$\mu ee + e\mu\mu$
WWW	9.9 ± 3.3	26 ± 9	23 ± 8	30 ± 10	15 ± 5
WZ	37.4 ± 2.2	121 ± 6	96 ± 5	119 ± 6	8.6 ± 0.5
ZZ	0.46 ± 0.05	5.11 ± 0.25	3.44 ± 0.18	4.12 ± 0.24	0.69 ± 0.03
Non-prompt	6.1 ± 3.0	35 ± 5	17 ± 9	37 ± 7	9.4 ± 1.5
γ conv.	20.9 ± 1.9	35.0 ± 3.1	76 ± 7	–	1.06 ± 0.11
Other	12.9 ± 1.0	25.7 ± 1.7	20.3 ± 1.3	25.3 ± 1.6	3.5 ± 0.4
Total	88 ± 4	249 ± 9	237 ± 10	216 ± 9	38 ± 4
Data	87	239	235	237	27

Table 3: Post-fit background, signal and observed yields for the three-lepton and four-lepton channels as well as the $t\bar{t}Z$ control region. Uncertainties of the predictions include both statistical and systematic uncertainties added in quadrature; correlations among systematic uncertainties are taken into account in the calculation of the total.

	4ℓ-DF	4ℓ-SF-Z	4ℓ-SF-noZ	3ℓ-1j	3ℓ-2j	3ℓ-3j	$t\bar{t}Z$ CR
WVZ	9.6 ± 3.5	5.0 ± 1.8	10 ± 4	62 ± 23	85 ± 30	84 ± 30	–
WZ	1.11 ± 0.13	–	1.08 ± 0.14	2580 ± 80	1830 ± 60	1110 ± 50	5.7 ± 0.4
ZZ	6.7 ± 0.4	933 ± 28	310 ± 10	344 ± 12	182 ± 13	98 ± 12	0.58 ± 0.06
$t\bar{t}Z$	5.1 ± 0.5	0.55 ± 0.08	4.5 ± 0.5	7.6 ± 1.1	22.6 ± 2.5	82 ± 8	122 ± 9
tWZ	1.9 ± 0.4	0.23 ± 0.10	1.6 ± 0.4	4.2 ± 0.9	11.2 ± 2.2	20 ± 4	10.3 ± 0.8
Non-prompt	–	–	0.18 ± 0.12	130 ± 50	77 ± 28	59 ± 24	0.47 ± 0.18
γ conv.	–	–	–	42 ± 8	32 ± 7	9.6 ± 3.4	0.4 ± 0.6
Other	0.4 ± 0.4	1.8 ± 1.1	1.0 ± 0.7	200 ± 15	182 ± 16	120 ± 10	24.4 ± 2.5
Total	24.8 ± 3.5	941 ± 27	329 ± 10	3370 ± 70	2430 ± 40	1580 ± 40	160 ± 10
Data	28	912	360	3351	2438	1572	170

Figure 4 shows the comparison between data and post-fit prediction of the combined m_{jj} distribution for the $\ell\nu\ell\nu qq$ channel, the number of selected events for the $\ell\nu\ell\nu\ell\nu$ channel, and the BDT output distributions in the 3ℓ-2j and 4ℓ-DF regions for the WVZ analysis. The 3ℓ-2j and 4ℓ-DF regions are chosen since they have the best sensitivity among the three-lepton and four-lepton channels. Data and predictions agree in all distributions.

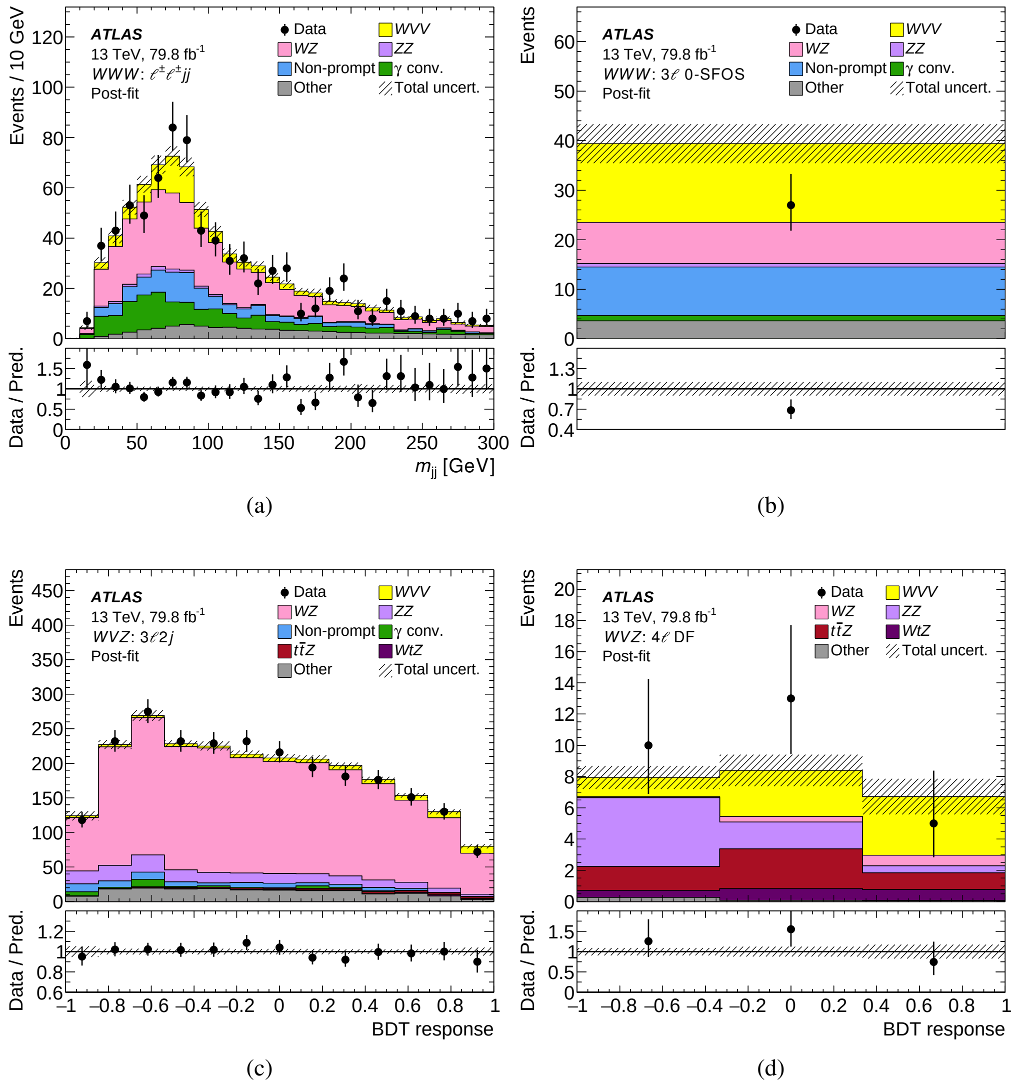


Figure 4: Post-fit distribution of (a) m_{jj} for the $WWW \to \ell\nu\ell\nu qq$ analysis (ee, $e\mu$, μe, $\mu\mu$ combined), (b) number of events for the $WWW \to \ell\nu\ell\nu\ell\nu$ analysis, and the BDT response in the (c) 3ℓ-2j and (d) 4ℓ-DF channels for the WVZ analysis. The contributions denoted “Other” are dominated by the (a) $W^{\pm}W^{\pm}$ + 2jets, (b) $t\bar{t}W$ and (c) tZ process, respectively. The uncertainty band includes both statistical and systematic uncertainties as obtained by the fit.

The overall observed (expected) significance for WVV production is found to be 4.1σ (3.1σ), constituting evidence for the production of three massive vector bosons. The combined best-fit signal strength for the WVV process, obtained by the fit to the eleven signal regions and one control region, is $\mu_{WVV} = 1.40^{+0.39}_{-0.37}$ with respect to the SM prediction (Section 2). The compatibility of the individual signal strengths is 0.13, determined by repeating the fit, assuming individual signal strengths, and evaluating the p-value of the χ^2 of the comparison. The statistical uncertainty on the measured signal strength is $^{+0.25}_{-0.24}$ and the systematic uncertainty is $^{+0.30}_{-0.27}$. The impact of the most important groups of systematic uncertainties on the measured value of μ_{WVV} is shown in Table 4. The largest systematic uncertainties come from uncertainties related to data-driven background evaluations affecting the WWW channels, from theoretical uncertainties related to renormalisation and factorisation scale variations and experimental uncertainties. The impact of each systematic uncertainty on the result is assessed and the ranking for the nuisance parameters with the largest contribution to the uncertainty in μ_{WVV} is shown in Figure 5.

Table 4: Summary of the effects of the most important groups of systematic uncertainties on μ_{WVV}. Uncertainties related to data-driven background evaluations affecting the WWW channels (data-driven); theoretical uncertainties related to renormalisation and factorisation scale variations, mostly in the diboson background, evaluated using simulations (theory); experimental uncertainties in the signal and background evaluations (instrumental); the statistical uncertainty of simulated events (MC stat. uncertainty); and modelling uncertainty evaluated by comparing different event generators (generators).

Uncertainty source	$\Delta\mu_{WVV}$	
Data-driven	+0.14	–0.14
Theory	+0.15	–0.13
Instrumental	+0.12	–0.09
MC stat. uncertainty	+0.06	–0.04
Generators	+0.04	–0.03
Total systematic uncertainty	+0.30	–0.27

Additional fits are performed separately in the WWW and the WVZ channels. For these fits the other signal strength is fixed to its SM expectation. For the fits of the WWW channels, the WZ control region defined in Section 4 is used in the fit. The inclusion of the WZ control region helps constraining the overall normalisation of the WZ+jets background, which in the combined fit is constrained by the WVZ three-lepton signal regions. The $t\bar{t}Z$ control region is used in the WVZ fit, however, it is not used in the WWW fit. The observed (expected) significance is 3.2σ (2.4σ) for WWW production and 3.2σ (2.0σ) for WVZ production.

Table 5 and Figure 6(a) summarise the observed and expected significances with respect to the background-only hypothesis and the observed best-fit values of the signal strength for the individual and combined fits. The measured signal strengths from the individual fits are converted to inclusive cross-section measurements using the signal samples described in Section 2 and the central values of the theoretical predictions. All uncertainties determined in the fit are included in the conversion, except for the normalisation uncertainty in the signal prediction. The results are: $\sigma_{WWW} = 0.65^{+0.16}_{-0.15}\,(\text{stat.})\,^{+0.16}_{-0.14}\,(\text{syst.})$ pb and $\sigma_{WWZ} = 0.55 \pm 0.14\,(\text{stat.})\,^{+0.15}_{-0.13}\,(\text{syst.})$ pb. For the σ_{WWZ} extraction, the WZZ normalisation is fixed to the SM expectation. The cross section of the latter is not reported, since there is not enough sensitivity to this channel to quote a separate cross-section value.

Figure 6(b) shows the data, background and signal yields, where the discriminant bins in all signal regions are combined into bins of $\log_{10}$(S/B), S being the expected signal yield and B the background yield. The background and signal yields are shown after the global signal-plus-background fit to the data.

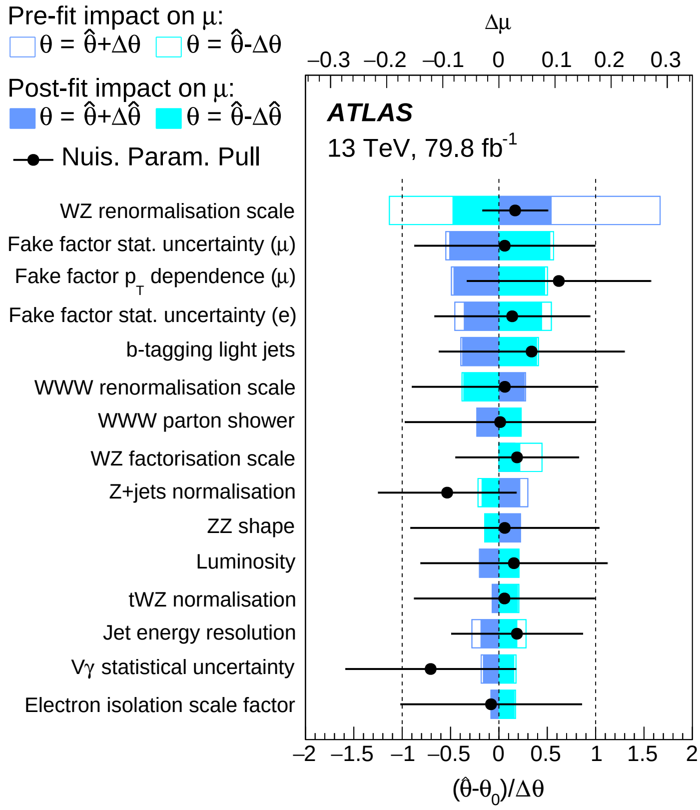
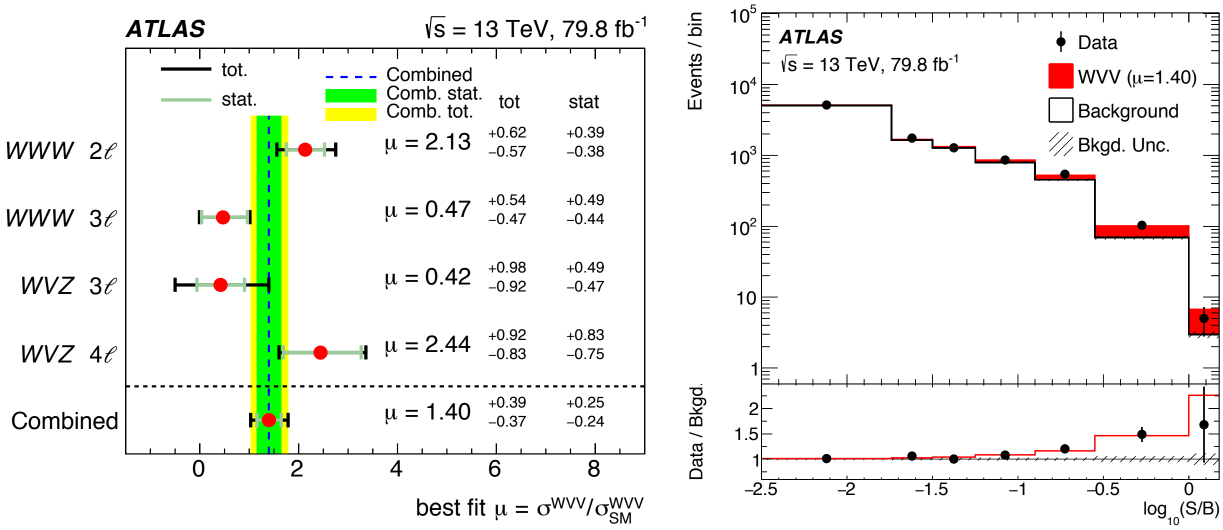


Figure 5: Impact of systematic uncertainties on the fitted signal-strength parameter μ for the combined WVV fit to data. The systematic uncertainties are listed in decreasing order of their post-fit impact in the fit, and only the 15 most important are displayed. The effect of varying each nuisance parameter θ is shown, where θ_0 is the pre-fit value, $\hat{\theta}$ is the post-fit value, and $\Delta\theta$ and $\Delta\hat{\theta}$ are the pre- and post-fit uncertainties, respectively.

Table 5: Observed and expected significances with respect to the SM background-only hypothesis for the four WVV channels entering the fit.

Decay channel	Significance	
	Observed	Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ



(a) (b)

Figure 6: (a) Extracted signal strengths μ for the four analysis regions and for the combination. (b) Event yields as a function of $\log_{10}$ (S/B) for data, background B and the signal S. Events in all eleven signal regions are included. The background and signal yields are shown after the global signal-plus-background fit. The hatched band corresponds to the systematic uncertainties, and the statistical uncertainties are represented by the error bars on the data points. The lower panel shows the ratio of the data to the expected background estimated from the fit, compared to the expected distribution including the signal (red line).

7 Conclusion

In conclusion, a search for the joint production of three massive vector bosons (W or Z) in proton–proton collisions using 79.8 fb^{-1} of data at $\sqrt{s}$ = 13 TeV collected by the ATLAS detector at the LHC, is presented. Events with two, three or four reconstructed electrons and muons are analysed. Evidence for the production of three massive vector bosons is observed with a combined significance of 4.1 standard deviations, where the expectation is 3.1 standard deviations. The measured production cross sections are $\sigma_{WWW} = 0.65^{+0.23}_{-0.21}$ pb, and $\sigma_{WWZ} = 0.55^{+0.21}_{-0.19}$ pb, in agreement with the Standard Model predictions.

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