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Observation of VVZ production at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

A search for the production of three massive vector bosons, $VVZ (V = W, Z)$, in proton–proton collisions at $\sqrt{s} = 13$ TeV is performed using data with an integrated luminosity of 140 fb^{-1} recorded by the ATLAS detector at the Large Hadron Collider. Events produced in the leptonic final states $WWZ \to \ell\nu\ell\nu\ell\ell$ $(\ell = e, \mu)$, $WZZ \to \ell\nu\ell\ell\ell\ell$, $ZZZ \to \ell\ell\ell\ell\ell\ell$, and the semileptonic final states $WWZ \to qq\ell\nu\ell\ell$ and $WZZ \to \ell\nu qq\ell\ell$, are analysed. The measured cross section for the $pp \to VVZ$ process is $660^{+93}_{-90}(\text{stat.})^{+88}_{-81}(\text{syst.})$ fb, and the observed (expected) significance is 6.4 (4.7) standard deviations, representing the observation of VVZ production. In addition, the measured cross section for the $pp \to WWZ$ process is $442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$ fb, and the observed (expected) significance is 4.4 (3.6) standard deviations, representing evidence of WWZ production. The measured cross sections are consistent with the Standard Model predictions. Constraints on physics beyond the Standard Model are also derived in the effective field theory framework by setting limits on Wilson coefficients for dimension-8 operators describing anomalous quartic gauge boson couplings.

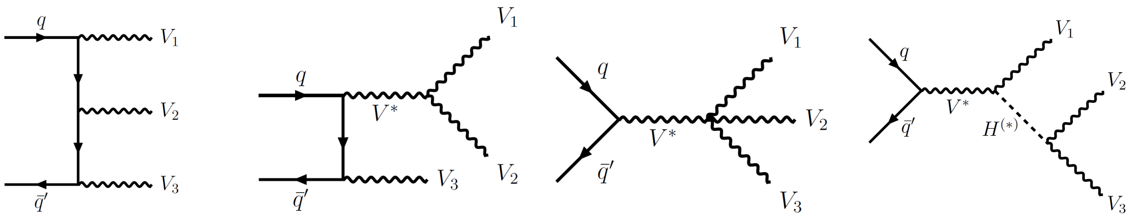
1 Introduction

In the Standard Model (SM), the non-Abelian structure of the electroweak sector predicts the self-interaction of vector bosons leading to vertices with three or four vector bosons. Studying processes containing vertices with four vector bosons is a sensitive test of the SM as deviations from the SM expectation would be hints of new physics at higher energy scales [1–4]. Four vector boson vertices can be probed in vector boson scattering processes [5, 6] or in three boson final states.

The production of three massive vector bosons in proton–proton (pp) collisions at the Large Hadron Collider (LHC) [7] was studied using data collected at a centre-of-mass energy of $\sqrt{s} = 13$ TeV by both the ATLAS [8] and CMS [9] experiments. ATLAS has provided evidence for the production of WWW and WVZ ($V = W, Z$) using data with an integrated luminosity of 79.8 fb^{-1} [10], and later observed WWW production using 139 fb^{-1} of data [11]. Meanwhile, CMS has observed the combined production of VVV ($WWW + WWZ + WZZ + ZZZ$) based on 137 fb^{-1} of data [12]. This article reports on a search for the production of three massive vector bosons of which at least one is a Z boson, i.e. WWZ, WZZ, and ZZZ, using 140 fb^{-1} of data.

The production of three massive vector bosons can occur via diagrams containing mono to quartic boson interaction vertices, and via the Higgsstrahlung process. Representative Feynman diagrams are shown in Figure 1.

Three distinct search channels based on the number of leptons in the final state are used, targeting different tri-boson final states, namely 3ℓ for WWZ and WZZ, 4ℓ for WWZ, and at least 5ℓ for WZZ and ZZZ processes, with $\ell = e, \mu$. The sets of selection criteria for the different search channels are designed to avoid overlap between the channels. The dominant background processes are WZ production for the 3ℓ channel, and WZ and ZZ production for the 4ℓ and 5ℓ channels. To enhance the sensitivity, the signal regions for the 3ℓ and 4ℓ channels are further split into sub-categories. Boosted decision tree (BDT) discriminants are trained individually for each channel to enhance the separation between signal and background events. These channels are then combined with a binned maximum-likelihood fit of the BDT discriminants, yielding a combined signal strength parameter μ for VVZ production with μ defined as the ratio of the measured tri-boson production cross section to its SM prediction. The signal strength is also determined separately for WWZ and WZZ production. Finally, limits on effective field theory (EFT) parameters describing the four-vector-boson interaction vertex are derived with discriminants optimised to enhance the sensitivity to EFT contributions to the SM processes.



(a) (b) (c) (d)

Figure 1: Representative Feynman diagrams for the production of three massive vector bosons, including diagrams with (a) mono boson vertices, diagrams sensitive to (b) triple and (c) quartic gauge boson couplings, and (d) the Higgsstrahlung process.

2 The ATLAS detector, data and simulation samples

The ATLAS detector at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle[1]. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadron calorimeters, and a muon spectrometer (MS). The inner tracking detector covers the pseudorapidity range of $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide 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 Tm 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 [13] is used to select interesting 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 [14] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The data used in the analysis were collected between 2015 and 2018 in pp collisions at $\sqrt{s} = 13$ TeV. Only events recorded with a fully operational detector and stable beams are included resulting in a total integrated luminosity of 140 fb^{-1} [15]. Candidate events are selected by single or multiple lepton (e or μ) triggers with transverse momentum thresholds varying depending on the lepton flavour, isolation requirements, and run period. Due to the presence of at least three leptons in the final state and the requirement of at least one lepton with $p_{\text{T}} > 27$ GeV in the event selection, the lepton triggers are fully efficient for the tri-boson signals in the signal regions defined in Section 3.2.

Signal and background processes were simulated with a range of Monte Carlo (MC) event generators and the ATLAS detector response [16] was modelled 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 Pythia8.186 [18] using the `A3` [19] set of tuned MC parameters and the `NNPDF2.3LO` [20] parton distribution function (PDF) set, on each generated event in all samples. Tri-boson signal and WWW background events [21] with three on-mass-shell vector bosons including processes involving an off-shell Higgs boson mediator were simulated using Sherpa2.2.2 [22] with the `NNPDF3.0NNLO` [23] PDF. Off-mass-shell tri-boson final states with an on-shell Higgs boson mediator, i.e. $WH \to WVV^*$ and $ZH \to ZVV^*$, were generated using Powheg Box2 [24–29] interfaced to Pythia8.186 and EvtGen1.6.0 [30]. All tri-boson processes were generated at next-to-leading-order (NLO) quantum chromodynamics (QCD) accuracy [31–34]. The expected cross section (VH included) is 329 fb for WWZ, 93.1 fb for WZZ, and 34.0 fb for ZZZ. The total theory uncertainty in the signal cross sections is about 10% and was evaluated by varying parameters in the simulation related to the renormalisation and factorisation scales, parton shower and PDF sets. For the interpretation within the EFT approach (described in Section 5), samples of WWZ

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Transverse momentum ($p_{\text{T}}$) is defined relative to the beam axis and is calculated as $p_{\text{T}} = p\sin\theta$ where p is the momentum. Transverse energy (E_{T}) is calculated as $E_{\text{T}} = E\sin\theta$ where E is the energy. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

and WZZ production with non-zero Wilson coefficients for the $M2$, $M3$, $M4$ and $M5$ operators in the Eboli model [35] were generated at leading-order (LO) with MadGraph2.7.3 [36] using the `NNPDF3.0NLO` PDF set and interfaced to Pythia8.245 [37] and the `A14` [38] tune. The EFT interpretation does not include the 5ℓ channel, so the ZZZ samples are not included as their impact is negligible in the 3ℓ and 4ℓ channels.

Diboson (WW, WZ, ZZ, $W\gamma$, and $Z\gamma$) processes [21] were modelled using Sherpa2.2.12 with the `NNPDF3.0NNLO` PDF set. Single boson (W/Z+jets) [39] production and electroweak production of $W^{\pm}W^{\pm}$ + 2 jets, WZ + 2 jets, and ZZ + 2 jets, were modelled using Sherpa2.2.11 and Sherpa2.2.2, respectively.

Top-quark pair events ($t\bar{t}$) were simulated using Powheg Box2 [40] interfaced to Pythia8.230 and EvtGen1.6.0. 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` tune. Production processes of a top-quark pair in association with a vector boson ($t\bar{t}Z$ and $t\bar{t}W$) were modelled at NLO with MadGraph2.2.3 with the `NNPDF3.0NLO` PDF set and interfaced to Pythia8.210 using the `A14` tune and EvtGen1.2.0 for heavy flavour decays. The $t\bar{t}H$ production was generated at LO in QCD with Powheg Box2 interface to Pythia8.210 and EvtGen1.6.0. Other background processes containing top quarks were generated with MadGraph5_aMC@NLO [41] interfaced to Pythia8.230, at LO ($t\bar{t}\gamma$, tZ, $t\bar{t}WW$, $t\bar{t}WZ$, and $t\bar{t}t\bar{t}$) or with Powheg Box2 [42] interfaced to Pythia8.212 and EvtGen1.6.0 (tWZ).

3 Object definitions, event selection and background estimation

3.1 Object definitions and preselection criteria

At the trigger level, candidate events are selected using all combinations of unprescaled single lepton, dilepton, tri-lepton, and four-lepton triggers [43, 44]. Triggers requiring a mixture of lepton flavours (for example, dilepton triggers with an electron and a muon at the trigger level) are also used. These triggers require leptons to satisfy certain transverse momentum threshold, identification, and isolation criteria. The combined trigger efficiency is fully efficient for tri-boson events in the fiducial regions. The candidate events are required to contain one reconstructed primary vertex [45]. If more than one reconstructed vertex is found, the vertex with the largest p_{T}^{2} sum of associated ID tracks is considered as the primary vertex.

Electrons are reconstructed from energy clusters in the EM calorimeter matched to ID tracks [46] and are identified using a likelihood discriminant constructed with information about the shape of the EM showers in the calorimeter, the track properties, and the quality of the track-to-cluster matching for the candidate. Electrons must satisfy a “LooseAndBLayerLH”[2] requirement and have $p_{\mathrm{T}} > 7$ GeV and $|\eta| < 2.47$. Electron candidates reconstructed within the transition region between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.52$, are also kept.

Muons are reconstructed in multiple ways based on information from the ID, the MS, and the calorimeters [47]. In the range of the ID coverage, the muon reconstruction is primarily performed by a global fit of fully reconstructed tracks in the ID and the MS (referred to as “combined muons”). In the central region ($|\eta| < 0.1$) of the detector where the MS lacks in coverage, muons can also be identified by matching a fully reconstructed ID track to either an MS track segment (referred to as “segment-tagged muons”) or a calorimetric energy deposit consistent with that of a minimum-ionizing particle (referred to

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[2] This requirement uses the same threshold for the likelihood discriminant as the “Loose” operating point but adds the requirement of a hit in the innermost pixel layer.

as “calorimeter-tagged muons”). For the last two cases, the muon momentum is determined by the ID track alone. In the forward MS region ($2.5 < |\eta| < 2.7$), MS tracks with hits in the three MS layers are accepted (referred to as “standalone muons”). Muons are required to satisfy the “Loose” identification requirement described in Ref. [47] and to have $|\eta| < 2.7$ and $p_{\mathrm{T}} > 5$ GeV for all types except for the calorimeter-tagged type where the requirement is increased to $p_{\mathrm{T}} > 15$ GeV.

Both electrons and muons 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.

Jets are reconstructed from particle-flow objects using the anti-k_t algorithm [48, 49] with a radius parameter of 0.4. The particle-flow algorithm combines information about ID tracks and energy deposits in the calorimeters to form the input for jet reconstruction [50]. Jets are selected by requiring $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.5$. To suppress jets arising from pile-up, a jet-vertex-tagging (JVT) technique [51] using a multivariate likelihood is applied to jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$, ensuring that the selected jets are matched to the primary vertex.

Jets containing b-hadrons are identified (b-tagged) using the DL1r b-tagging algorithm [52] based on a deep neural network that combines information from displaced tracks and reconstructed secondary and tertiary vertices inside jets. A jet is b-tagged if the response value of the DL1r algorithm exceeds a predefined threshold. The operating point defined with an efficiency of 77% for b-jets measured in simulated $t\bar{t}$ events is used.

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 physics objects in the event [53]. This sum includes a term to account for the energy from low-momentum particles that are not associated with a reconstructed lepton or jet.

The object reconstruction and identification algorithms do not always result in unambiguous identifications of physics objects. An overlap removal procedure is applied to the leptons and jets in the following order. Calorimeter-tagged muons sharing a track with any electrons are removed. Electrons sharing an ID track with 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.

The preselected events are required to have at least three charged leptons satisfying the baseline lepton selection criteria. In addition, at least one same-flavour opposite-sign charge (SFOS) lepton pair that is consistent with the Z boson pole mass ($m_Z = 91.188$ GeV) within 40 GeV is required. Table 1 shows all preselection criteria used.

3.2 Event selection criteria

The 3ℓ channel requires exactly three charged leptons and at least one reconstructed jet in the final state. All SFOS dilepton pairs should have an invariant mass $m_{\ell\ell} > 12$ GeV. Events are required to have at least one SFOS lepton pair that is consistent with m_Z within 20 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 is taken as the Z boson candidate. These two leptons are assigned to the Z boson decay (labelled Z-leptons). The remaining third lepton is assigned to the W boson decay (labelled W-lepton). To reduce instrumental

Table 1: Summary of the object selection and event preselection criteria used in the analysis.

Object selection criteria	
Electron	Passes the "LooseAndBLayerLH" quality requirement $|d_0|/\sigma_{d_0} < 5$, $|z_0 \times \sin\theta| < 0.5$ mm $p_\mathrm{T} > 7$ GeV, $|\eta| < 2.47$
Muon	Passes the "Loose" quality requirement $|d_0|/\sigma_{d_0} < 3$, $|z_0 \times \sin\theta| < 0.5$ mm $p_\mathrm{T} > 5$ GeV ($p_\mathrm{T} > 15$ GeV for calorimetr-tagged muons), $|\eta| < 2.7$
Jet	Passes the JVT requirement, $p_\mathrm{T} > 20$ GeV, $|\eta| < 4.5$
Event preselection criteria	
Trigger	Single lepton, dilepton, tri-lepton, or quad-lepton triggers
Number of charged leptons	≥ 3
Z boson invariant mass	$|m_{\ell\ell} - m_Z| < 40$ GeV

backgrounds, events with both Z-electrons falling into the calorimeter transition region $1.37 < |\eta| < 1.52$ are rejected. In addition, events with the third electron falling into the calorimeter transition region are rejected.

All three leptons are required to have $p_\mathrm{T} > 15$ GeV and at least one must have $p_\mathrm{T} > 27$ GeV. The electrons are required to satisfy the "Loose_VarRad"[3] [54] isolation requirement. The muons are required to satisfy the "PFlow_Loose_VarRad"[4] isolation requirement [47]. Backgrounds originating from misidentified leptons are suppressed by requiring the W-lepton to satisfy more stringent selection criteria. The W-lepton is required to satisfy the "TightLH" [5] quality requirement for electrons and the "Tight" quality requirement for muons [47]. Both W-electrons and W-muons are required to satisfy the "PLImprovedTight"[6] isolation requirement. At least one jet with $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.5$ is required to be present in the final state. Events with at least one b-jet are rejected.

To gain sensitivity, the 3ℓ channel makes use of events containing four leptons that satisfy the 3ℓ channel selection shown in Table 2, but fail to satisfy the 4ℓ channel selection criteria shown in Table 3. These 4ℓ events are required to contain only one lepton pair with $|m_{\ell\ell} - m_Z| < 20$ GeV. One of the other two leptons is required to satisfy the 3ℓ quality requirements for a W-lepton, while the other lepton is required to fail this requirement. This increases the signal yield by 2% and the estimated background by 1.5%.

Three signal regions (SRs) are defined according to the number of jets and the invariant mass of the two leading jets in the event: the 3ℓ-1j SR is defined by requiring events with exactly one reconstructed jet; the requirements of at least two jets with the invariant mass of the two leading jets, m_{jj}, lying within a window close to the W or Z boson pole mass, i.e. $60 < m_{jj} < 110$ GeV, defines the 3ℓ-2j-inV SR; the remaining events compose the 3ℓ-2j-outV SR. With these selection criteria applied, the signal-to-background ratio is

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[3] The sum of the p_T of all prompt tracks within a cone of ΔR around the electron, shrinking with p_T (max $\Delta R = 0.3$), must be less than 15% of the electron p_T, and the E_T of all energy depositions within $\Delta R = 0.2$ of the electron must be less than 20% of the electron p_T.

[4] The sum of the p_T of all prompt tracks within a cone of ΔR around the muon, shrinking with p_T (max $\Delta R = 0.3$), is added to 40% of the sum of the E_T of energy depositions within $\Delta R = 0.2$ of the muon that are not matched to tracks and the total is required to be less than 16% of the muon p_T. Calorimeter energy depositions are calculated using the particle-flow algorithm.

[5] This definition has the same requirements as the "Tight" working point defined in Ref. [55].

[6] This requirement is the "Tight" working point of the "Prompt Lepton Tagger" [56], a multivariate isolation discriminant used to reject non-prompt leptons from heavy-flavour decays.

Table 2: Overview of the criteria used to select inclusive 3ℓ events and the three 3ℓ SRs.

Inclusive 3ℓ event selection	
Satisfy preselection criteria	✓
Lepton	$p_{\mathrm{T}} > 15$ GeV and at least one lepton with $p_{\mathrm{T}} > 27$ GeV
Lepton from the Z decays	"Loose_VarRad" isolation for electrons and "PFLow_Loose_VarRad" isolation for muons
Lepton from the W decays	"Tight" identification and "PLImprovedTight" isolation
Invariant mass of any SFOS dilepton pairs	> 12 GeV
Invariant mass of the Z boson	$\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV
Number of leptons	$= 3$
Number of b-jets	$= 0$

3ℓ signal regions			
	3ℓ-1j	**3ℓ-2j-inV**	**3ℓ-2j-outV**
Satisfy inclusive 3ℓ selection criteria	✓	✓	✓
BDT score > 0.42	✓	✓	✓
Number of jets	$= 1$	≥ 2	≥ 2
m_{jj}	–	> 60 GeV and < 110 GeV	< 60 GeV or > 110 GeV

close to 1% for the 3ℓ-1j channel, 5% for the 3ℓ-2j-inV channel, and 3% for the 3ℓ-2j-outV channel. To reduce the WZ+jets background, each event is required to have a BDT score (described in Section 4) that is larger than 0.42. Table 2 summarises all selection criteria used and the definitions of these three SRs.

The 4ℓ channel requires exactly four leptons in the event. The SFOS lepton pair with its invariant mass, $m_{\ell\ell}$, closest to m_Z is identified as the Z boson candidate and must fulfil $|m_{\ell\ell} - m_Z| < 20$ GeV. The remaining two leptons are assigned as leptons from W decays and must satisfy the "PLImprovedTight" isolation and "Medium" ("MediumLH"[7]) quality requirements for muons (electrons). All SFOS lepton pairs must have an invariant mass of $m_{\ell\ell} > 12$ GeV. The set of four leptons is required to satisfy the ordered p_{T} thresholds of 30, 15, 8, and 6 GeV. The angular distance between any two leptons is required to be $\Delta R > 0.1$. Furthermore, each event must have $E_{\mathrm{T}}^{\mathrm{miss}} > 10$ GeV and no jets reconstructed as b-tagged jets. Events that satisfy the selection are categorised into three SRs depending on the flavours of the two W-leptons. Those events where the two leptons have different flavour compose the 4ℓ-DF SR and events with two same-flavour leptons are split into two SRs based on their invariant mass: events satisfying $|m_{\ell\ell} - m_Z| < 20$ GeV define the 4ℓ-SF-inZ SR, while the remaining events compose the 4ℓ-SF-outZ SR. Table 3 summarises the selection criteria and the definitions of these three SRs.

The 5ℓ channel requires at least five leptons with at least two SFOS pairs in the event. The two SFOS lepton pairs with their invariant mass closest to m_Z are identified as Z boson candidates and must fulfil $|m_{\ell\ell} - m_Z| < 20$ GeV. The remaining lepton is assigned as a lepton from another Z/W boson decay and no additional quality requirements or isolation requirements are applied. Events with at least one b-jet are rejected. Table 4 summarises the selection criteria.

To further increase the separation between the signal and background events in the SRs, seven BDT discriminants are trained using the XGBoost package [57][8] and are applied separately to each of the seven SRs. For the 3ℓ channel, the BDT is trained with 17 variables for 3ℓ-1j, 20 variables for 3ℓ-2j-inV, and 24

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[7] This definition has the same requirements as the "Medium" working point defined in Ref. [55].

[8] Julia packages (`UnROOT.jl` [58] and `XGBoost.jl`) were used for the 4ℓ channel.

Table 3: Overview of the criteria used to select inclusive 4ℓ events and the three 4ℓ SRs.

Inclusive 4ℓ event selection	
Satisfy preselection criteria	✓
Lepton	Exactly four leptons with $p_{\mathrm{T}} > 30, 15, 8, 6$ GeV
Lepton from the Z decays	“Loose_VarRad” isolation for electrons and “PFLow_Loose_VarRad” isolation for muons
Leptons from the W decays	“Medium” identification and “PLImprovedTight” isolation
Invariant mass of any SFOS dilepton pairs	> 12 GeV
Invariant mass of the Z boson	$\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV
Minimum angular distance between any lepton pairs	> 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 10 GeV
Number of b-jets	$= 0$

4ℓ signal regions			
	4ℓ-DF	**4ℓ-SF-inZ**	**4ℓ-SF-outZ**
Satisfy inclusive 4ℓ selection criteria	✓	✓	✓
Flavour for lepton from the W decays	$e\mu$	same-flavour	same-flavour
$m_{\ell\ell}$ for the two W−leptons	−	$\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert > 20$ GeV

Table 4: Overview of the criteria used to select inclusive 5ℓ events, which form the 5ℓ SR.

Inclusive 5ℓ event selection (5ℓ SR)	
Satisfy preselection criteria	✓
Leptons	At least five leptons “Loose_VarRad” isolation for electrons and “PFlow_Loose_VarRad” isolation for muons
Z boson candidates	At least two SFOS pairs with $\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV
Z boson invariant mass	$\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV
Number of b-jets	$= 0$

variables for 3ℓ-2j-outV, with some of these variables overlapping between the channels. For the 4ℓ channel, the same 23 variables are used as inputs for the BDT training for 4ℓ-DF, 4ℓ-SF-inZ, and 4ℓ-SF-outZ. For the 5ℓ channel, the BDT is trained with 11 variables. All backgrounds except fake backgrounds (due to non-prompt leptons from hadron decay or jets misidentified as leptons) are included in the BDT training. Since XGBoost cannot handle negative-weight events, the absolute value of each event weight is used. A five-fold training and cross-validation procedure is used to produce the final discriminant for each SR, and each of the five models is trained on 80% of the expected signal and background events. Each of the five trained BDTs is applied to the remaining 20% of the total events, and this final BDT score is used to produce the BDT distribution used in the fit.

3.3 Background estimation

The SM background processes can be divided into two categories: processes with three, four, or at least five prompt leptons in the final state, and fake background processes. Depending on the source, the background is estimated with data-driven or simulation-based techniques, as described below, or a combination of both.

The dominant background source in the 3ℓ channel is from WZ+jets production, followed in importance by ZZ+jets production. The WZ+jets process contributes 83% of the expected background in the 3ℓ-1j SR, 79% in the 3ℓ-2j-inV SR, and 81% in the 3ℓ-2j-outV SR. The ZZ+jets process contributes 11% of the expected background in the 3ℓ-1j SR, 10% in the 3ℓ-2j-inV SR, and 7% in the 3ℓ-2j-outV SR. Due to the presence of three isolated leptons in the final states, the fake background contribution from the Z+jets process is $< 3\%$. As a result, all backgrounds are estimated with MC simulated events.

The dominant background sources in the 4ℓ channel are from ZZ+jets and fake background processes. The ZZ+jets process contributes 50% of the expected background in the 4ℓ-DF SR, 98% of the events in the 4ℓ-SF-inZ SR, and 93% in the 4ℓ-SF-outZ SR. The fake background mainly originates from the WZ+jets and Z+jets processes where one or two jets are identified as isolated leptons. The contribution from $t\bar{t}$ production is found to be negligible due to the b-jet veto requirement. The fake background contributes 17% of the expected background in the 4ℓ-DF SR, 1% in the 4ℓ-SF-inZ SR, and 3% in the 4ℓ-SF-outZ SR. The $t\bar{t}Z$ process also contributes 21% of the expected background in the 4ℓ-DF SR. Due to its contribution to the most sensitive 4ℓ-DF SR, the fake background is estimated by using a data-driven method as described in Ref. [59], while all other backgrounds are estimated with MC simulations.

The dominant backgrounds in the 5ℓ channel originate from fake background processes such as ZZ+jets and $t\bar{t}Z$ production. The ZZ+jets process contributes 95% of the expected background in the SR, while the $t\bar{t}Z$ process contributes 2.5%. These backgrounds have one or two jets misidentified as isolated leptons and are estimated by using a combination of data-driven and simulation-based techniques.

Five control regions (CRs) are defined to check the background modelling in different channels: WZ+jets, ZZ+jets, Z+jets, and two $t\bar{t}Z$ CRs (one for the 3ℓ channel and the other for the 4ℓ channel). The two $t\bar{t}Z$ CRs are orthogonal to each other due to the requirement on the number of leptons in the event. The WZ+jets CR is defined with the same set of selection criteria as used for the inclusive 3ℓ SRs except for a requirement that the BDT score (described in Section 4), be less than 0.42. The purity of WZ events in this CR is $\sim 76\%$. The ZZ+jets CR has the same selection criteria as used in the 4ℓ-SF-inZ SR except the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement is reversed to have $E_{\mathrm{T}}^{\mathrm{miss}} < 10$ GeV. The purity of ZZ events in this CR is $\sim 99\%$. In addition, the two 3ℓ SRs (3ℓ-1j and 3ℓ-2j-inV) and the two 4ℓ SRs (4ℓ-SF-inZ and 4ℓ-SF-outZ) with significant contributions from the WZ+jets and ZZ+jets processes, help constrain the estimates for these two background processes. The Z+jets CR has the same selection criteria as used in the 3ℓ-2j-inV SR except the W-lepton is required to have $8 < p_{\mathrm{T}} < 15$ GeV, the invariant mass of the three charged leptons is required to be below 150 GeV, and there is exactly one jet reconstructed in the event and this jet is not tagged as a b-jet. The purity of Z+jets events in this CR is $\sim 72\%$. The $t\bar{t}Z$ CR in the 3ℓ channel is defined in the same way as the signal region, with the exception that at least four jets are required, of which at least two are b-tagged. The purity of $t\bar{t}Z$ events in this CR is $\sim 66\%$. The $t\bar{t}Z$ CR in the 4ℓ channel is defined in the same way as the 4ℓ-SF-inZ SR, with the exception that at least one b-jet be present in the event. The purity of $t\bar{t}Z$ in this CR is $\sim 74\%$.

The data-driven method used to estimate the fake background in the 4ℓ and 5ℓ channels defines lepton-like jets by requiring the leptons to meet a looser selection criterion but fail to meet the signal-lepton requirement. Compared with the signal leptons, muon-like jets have to satisfy the "Loose" quality requirement and electron-like jets have to satisfy the "LooseAndBLayerLH" quality requirements for the 4ℓ channel, while both muon-like and electron-like jets are required to satisfy the "VeryLoose" quality requirement for the 5ℓ channel. In addition, $|d_0|/\sigma_{d_0}$ is required to be less than 10 and no requirements are applied on the isolation variables for both muon-like and electron-like jets. Events containing up to two lepton-like jets are weighted by a "fake factor" to predict the non-prompt lepton background contribution, selected from data for the 4ℓ channel and from MC simulation for the 5ℓ channel. The fake factor is the ratio of the number of non-prompt leptons satisfying the signal lepton criteria over the number satisfying the lepton-like jet criteria. Its value is derived from data samples enriched in Z+jets and $t\bar{t}$ production. For the 4ℓ channel, the dominant fake background originates from the WZ+jets process where most jets are light-flavour jets. For the 5ℓ channel, the dominant fake background originates from both ZZ+jets and $t\bar{t}Z$ processes where jets are a mixture of light-flavour and heavy-flavour jets. The fake factor measured in the Z+jets sample is thus used for the fake background estimate for the 4ℓ channel, while the fake factors measured in the Z+jets and $t\bar{t}$ samples are combined according to the light-flavour to heavy-flavour background ratio expected in the SR for the 5ℓ channel.

The normalisations of simulated WZ+ jets, ZZ+jets, Z+jets, and $t\bar{t}Z$ backgrounds are determined from data in the likelihood fits of SRs and CRs described in Section 4.

4 Signal extraction and combination

The 3ℓ, 4ℓ, and 5ℓ regions are combined using the profile likelihood method based on a simultaneous fit to distributions in the SRs and CRs. Seven SRs defined in Section 3.2 and five CRs defined in Section 3.3 are used in the fit. The distributions used in the fit are the seven BDT distributions for the seven SRs and the jet multiplicity distributions in the WZ+jets and ZZ+jets CRs. The number of selected events in the Z+jets CR, the $t\bar{t}Z$ CR in the 3ℓ channel, and the $t\bar{t}Z$ CR in the 4ℓ channel are each included as a single bin in the fit.

For the signal BDT distributions, a total of 58 bins are used: 10 bins for each SR of the 3ℓ channels, 10 bins collectively for the 4ℓ-DF channels, eight bins each for the 4ℓ-SF-inZ and 4ℓ-SF-outZ channels, and two bins for the 5ℓ channel. For the CR distributions, a total of nine bins are used: three bins each for the WZ (1, 2, or ≥ 3 jets) and ZZ (0, 1, or ≥ 2 jets) CRs, and one bin each for the Z+jets CR, the $t\bar{t}Z$ CR in the 3ℓ channel, and the $t\bar{t}Z$ CR in the 4ℓ channel. In total, 67 bins are used in the combined fit.

A binned likelihood function [60] 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 expected number of signal events, and $\boldsymbol{\theta}$, a set of nuisance parameters that encode the effect of systematic uncertainties in the signal and background expectations. The nuisance parameters are implemented in the likelihood function as Gaussian, log-normal or Poisson constraints, depending on their origin. Correlations of systematic uncertainties arising from common sources are maintained across processes and channels.

The fit includes nine unconstrained parameters that scale the number of events for a particular process predicted by MC simulation: the signal strength μ, three scale factors ($\mu_{WZ+1\,\text{jets}}$, $\mu_{WZ+2\,\text{jet}}$, and $\mu_{WZ+\geq 3\,\text{jets}}$) for $WZ + 1$ jets, $WZ + 2$ jet, and $WZ+ \geq 3$ jets, three scale factors ($\mu_{ZZ+0\,\text{jets}}$, $\mu_{ZZ+1\,\text{jet}}$, and $\mu_{ZZ+\geq 2\,\text{jets}}$) for $ZZ + 0$ jets, $ZZ + 1$ jet, and $ZZ+ \geq 2$ jets, one scale factor ($\mu_{Z\text{+jets}}$) for the Z+ jets process, and one scale factor ($\mu_{t\bar{t}Z}$) for the $t\bar{t}Z$ process. For the combined fit, the same value for $\mu = \mu_{VVZ}$ is assumed for the WWZ, WZZ and ZZZ processes. The ratio of on-shell WVZ production to $VH \rightarrow VWW^*/VZZ^*$ production is determined from MC simulation and is allowed to vary within the theoretical uncertainties of the two processes.

Experimental uncertainties are related to the lepton trigger, reconstruction and identification efficiencies [55, 61], lepton isolation criteria [56], lepton energy (momentum) scale and resolution [61, 62], jet energy scale and resolution [63], jet vertex tagging [51], b-tagging [64–66], modelling of pile-up and missing transverse

Table 5: Data and post-fit predicted yields for all SRs. Uncertainties in 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 uncertainties.

Signal region	3ℓ-1j	3ℓ-2j-inV	3ℓ-2j-outV	4ℓ-DF	4ℓ-SF-inZ	4ℓ-SF-outZ	5ℓ
VVZ	104±17	99±15	173±27	26.7±4.6	18.6±2.1	26.8±4.0	3.9±0.6
WZ+jets	4271±91	932±26	2656±81	–	–	–	–
ZZ+jets	547±46	113±14	239±27	19.7±1.2	1447±35	383.2±9.9	–
Z+jets	130±43	35±12	59±18	–	–	–	–
$t\bar{t}Z$	8.2±1.0	35.5±3.1	92.5±7.0	8.3±0.9	1.8±0.2	7.0±0.7	–
Fake	–	–	–	6.5±2.0	14.5±8.5	11.6±4.2	4.9±0.6
Others	219±12	65.1±5.5	221±12	4.5±0.4	12.2±0.4	10.7±0.4	–
Total expected	5280±68	1278±28	3440±54	65.8±5.1	1494±34	439±10	8.9±0.9
Data	5273	1280	3423	65	1513	429	13

momentum [53], and integrated luminosity [15, 67]. Nuisance parameters related to these uncertainties are treated as correlated between all channels.

For each of the background processes evaluated using simulation, a nuisance parameter representing its normalisation uncertainty is included. For dominant backgrounds from the WZ+jets and ZZ+jets processes, the simultaneous fit model has the power to constrain their normalisations at the ~5% level.

Uncertainties in data-driven background evaluations mainly come from statistical and systematic uncertainties in the lepton fake factor measurement. Additional uncertainties come from the statistical uncertainties of the subsamples used to extrapolate the background evaluations to the SRs. Nuisance parameters are treated as correlated for backgrounds evaluated using the same method and from the same sources of systematic uncertainty.

Shape-only variations of the signal and simulation-based background distributions due to QCD renormalisation and factorisation scales, PDF, and parton-shower matching scales are considered in the simultaneous fit. The corresponding nuisance parameters for the signal distributions are treated as correlated between the WWZ, WZZ and ZZZ channels.

Table 5 shows the post-fit background, signal, and observed yields for all SRs. The three most sensitive channels are 3ℓ-2j-outV, 4ℓ-DF, and 5ℓ. The fitted scale factors for various background processes are: $\mu_{WZ+1\text{ jets}} = 1.03 \pm 0.11$, $\mu_{WZ+2\text{ jet}} = 0.95 \pm 0.16$, $\mu_{WZ+\geq 3\text{ jets}} = 0.95 \pm 0.26$, $\mu_{ZZ+0\text{ jets}} = 1.03 \pm 0.10$, $\mu_{ZZ+1\text{ jet}} = 0.99 \pm 0.13$, $\mu_{ZZ+\geq 2\text{ jets}} = 0.84 \pm 0.24$, $\mu_{Z\text{+jets}} = 0.83 \pm 0.10$, and $\mu_{t\bar{t}Z} = 1.31 \pm 0.17$. Contributions from SM processes producing the same detector signature as events in these SRs besides those listed are combined into "Others". The uncertainties shown include both statistical and systematic uncertainties. Data and predictions agree within uncertainties in all channels. The contribution of the VH process to the VVZ yield depends on the decay channel and ranges between 3% (for 4ℓ-SF-inZ) and 50% (for 3ℓ-1j) in the seven SRs.

Figure 2 shows the comparison of the observed number of events to the predicted yields after fitting for both SRs and CRs. Figure 3 shows the comparison of the BDT distribution between data and predictions for all seven SRs. The two variables with the highest discriminating power are: H_T^{tot} (scalar sum of the p_{T} of leptons and jets) and the second leading jet p_{T} for the 3ℓ-2j-outV channel, the invariant mass of the second Z-lepton pair and the jet multiplicity for the 4ℓ-DF channel, and the $E_{\text{T}}^{\text{miss}}$ significance and the W-lepton p_{T} for the 5ℓ channel.

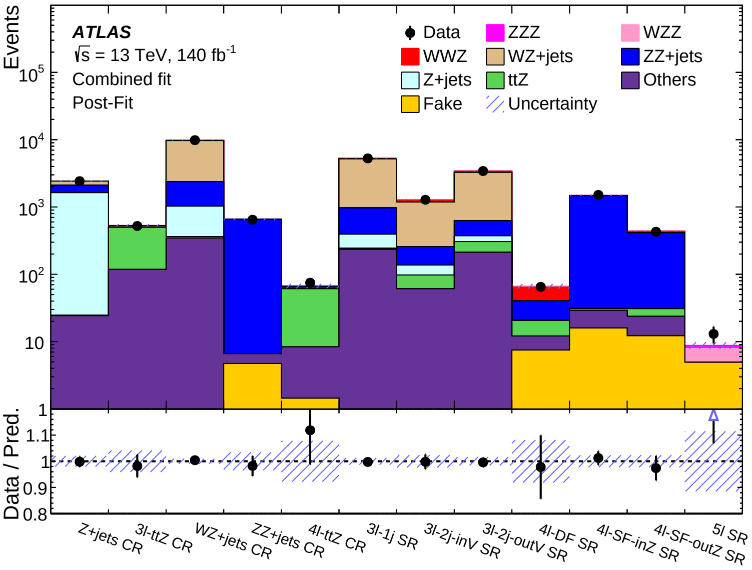
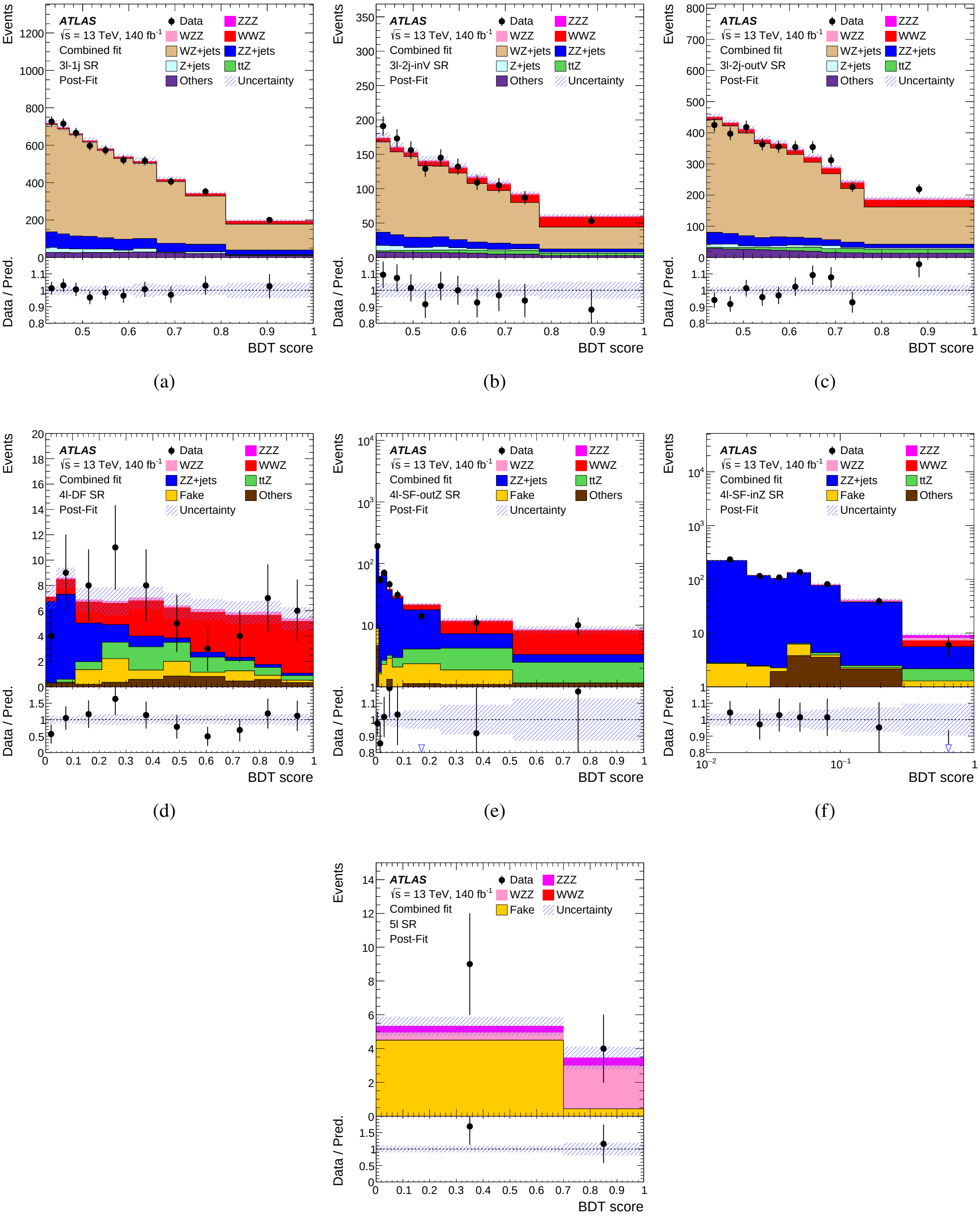


Figure 2: Comparison of the observed numbers of events to the predicted yields after fitting for all SRs and CRs. The bottom panel shows the ratio of the data and SM predictions. The uncertainty band includes both statistical and systematic uncertainties obtained by the fit.

Additional fits are performed separately for each channel to determine the signal strength of the WWZ process (μ_{WWZ}) and the WZZ process (μ_{WZZ}). Due to limited statistics, there are no specific SRs defined for ZZZ production, and thus no separate fit is performed to determine the signal strength of the ZZZ process. For these fits the other signal strength is fixed to its SM expectation.

The measured signal strengths combined with the SM predicted cross sections are used to derive the measured cross sections of various processes. The combined observed (expected) signal strength for the VVZ process is $\mu_{VVZ} = 1.43 \pm 0.20$ (stat.)$^{+0.21}_{-0.19}$(syst.) ($1.00^{+0.27}_{-0.25}$). The measured cross section is found to be 660^{+93}_{-90}(stat.)$^{+88}_{-81}$(syst.) fb and the observed (expected) significance corresponds to 6.4 (4.7) σ, marking the observation of VVZ production. The observed (expected) significance of WWZ production is 4.4 (3.6) σ, representing the evidence of this process at the LHC. Table 6 shows the measured signal strengths, cross sections and observed (expected) sensitivities for the VVZ, WWZ, and WZZ processes. The systematic uncertainties in the measured signal strengths are dominated by QCD scale uncertainties in the signal processes, uncertainties in reconstructed jet energy scale, resolution and b-tagging, and limited MC statistics of the signal samples.

If VH production is considered as part of the background, the combined observed cross section is found to be $\sigma(pp \to VVZ) = 382^{+65}_{-63}$(stat.)$^{+57}_{-60}$(syst.) fb with an observed signal strength of $1.59^{+0.24}_{-0.29}$ (stat.)$^{+0.30}_{-0.25}$ (syst.). The observed (expected) significance corresponds to 5.5 (3.7) σ. The ratio of on-shell VVZ production to $VH \to VWW^*/VZZ^*$ production is determined from MC simulation and is allowed to vary within the theoretical uncertainties of the two processes.



(a) (b) (c)

(d) (e) (f)

(g)

Figure 3: Comparison of the BDT distribution between data and predictions for the (a) 3ℓ-1j, (b) 3ℓ-2j-inV, (c) 3ℓ-2j-outV, (d) 4ℓ-DF, (e) 4ℓ-SF-outZ, (f) 4ℓ-SF-inZ, and (g) 5ℓ SRs. The bottom panel shows the ratio of the data and SM predictions. The uncertainty band includes both statistical and systematic uncertainties obtained by the fit.

Table 6: Measured signal strengths and inclusive cross sections and observed (expected) sensitivities for WWZ, WZZ, and VVZ production. The uncertainties listed are statistical and systematic.

Process	Signal strength	Cross section (fb)	Observed (expected) sensitivity
VVZ	$1.43 \pm 0.20(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$	$660^{+93}_{-90}(\text{stat.})^{+88}_{-81}(\text{syst.})$	6.4 (4.7) σ
WWZ	$1.33 \pm 0.28(\text{stat.})^{+0.21}_{-0.17}(\text{syst.})$	$442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$	4.4 (3.6) σ
WZZ	$2.13^{+1.18}_{-0.96}(\text{stat.})^{+0.76}_{-0.41}(\text{syst.})$	$200^{+111}_{-91}(\text{stat.})^{+65}_{-37}(\text{syst.})$	2.8 (1.6) σ

5 EFT analysis

The production of three massive vector bosons allows to study the quartic vector boson vertex. The EFT approach was chosen to constrain physics beyond the SM at higher mass scales. The EFT extends the SM Lagrangian with additional terms of higher dimensions,

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \dots, \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{f_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} \quad \text{for } d > 4, \tag{1}$$

with f_i the Wilson coefficient, d the dimension of the operator, Λ an arbitrary energy scale set to 1 TeV, and O_i the EFT operator extending the SM. The Eboli parameterisation [35] is used, where the lowest dimension operators acting on the quartic gauge boson vertex are of dimension 8 with the assumption of a light Higgs boson and thus a linear realisation of the $SU(2)_L \otimes U(1)_Y$ symmetry breaking [35]. The Wilson coefficients of the most sensitive operators to massive tri-boson final states are f_{M2}, f_{M3}, f_{M4}, and f_{M5}. One dimensional limits are derived by allowing only one coefficient to vary from zero and setting constraints using multivariate techniques, combining the 3ℓ and 4ℓ channels in a simultaneous fit. To account for QCD NLO corrections a k-factor is applied to the EFT MC samples. To increase the sensitivity to EFT effects, a BDT is trained on events with contributions from all EFT operators under consideration. The training is repeated for each signal region in the 3ℓ and 4ℓ channels, following the same approach as described in Section 3.2.

The EFT expectation is parameterised as

$$N_{b,H}(\mathbf{f}, \boldsymbol{\theta}) = \sum_p \sum_d N_b^{pd,\text{SM}}(\boldsymbol{\theta}) \left(1 + \sum_i A_{bi}^{pd} f_i + \sum_i B_{bi}^{pd} f_i^2 + \sum_{i<j} C_{bij}^{pd} f_i f_j \right) + N_b^{\text{bkg,SM}}(\boldsymbol{\theta}), \tag{2}$$

with expected number of events, $N_{b,H}$ for a bin b with Wilson coefficients $\mathbf{f}$, and the nuisance parameters $\boldsymbol{\theta}$. The expected number of SM events in tri-boson process p and decay channel d is $N_b^{pd,\text{SM}}(\boldsymbol{\theta})$, with expected number of background events $N_b^{\text{bkg,SM}}(\boldsymbol{\theta})$. The EFT contributions is modelled with A_{bi}^{pd}, B_{bi}^{pd} and C_{bij}^{pd} [68]. The likelihood is constructed as

$$L(\boldsymbol{N} \mid \boldsymbol{f}, \boldsymbol{\theta}) = \prod_b^{n_\text{bins}} \left(\frac{N_{b,H}^{N_b} e^{N_{b,H}}}{N_b!} \right) \times \prod_i^{n_\text{sys}} \xi_i\,(\theta_i)\ , \tag{3}$$

with $\boldsymbol{N}$ signal events per bin over a total number of bins n_bins and ξ_i the constraints on each nuisance parameter, n_sys, to account for the experimental systematic uncertainties. The one dimensional 95% confidence level (CL) limits on the Wilson coefficients f_i are then extracted using a profile likelihood ratio

Table 7: The observed (expected) non-unitarised limits on Wilson coefficients for the 3ℓ and 4ℓ channels separately, and the combined limits.

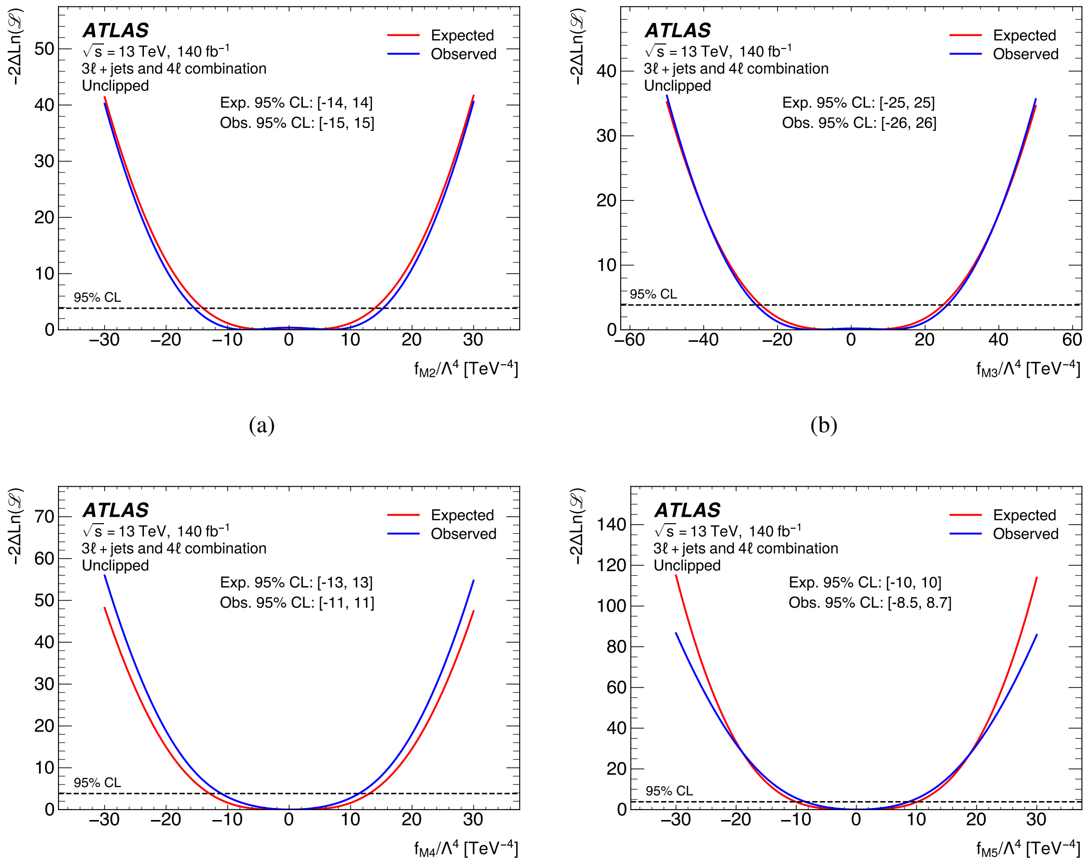
Observed (expected) 95% CL limits on Wilson coefficients (TeV^{-4})			
Coefficient	3ℓ	4ℓ	Combination
f_{M2}/Λ^4	$[-15, 15]$ ($[-17, 17]$)	$[-23, 23]$ ($[-18, 18]$)	$[-15, 15]$ ($[-14, 14]$)
f_{M3}/Λ^4	$[-25, 25]$ ($[-29, 30]$)	$[-39, 40]$ ($[-31, 31]$)	$[-26, 26]$ ($[-25, 25]$)
f_{M4}/Λ^4	$[-13, 14]$ ($[-16, 16]$)	$[-17, 17]$ ($[-16, 16]$)	$[-11, 11]$ ($[-13, 13]$)
f_{M5}/Λ^4	$[-11, 11]$ ($[-13, 13]$)	$[-12, 12]$ ($[-13, 13]$)	$[-8.5, 8.7]$ ($[-10, 10]$)

Table 8: The observed and expected unitarised limits on Wilson coefficients for the combination of the 3ℓ and 4ℓ channels on dimension 8 operator Wilson coefficients, together with the energy scale at which the unitarity bound is crossed.

Coefficient	Expected limit [TeV^{-4}]	Exp. $\sqrt{\hat{s}_c}$ [TeV]	Observed limit [TeV^{-4}]	Obs. $\sqrt{\hat{s}_c}$ [TeV]
f_{M2}/Λ^4	$[-18, 17]$	1.2	$[-19, 19]$	1.2
f_{M3}/Λ^4	$[-28, 29]$	1.5	$[-28, 29]$	1.5
f_{M4}/Λ^4	$[-14, 14]$	1.6	$[-12, 12]$	1.7
f_{M5}/Λ^4	$[-11, 11]$	2.1	$[-9.1, 9.3]$	2.2

test allowing only the coefficient under consideration to vary while setting the other coefficients to zero. The expected and observed 95% CL limits for the 3ℓ and 4ℓ channel separately and combined, including statistical and systematic uncertainties, are shown in Table 7. The combined log-likelihood curves for the Wilson coefficients f_{M2}, f_{M3}, f_{M4}, and f_{M5} are shown in Figure 4.

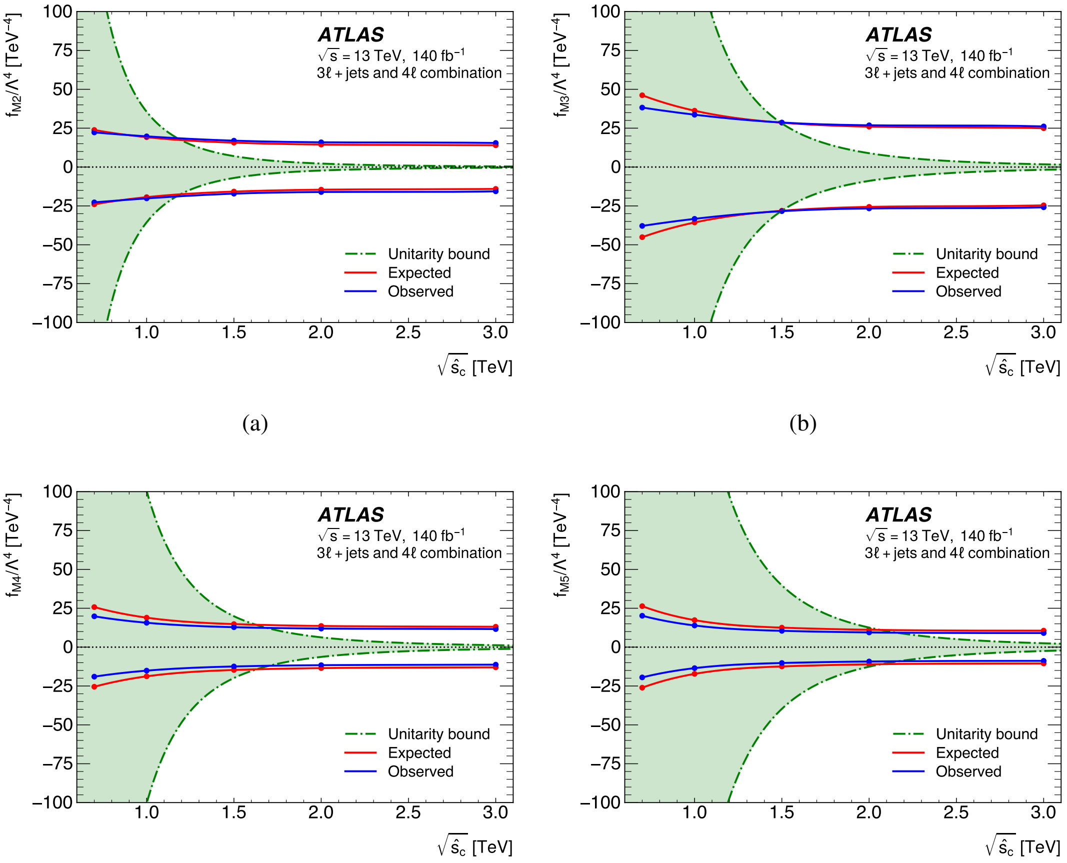
The unitarity bounds of the Wilson coefficients were estimated by adapting the existing calculation for dimension-8 operators in two-to-two scattering process into vector boson scattering processes [69] and setting the parton centre-of-mass energy $\sqrt{\hat{s}}$ to the maximum of the three diboson invariant mass combinations $m_{max}(V_iV_j)$. The limits are then derived as a function of the clipping parameter $\sqrt{\hat{s}_c}$, where the EFT contribution in events with $m_{max}(V_iV_j) > \sqrt{\hat{s}_c}$ is set to zero. The clipping scans for the Wilson coefficients f_{M2}, f_{M3}, f_{M4}, and f_{M5} are shown in Figure 5 together with the unitarity limits. The most constraining limit respecting unitarity is found at the intersection of the calculated limit with the unitarity bound, and listed for all operators in Table 8. These constraints are comparable to published limits derived in the $W\gamma jj$ final state [70, 71].



(a) (b)

(c) (d)

Figure 4: The combined 3ℓ+jets and 4ℓ channel log-likelihood curves for the Wilson coefficients (a) f_{M2}, (b) f_{M3}, (c) f_{M4}, and (d) f_{M5}. Expected and observed log-likelihood curves are shown, no unitarisation is applied.



(a)

(b)

(c)

(d)

Figure 5: The clipping scans for the Wilson coefficients (a) f_{M2}, (b) f_{M3}, (c) f_{M4}, and (d) f_{M5} are shown together with the unitarity limits as a function of the clipping parameter $\sqrt{\hat{s}_c}$, where the EFT contribution in events with $m_{max}(V_iV_j) > \sqrt{\hat{s}_c}$ is set to zero.

6 Conclusions

A search for the joint production of three massive vector bosons (WWZ, WZZ, and ZZZ) is presented using 140 fb^{-1} of data at $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the LHC. Events with three, four, or five or more reconstructed electrons and muons are analysed. The measured cross section for the $pp \to VVZ$ process is $660^{+93}_{-90}(\text{stat.})^{+88}_{-81}(\text{syst.})$ fb, and the observed (expected) significance is 6.4 (4.7) standard deviations, representing the first observation of VVZ production. In addition, the measured cross section for the $pp \to WWZ$ process is $442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$ fb, and the observed (expected) significance is 4.4 (3.6) standard deviations, representing the first evidence of WWZ production. The measured cross sections are consistent with the SM predictions. Constraints on physics beyond the SM are also derived in the EFT framework by setting limits on Wilson coefficients for dimension-8 operators describing anomalous quartic gauge boson couplings. The constraints are comparable to published limits in the $W\gamma jj$ final state.

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