Search for diboson resonance production
in the $\ell\nu qq$ final state using $pp$ collisions at $\sqrt{s} = 13$ TeV
with the ATLAS detector at the LHC

The ATLAS Collaboration

Abstract

A search is presented for new resonances decaying to $WW$ or $WZ$ final states, where one $W$ boson decays leptonically (to an electron or a muon plus a neutrino) and the other $W/Z$ boson decays hadronically. The data analyzed comprises 13.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV, recorded by the ATLAS detector at the CERN Large Hadron Collider. The results are interpreted in the context of a spin-2 Randall-Sundrum bulk graviton, a new heavy vector boson, or an additional Higgs boson in the narrow width approximation. No evidence for resonant diboson production is observed. Resonance masses below 1240 GeV are excluded at 95% confidence level for a spin-2 Randall-Sundrum bulk graviton. The results also exclude a possible new neutral (charged) heavy vector boson coupling to the Higgs and the SM gauge bosons with masses below 2500–2810 (2400–2540) GeV, depending on the model, at 95% confidence level.

Note: the current version of note was updated on 30, August 2016 to correct a mistake in the description of muon and small-$R$ jet overlap removal procedure.
1 Introduction

Several scenarios of new physics (NP) beyond the standard model (SM), such as technicolour [1–3], warped extra dimensions [4–6], and grand unified theories [7], predict new particles in the TeV range that predominantly decay to a pair of on-shell SM gauge bosons (W/Z). Similarly, many NP models also require an extended Higgs sector [8–10] in addition to the SM Higgs boson discovered by the ATLAS [11] and CMS [12] collaborations in 2012.

Searches for new diboson resonances have been performed in several decay channels at the Tevatron and the Large Hadron Collider (LHC), but no evidences of such resonances have been observed [13–24]. In this note, an updated search is presented for WW/WZ resonances where one W boson decays leptonically (W → ℓν with ℓ = e, µ) and the other W/Z boson decays hadronically (W/Z → q̄q′/qq with q, q′ = u, d, c, s or b). The analysis is based on 13.2 fb\(^{-1}\) of pp collision data at a centre-of-mass energy √s = 13 TeV, collected by the ATLAS experiment at the LHC in 2015 and 2016 (3.2 and 10.0 fb\(^{-1}\) of data, respectively). The search is optimized for a high-mass resonance, where the two final-state jets, corresponding to the quarks decaying from a W/Z boson at high momentum, have a small opening angle and can be reconstructed as a single jet with large radius parameter (large-R jet). Compared to the previous search [25] using 13 TeV ATLAS data recorded in 2015, an additional low purity signal region is included in the current analysis by retaining large-R jets whose substructures are less consistent with ones from hadronically-decaying W/Z bosons. Combining this low-purity signal region with the high-purity one yields roughly a 10% increase in search sensitivity for diboson resonances with masses above 500 GeV.

Several signal models are used to optimize the analysis strategy and interpret the results. A heavy vector triplet (HVT) model, based on a simplified phenomenological Lagrangian [26], is used to model both WW and WZ resonances. Here, the new heavy vector boson, V′ = W′, Z′, couples to the Higgs and the SM gauge bosons via the combination of parameters g\(_V\)c\(_H\) and to the fermions via the combination g\(_2^-\)g\(_V\)c\(_F\). The parameter g\(_V\) represents the typical strength of the vector boson interaction. The parameters c\(_H\) and c\(_F\) describe deviations from the nominal Higgs and fermion couplings, respectively; they are expected to be on the order of unity in most models. Two benchmarks [26] are considered in this analysis. In the first one, referred to as model-A with g\(_V\) = 1, the branching ratios of the new HVT to fermions and gauge bosons are similar to those predicted by some extensions of the SM gauge group [27]. This model, although severely constrained by searches for new resonances decaying to leptons [28–31], is included because of its similarity to the W′ boson from an extended gauge model used as a benchmark in previous searches [23, 25]. In the second model, referred to as model-B with g\(_V\) = 3, the fermionic couplings of the new HVT are suppressed, and branching ratios are similar to those predicted by composite Higgs boson models [32–34]. In both benchmarks, the parameter c\(_F\) is assumed to be universal for simplicity [26] although it could in principle be different for quarks, leptons, or third generation fermions. Other combinations of parameters, g\(_V\)c\(_V\)V, g\(_V\)^2c\(_V\)V H H and c\(_V\)W, control multiboson production and have a negligible impact on the overall cross sections for the processes of interest. The width of the HVT is narrower than the detector resolution, and the kinematic distributions relevant to this search are very similar. Off-shell and interference effects are not considered.

A Kaluza-Klein (KK) graviton (G*) is used to model a narrow resonance decaying to a WW final state. The KK graviton interpretation is based on an extended Randall-Sundrum model of a warped extra dimension (RS1) [35], where the SM fields can propagate into the bulk of the extra dimension. This extended “bulk” RS model, referred to as bulk RS hereafter, avoids constraints on the original RS1 model from limits on flavour-changing neutral currents and electroweak precision tests and has a dimensionless coupling
constant $k/M_{Pl} \sim 1$, where $k$ is the curvature of the warped extra dimension and $M_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck mass.

Results for the $WW$ final state are also interpreted in the context of an additional Higgs boson at high mass in the narrow width approximation (NWA), where the Higgs width is set at 4 MeV, which is much less than the experimental resolution. Possible interference effects of the heavy Higgs boson with the SM diboson production are neglected. Finally, in the $WW$ case, results are interpreted within a CP-even scalar singlet $S$ model [36]. The model is parameterised by an energy scale $\Lambda = 1$ TeV, a coefficient $c_H$ scaling the coupling of $S$ to the Higgs boson and a coefficient $c_3$ scaling the coupling of $S$ to gluons. Two benchmark scenarios are considered, one in which $c_3$ is set via naive dimensional analysis (NDA) to be $c_3 = (1/4\pi)^2$, with $c_H = 0.9$; and another in which the coupling to gluons is unsuppressed and $c_3 = 1/8\pi$, with $c_H = 0.5$. The value of $c_3$ determines the production cross-section and the decay width to gluons, while decays to $W$ or $Z$ bosons account for the remaining decay width. In the unsuppressed scenario considered in this analysis, the total branching ratio to $WW$ increases from 59% at 500 GeV, to 70% at 2 TeV and to 73% at 5 TeV, while in the NDA scenario this branching ratio is always above 99%.

2 The ATLAS detector

The ATLAS detector [37] is a general-purpose particle detector used to investigate a broad range of physics processes\(^1\). The ATLAS detector includes inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer with a toroidal magnetic field. The inner detector (ID) consists of a silicon pixel detector, a silicon strip detector and a straw tube tracker. It is situated inside a 2 Tesla field generated by the solenoid and provides precision tracking for charged particles with pseudorapidity $|\eta| < 2.5$. The straw tube detector also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It is composed of sampling calorimeters with either liquid Argon or scintillator tiles as the active medium. The muon spectrometer (MS) provides muon identification and measurement in the range $|\eta| < 2.7$, and triggering for $|\eta| < 2.4$, combining information from resistive-plate, thin-gap and cathode-strip chambers and monitored drift tubes. The ATLAS detector has a two-level trigger system that is based on custom hardware followed by a software-based level to reduce the event selection rate to approximately 1 kHz for offline analysis.

3 Simulated MC samples

Samples of simulated events are used to optimize the event selection and to estimate the background from various SM processes. Benchmark signal samples of the bulk RS graviton and the HVT model are generated using MadGraph-2.2.2 [38] interfaced to Pythia 8.186 [39] with the NNPDF23LO [40] parton density functions (PDFs). The mass range explored is from 500 GeV to 4.5 TeV. For the bulk RS graviton model, the parameter $k/M_{Pl}$ is assumed to be 1. The heavy Higgs boson samples in the narrow

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

3
width approximation are produced using \textsc{Powheg-Box} 2.0 \cite{41}, interfaced with \textsc{Pythia} 8.186, and the CTEQ6L1 PDFs \cite{42} are used. The analysed mass range spans in this case from 500 GeV to 3 TeV.

The main SM background arises from $W$ bosons produced in association with jets ($W$+jets). Additional sources of SM background include events from the production of top-quarks, multijets, dibosons and $Z$+jets. Production of $W$ and $Z$ bosons in association with jets is simulated using \textsc{Sherpa} 2.2 \cite{43} with the CT10 PDFs \cite{44}, where $b$– and $c$–quarks are treated as massive particles. Single-top and $t\bar{t}$ simulated events are generated with \textsc{Powheg-Box} 2.0 using CT10 PDFs interfaced to \textsc{Pythia} 6.428 \cite{45} for parton showering, using the Perugia2012 \cite{46} tune with CTEQ6L1 PDFs for the underlying event description. Diboson samples ($WW$, $WZ$ and $ZZ$) are generated using \textsc{Sherpa} 2.1 with the CT10 PDFs. \textsc{EvtGen} 1.2.0 \cite{47} is used for properties of the bottom and charm hadron decays.

The effect of multiple $pp$ interactions in the same and neighboring bunch crossings (pile-up) is included by overlaying minimum-bias events simulated with Pythia 8.186 on each generated signal and background event. The number of overlaid events is such that the distribution of the average number of interactions per $pp$ bunch crossing in the simulation matches that observed in the data. The generated samples are processed through a Geant4-based detector simulation \cite{48, 49}, and the standard ATLAS reconstruction software.

### 4 Object definitions

The events in the combined 2015+2016 dataset were collected during periods of stable beams collisions, with all relevant subsystems in fully operational conditions. The data were recorded at a centre-of-mass energy $\sqrt{s} = 13$ TeV, between June and November 2015, corresponding to an integrated luminosity of $3.2 \text{fb}^{-1}$, and between May and July 2016, corresponding to an integrated luminosity of $10.0 \text{fb}^{-1}$.

Events are required to have at least one primary vertex that has no less than two associated tracks, each with transverse momentum $p_T > 400$ MeV, where the $p_T$ is defined as the magnitude of the component of the momentum orthogonal to the beam axis. If there is more than one primary vertex reconstructed in the event, the one with the largest track $\sum p_T^2$ is chosen as the hard-scatter primary vertex and is subsequently used for calculation of the main physics objects in the analysis: electrons, muons, jets and missing transverse momentum. Only events with exactly one “signal” lepton and no “vetoed” extra leptons are selected, where the definitions of “signal” and “vetoed” leptons are given below.

Electrons are selected from clusters of energy depositions in the calorimeter that match a track reconstructed in the ID. They are identified using the likelihood (LH) identification criteria described in Ref. \cite{50}. Signal electrons used in this analysis are required to pass “TightLH” identification (corresponding to approximately 88 % efficiency for an electron with transverse energy, $E_T$, of 100 GeV) and have transverse momentum $p_T > 27$ GeV, while vetoed electrons are required to pass “LooseLH” (for an identification efficiency of 96 % at 100 GeV) and $p_T > 7$ GeV; all have to satisfy $|\eta| < 2.47$, excluding the transition region between the barrel and endcaps in the LAr calorimeter (1.37 < $|\eta|$ < 1.52). The selected electron candidates are further required to be isolated from other tracks and calorimetric activities. This is done by examining the scalar sum of transverse momentum of tracks and sum of transverse energy deposits within a cone of $\Delta R = 0.2$ around the electron track, excluding the transverse energy of electron itself and correcting for the expected pile-up contributions. The isolation requirement for electrons is chosen to ensure approximately 99 % and 95 % selection efficiency, for vetoed and signal electrons, respectively.
Muons are reconstructed by combining ID and MS tracks that have consistent trajectories and curvatures [51]. Based on the quality of their reconstruction and identification, signal muons are required to pass the “Medium” selection and have $p_T > 25$ GeV, while vetoed muons are required to pass “Loose” selection and $p_T > 7$ GeV; all have to satisfy $|\eta| < 2.5$. In addition, a similar isolation requirement as for electron candidates is applied to muon candidates, but within a cone $\Delta R = 0.3$ and considering only tracks.

In order to ensure that leptons originate from the interaction point, a requirement of $|d_0|/\sigma_{d_0} < 5$ (3) and $|z_0 \sin \theta| < 0.5$ mm is imposed on the electrons (muons), where $d_0(z_0)$ is the transverse (longitudinal) impact parameter of the lepton with respect to the reconstructed hard-scatter primary vertex and $\sigma_{d_0}$ is the uncertainty on the measured $d_0$.

In this analysis, jets are reconstructed from three-dimensional clusters of energy depositions in the calorimeter using the anti-$k_t$ algorithm [52] with distance parameters of $R = 1.0$ and $R = 0.4$, hereafter referred to as large-$R$ jets (denoted as “$J$”) and small-$R$ jets (denoted as “$j$”), respectively. The jet four-vector is calculated as the sum of the four momenta of its constituents, which are assumed to be massless.

For the large-$R$ jets, the original constituents are reclustering [53] using the $k_t$ algorithm [54] with a distance parameter of $R_{\text{sub-jet}} = 0.2$, to form a collection of sub-jets. The sub-jets are discarded if they carry less than 5% of the transverse momentum of the original jet. The constituents in the remaining sub-jets are then used to recalculate the large-$R$ jet four-momentum, and the jet energy and mass are further calibrated to particle-level using correction factors derived from simulation [55]. The large-$R$ jets are required to have $p_T > 200$ GeV, $|\eta| < 2.0$ and an angular separation $\Delta R > 1.0$ from electron candidates. The momenta of small-$R$ jets are corrected for losses in passive material, the non-compensating response of the calorimeter and contributions from pile-up [56]. They are required to have $p_T > 20$ GeV and $|\eta| < 2.4$. For large-$R$ jets, on the other hand, compensations for losses in passive material and the non-compensating response of the calorimeter are applied, while pileup corrections are not applied explicitly [55].

For small-$R$ jets with $p_T < 60$ GeV, the “Jet Vertex Tagger” (JVT) multivariable [57] is required to be larger than 0.59, vetoing jets not compatible with originating from the primary vertex, in order to suppress jets from pile-up interactions. In addition, small-$R$ jets are discarded if they are within a cone of size $\Delta R < 0.2$ around the direction of an electron candidate. However, if the distance between a jet and an electron candidate is within $0.2 < \Delta R < 0.4$, the jet is retained but the nearby electron is rejected from the analysis.

As for overlap with muons, a muon candidate within $\Delta R < 0.4$ of a small-$R$ jet is discarded unless it is within $\Delta R < 0.2$ and the small-$R$ jet has fewer than three tracks and satisfies $p_T(\mu)/p_T(j) > 0.5$ and $p_T(\mu)/\sum p_T > 0.7$, where $\sum p_T$ is the sum of the transverse momenta of tracks associated with the small-$R$ jet. In such a case, the muon is retained but the nearby small-$R$ jet is rejected from the analysis.

Small-$R$ jets containing $b$-hadrons are identified using the MV2 $b$-tagging algorithm [58, 59] with an efficiency of 85%, determined from $t\bar{t}$ simulated events. The small-$R$ jets identified as $b$-quark-induced are called $b$-jets in this note. The corresponding misidentification rate for selecting jets originating from a light quark or gluon is less than 1%. The misidentification rate for selecting jets containing $c$-hadrons is approximately 17%.

The missing transverse momentum, with magnitude $E_{\text{miss}}^T$, is calculated as the negative vectorial sum of the transverse momenta of all calibrated selected objects, such as electrons, muons, and jets. Tracks compatible with the primary vertex and not matched to any of those objects are also included in the reconstruction as soft terms [60, 61].
5 Event selection

The data were recorded by single-electron and $E_T^{\text{miss}}$ triggers. The single electron trigger has minimum $E_T$ threshold of 24 GeV and 26 GeV for the data recorded in 2015 and 2016, respectively. It has approximately 90% efficiency with respect to a selected offline electron. The $E_T^{\text{miss}}$ trigger has an online threshold of 70 GeV for the 2015 data and of 100 GeV for the 2016 data, where the muon term is not used to compute $E_T^{\text{miss}}$ in the trigger algorithm. It is almost fully efficient for selected events in the muon final state.

The analysis selects events that contain exactly one reconstructed lepton, at least one large-$R$ jet and satisfy $E_T^{\text{miss}} > 100$ GeV. The leptonically decaying $W$ candidate is required to have $p_T(\ell \nu) > 200$ GeV, where $p_T(\ell \nu)$ is the transverse momentum of the lepton-neutrino system. The transverse momentum of the neutrino from the leptonically decaying $W$ boson is assumed to be equal to the missing transverse momentum. The momentum of the neutrino in the $z$-direction, $p_z$, is obtained by imposing a $W$ boson mass constraint on the lepton and neutrino system, which leads to a quadratic equation. The $p_z$ is defined as either the real component of the complex solution or the smaller in absolute value of the two real solutions.

The large-$R$ jet with the highest $p_T$ is selected as the candidate of the hadronically-decaying $W/Z$ boson.

According to the signal topology, the two bosons correspond to the two-body decay of a resonance so their transverse momenta are expected to be close to half the reconstructed resonance mass $m_{\ell \nu \ell \nu}$. As a result, selected events are further required to satisfy $p_T(J)/m_{\ell \nu \ell \nu} > 0.4$ and $p_T(\ell \nu)/m_{\ell \nu \ell \nu} > 0.4$, where these thresholds are found to be optimal with respect to signal acceptance versus background rejection for all resonance masses and signal hypotheses.

The events that pass the selection criteria above are further categorized into background (control) and signal regions. They are defined as follows:

- $WW$ ($WZ$) signal region: the invariant mass of the selected large-$R$ jet is within 15 GeV of the expected $W/Z$ mass peak from simulated events (values of 83.2 GeV and 93.4 GeV are used for the boson masses, respectively). In addition, events are rejected if there is a small-$R$ jet that is identified as a $b$-jet with a separation of $\Delta R > 1.0$ from the hadronically decaying $W$ ($Z$) candidate. The latter requirement rejects more than 70% of background events from $t\bar{t}$ production while keeping more than 95% of signal events, independent of the resonance mass. The $WW$ and $WZ$ signal regions are not combined in the analysis.

- $t\bar{t}$ control region: an event is considered to be in the $t\bar{t}$ control region if it satisfies the selection criteria defined for the $WV$ signal region except for the $b$-jet requirement. Instead, events are explicitly required to have at least one $b$-tagged small-$R$ jet with a separation from the selected large-$R$ jet $\Delta R > 1.0$.

- $W+jets$ control region: an event is considered to be in the $W+jets$ control region if it satisfies the selection criteria defined for the $WW/WZ$ signal region except for the invariant mass requirement of the large-$R$ jet, which is required to be in a sideband region. The lower (higher) mass sideband region is defined as $50 < m_J < 68.2$ GeV ($m_J > 108.4$ GeV).

Events in the signal and background regions are further divided into high-purity and low-purity categories, depending on whether the large-$R$ jet satisfies a selection cut on the jet substructure variable $D_2^{(\beta=1)}$ [62]. The latter is widely used in ATLAS to help distinguish the boosted hadronically decaying $W/Z$ bosons.
from jets originated from non-top quarks or gluons; its definition can be found in Ref. [63] (equations 1.1, 2.1, 2.2).

The selection cut on the $D_2^{(β=1)}$ variable is different for $W$ and $Z$ bosons, and depends on the mass of the resonance. For the high-purity category, this selection together with the mass window requirement is optimized to have 50\% identification efficiency for the hadronically decaying $W/Z$ boson and to reject more than 90\% of the total background. Events whose hadronically decaying $W/Z$ boson candidates pass the mass window requirement but fail the selection on $D_2^{(β=1)}$ variable are assigned to be in the low-purity category. Such a selection recovers an additional 10 – 30\% signal efficiency, depending on the transverse momentum of the large-$R$ jet.

The complete event selection criteria are summarized in Table 1. Figure 1 shows the reconstructed $m_\ell\nu J$ distributions for data and predicted background events, together with selected benchmark signal models, in the control regions, for the high- and low-purity categories. In the figure, all background contributions and uncertainties are obtained from the fit to the data, as discussed in Section 8. Good agreement is observed between the data and the background prediction.

The signal acceptance times efficiency for the HVT and Randall-Sundrum graviton hypotheses, after all selection requirements, varies between 8\% and 22\% for the high-purity category (between 2\% and 12\% for the low-purity category), in the mass range below 1.5 TeV. Above this mass, the signal acceptance times efficiency is equal to about 22\% for all masses in the high-purity signal region, while in the low-purity signal region the value decreases due to the worsening of the jet mass resolution, reaching 6\% around 4 TeV. In both signal regions, the acceptance for a heavy Higgs boson signal is about 40\% lower.

Studies using simulated events show that the dominant background in each of the signal regions are events from the $t\bar{t}$ production ($\sim 30\%$ and $\sim 10\%$ in high-purity and low-purity categories, respectively) and the $W$+jets production ($\sim 60\%$ and $\sim 80\%$ in high and low purity categories, respectively). As for the $W$+jets control sample, more than 80\% of events in the lower mass sideband are from $W$+jets production. However in the higher mass sideband, the fraction of events from the $W$+jets production is smaller ($\sim 52\%$ and $\sim 61\%$ in high and low purity categories, respectively) while the contribution from the $t\bar{t}$ production ($\sim 37\%$ and $\sim 30\%$ in high and low purity categories, respectively) is more significant.

Finally, concerning the $t\bar{t}$ control region, studies using simulated events show that $\sim 86\%$ of the events here are from $t\bar{t}$ production, where the rest are from single-top, $W/Z$+jets or diboson production.

### 6 Background estimation

The $WW/WZ$ invariant mass, $m_\ell\nu J$, is the observable used to search for a localized excess of events beyond the SM prediction. It is reconstructed on an event-by-event basis, taking into account the constraint on the $W$ boson mass described above. The background shapes for events from the SM production of $W$+jets and $t\bar{t}$ are modeled using simulated events. Their normalizations are determined from a combined fit to the events in the signal and control regions. Since the background contributions from the $Z$+jets, single-top and SM diboson productions are very small, their shapes and normalizations are taken from simulation. The diboson cross section is fixed to the value obtained by an inclusive next-to-leading order calculation with a 30\% systematical uncertainty assumed.
Figure 1: The post-fit $m_{\ell\nu J}$ distributions for the high-purity (HP) category in the (top-left) $W$+jets control region and (top-right) $t\bar{t}$ control region, and for the low-purity (LP) category in the (bottom-left) $W$+jets control region and (bottom-right) $t\bar{t}$ control region. Pre-fit HVT signal expectation at $m = 2$ TeV is overlaid. The background expectation is shown after the profile likelihood fit to the data. The band denotes the total statistical and systematic uncertainty on the background after the fit to the data. The lower panels show the ratio of the observed data to the SM background estimation.
Table 1: Summary of selection criteria used to define the signal region (SR), W+jets control region (W CR) and t\bar{t} control region (t\bar{t} CR), in the high-purity (HP) and low-purity (LP) categories.

<table>
<thead>
<tr>
<th>Selection</th>
<th>SR: HP (LP)</th>
<th>W CR: HP (LP)</th>
<th>t\bar{t} CR: HP (LP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W \rightarrow \ell \nu ) selection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of signal leptons</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of vetoed leptons</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_T^{\text{miss}} )</td>
<td></td>
<td>&gt; 100 GeV</td>
<td></td>
</tr>
<tr>
<td>( p_T(\ell \nu) )</td>
<td></td>
<td>&gt; 200 GeV</td>
<td></td>
</tr>
<tr>
<td>( W/Z \rightarrow J ) selection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of large-( R ) jets</td>
<td></td>
<td>( \geq 1 )</td>
<td></td>
</tr>
<tr>
<td>Passing the ( D(\beta=1)^2 ) cut</td>
<td>yes (no)</td>
<td>yes (no)</td>
<td>yes (no)</td>
</tr>
<tr>
<td>(</td>
<td>m_{W/Z} - m_J</td>
<td>)</td>
<td>&lt; 15 GeV</td>
</tr>
<tr>
<td>Topology cuts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p_T(\ell \nu)/m_{WV} )</td>
<td></td>
<td>&gt; 0.4</td>
<td></td>
</tr>
<tr>
<td>( p_T(J)/m_{WV} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top-quark veto</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of ( b )-tagged jets</td>
<td>0</td>
<td></td>
<td>( \geq 1 )</td>
</tr>
</tbody>
</table>

The contribution of multijet production is found to be negligible; it originates from events where either another object is incorrectly identified as a lepton or a real but non-prompt lepton is produced in heavy flavour decays of hadrons. The background shape of multijet background events is obtained from an independent data sample that satisfies the signal selection criteria except for the lepton requirement: the electrons are required to satisfy a looser identification criterion ("MediumLH" but failing "TightLH") and fail the isolation requirement; the selected muons are required to satisfy all the selection criteria but inverting the transverse impact parameter significance cut. The contributions of other processes with real leptons to the control sample are subtracted from data using samples of simulated events in the extraction of the multijet background shape. The normalization of the multijet background is estimated by a fit to the transverse mass\(^2\) distribution of the leptonically decaying \( W \) candidates using data events in the \( W \) control region, where the \( E_T^{\text{miss}} \) cut has been inverted to enrich the presence of the multijet background. In the fit, the normalizations of the \( W \)-jets and the multijet components are allowed to float, with all the other backgrounds being fixed to their distributions from simulated events. The normalization factors obtained with this method are consistent with those from the final fit, within their uncertainties.

7 Systematic uncertainties

The main systematic uncertainties on the background estimate arise from the potential mis-modeling of the background components. An uncertainty on the shape of the W+jets background is obtained by comparing the \( m_{\ell\nu,J} \) shape distribution in simulation and in data in the W+jets control region (separately for events in low and high mass sidebands) after the expected t\bar{t} and diboson contributions are subtracted. The ratio is fitted with a first order polynomial and used as a systematic uncertainty.

The data and simulation show good agreement for events in the t\bar{t} control region. The uncertainty in the shape of the \( m_{\ell\nu,J} \) distribution from the t\bar{t} background is estimated by comparing a sample generated by the \textsc{A}\textsc{MC}@\textsc{NLO} [38] interfaced with \textsc{Pythia} 8.186 to the nominal sample (\textsc{Powheg-Box} 2.0, also interfaced with \textsc{Pythia}). Additional systematic uncertainties are evaluated by comparing the nominal

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\(^2\) The transverse mass is defined as is defined as \( m_T = \sqrt{2p_T(\ell)p_T(\nu) \cdot (1 - \cos \Delta \phi_{\ell,\nu})} \), where \( \Delta \phi_{\ell,\nu} \) is the azimuthal angle between the lepton and neutrino candidates.
sample showered with Pythia to one showered with Herwig \[64\]. Samples of $t\bar{t}$ with the factorization and renormalization scales doubled and halved are compared to the nominal, and the largest differences observed is taken as additional uncertainty.

Experimental uncertainties on a number of other quantities have been considered, affecting the shape and normalization of both the background and signal distributions. Effects included are: the energy scale and resolution of small-$R$ jets, trigger efficiencies, lepton identification, reconstruction and isolation efficiencies, lepton momentum scales and resolutions, $b$-tagging efficiency and misidentification rates, and missing transverse momentum resolution.

The uncertainties on the scale of the $D_2^{(\beta=1)}$ variable and on the large-$R$ jet energy and mass are evaluated by comparing the ratio of calorimeter-based to track-based energy and mass measurements in dijet data and simulation \[62\]; the resolution uncertainty on $D_2^{(\beta=1)}$, instead, is obtained from a combination of 7 TeV $t\bar{t}$ measurements and a comparison between different MC generators.

The dominant uncertainties on the signal yield arise from the choice of PDFs and from the uncertainty on the amount of initial and final state radiation (ISR and FSR, respectively) present in simulated signal events. The PDF uncertainties are estimated by taking the acceptance difference between the NNPDF23LO and MSTW2008LO PDFs \[65\] and adding it in quadrature to the difference between the NNPDF23LO error sets, while the ISR/FSR contributions are computed varying the respective scales at generator level.

The preliminary uncertainty on the combined 2015+2016 integrated luminosity is 2.9\%. It is derived, following a methodology similar to that detailed in Refs. \[66, 67\], from a preliminary calibration of the luminosity scale using $x$–$y$ beam-separation scans performed in August 2015 and May 2016. This uncertainty is applied to the normalization of the signal and also to the backgrounds for which the normalization is derived from MC simulations.

After the fit to data, the dominant systematic sources are found to correspond to the scale and resolution uncertainties of the $D_2^{(\beta=1)}$ variable, the energy and mass scale of the large-$R$ jets, and the uncertainties on the shapes of the $W$+jets and $t\bar{t}$ backgrounds. The overall effect on the fitted signal strength varies between 10−20\%, depending on the resonance mass. While systematic uncertainties dominate the search sensitivity at low masses, at high masses (above 2 TeV) those are subleading with respect to the statistical uncertainties.

### 8 Results

A simultaneous binned maximum-likelihood fit to $m_{\ell\nu J}$ distributions of the events in the signal region, the $t\bar{t}$ control region and the $W$+jets control region is performed using the statistical analysis package RooStats \[68\]. The likelihood is defined as the product of the Poisson likelihoods for all of signal and control regions for high- and low-purity categories, simultaneously for the electron and muon channels. The fit includes six contributions: signal, $W$+jets, $t\bar{t}$, single-top, $Z$+jets and diboson production processes. Systematic uncertainties are taken into account as constrained nuisance parameters with Gaussian sampling distributions. For each source of systematic uncertainty, the correlations across bins and between different kinematic regions, as well as those between signal and background, are taken into account. Twenty $m_{\ell\nu J}$ bins between 500 and 5000 GeV are used in the fit, with variable bin width to account for the expected resolution of the resonance peak as a function of the resonance mass while still keeping reasonably high statistics in each bin.
The background-only fit is first performed by fixing the signal strength to zero, assuming the absence of new physics. It yields the normalization factors, defined as the ratio between the number of fitted events to the number of MC predicted events, for the main backgrounds in the analysis. For the WW (WZ) high-purity category, the normalization factors are \(0.81 \pm 0.06\) (0.87 \(\pm 0.08\)) for the \(t\bar{t}\) background, and \(0.98 \pm 0.09\) (0.97 \(\pm 0.09\)) for the W+Jets background. In the low-purity category, the normalization factors are \(0.86 \pm 0.07\) (0.92 \(\pm 0.10\)) for the \(t\bar{t}\) background, and \(0.93 \pm 0.07\) (0.96 \(\pm 0.08\)) for the W+jets background.

Tables 2 and 3 show the number of events predicted and observed in the control regions and WW, WZ signal regions, respectively. The reconstructed \(m_{\ell\nu J}\) distributions for data and predicted background events, together with selected benchmark signal models, are shown in Fig. 2 for the high- and low-purity WV signal regions. Good agreement is observed between the data and the background prediction. The uncertainties on the total backgrounds, shown after the fit, are smaller than the individual components because of their mutual correlations.

In the absence of a statistically significant excess in the data over the background prediction, the result is interpreted as 95 % confidence level (CL) upper limit on the production cross section times the branching fraction for various benchmark models. The exclusion limits are calculated with the modified frequentist method \(CL_s\) [69], and the profile-likelihood test statistic [70], using the binned \(m_{\ell\nu J}\) distributions in signal and control regions. Figures 3, 4, 5 and 6 show the 95% CL upper limits on the production cross section, multiplied by the decay branching fraction into WW or WZ, as a function of the resonance mass, for the HVT, the heavy Higgs-boson and the spin-2 Randall-Sundrum bulk \(G^*\) hypotheses, respectively.

Resonances with masses below 2500 (2400) GeV are excluded for the neutral (charged) \(V'\) in model-A, below 2810 (2540) GeV for the neutral (charged) \(V'\) in model-B, and below 1240 GeV for bulk RS \(G^*\) with coupling constant \(k/M_{Pl} = 1\). The current exclusion limit for the latter model is about 200 GeV higher than the limits in previous analysis [25] using 13 TeV ATLAS data recorded in 2015. Finally, in the scalar singlet hypothesis, the whole mass range under study can be excluded in the unsuppressed scenario, while no exclusion can be set in the NDA scenario with the current dataset.

### 9 Conclusion

A search is presented for new resonances decaying to WW or WZ final states, where one W boson decays leptonically (to an electron or a muon plus a neutrino) and the other W/Z boson decays hadronically, using 13.2 fb\(^{-1}\) of \(pp\) collision data at \(\sqrt{s} = 13\) TeV, recorded with the ATLAS detector at the CERN Large Hadron Collider. No evidence for resonant diboson production is observed. Resonance masses below 1240 GeV are excluded at 95 % confidence level for a spin-2 Randall-Sundrum bulk graviton. The results also exclude a possible new neutral (charged) heavy vector boson coupling to the Higgs and the SM gauge bosons with masses below 2500–2810 (2400–2540) GeV, depending on the model, at 95 % confidence level.
Table 2: Event yields in the $WW$ signal region, $W$+jets control region and $t\bar{t}$ control region for the high-purity and low-purity categories, for data and predicted background contributions after the fit to the data. Systematic uncertainties on the background components are also calculated after the fit, while the uncertainties associated to the observed data are statistical-only.

<table>
<thead>
<tr>
<th></th>
<th>$WW$ signal region</th>
<th>$W$+jets control region</th>
<th>$t\bar{t}$ control region</th>
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<td><strong>High-purity category</strong></td>
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<td>$3182 \pm 65$</td>
<td>$215 \pm 12$</td>
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<tr>
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<td>$322 \pm 23$</td>
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<td>Z+jets</td>
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<td>$53 \pm 6$</td>
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<tr>
<td>Diboson</td>
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<td>$70 \pm 11$</td>
<td>$19.0 \pm 3.8$</td>
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<td>$4530 \pm 80$</td>
<td>$3500 \pm 80$</td>
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<td>$4534 \pm 67$</td>
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<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>$W$+jets</td>
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<td>$7320 \pm 110$</td>
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<td>$t\bar{t}$</td>
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<td>Data</td>
<td>$6849 \pm 83$</td>
<td>$9276 \pm 96$</td>
<td>$4270 \pm 65$</td>
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</table>

Table 3: Event yields in $WZ$ signal region, $W$+jets control region and $t\bar{t}$ control region for the high-purity and low-purity categories, for data and predicted background contributions after the fit to the data. Systematic uncertainties on the background components are also calculated after the fit, while the uncertainties associated to the observed data are statistical-only.

<table>
<thead>
<tr>
<th></th>
<th>$WZ$ signal region</th>
<th>$W$+jets control region</th>
<th>$t\bar{t}$ control region</th>
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<td>$3050 \pm 120$</td>
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<td>$1130 \pm 82$</td>
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<td>$221 \pm 26$</td>
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<td>$4520 \pm 97$</td>
<td>$3510 \pm 94$</td>
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<td>$7250 \pm 196$</td>
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<td>$9300 \pm 180$</td>
<td>$4260 \pm 95$</td>
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<td>$5059 \pm 71$</td>
<td>$9276 \pm 96$</td>
<td>$4270 \pm 65$</td>
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</table>
Figure 2: The post-fit $m_{llJ}$ distributions for the high-purity (HP) category in the (top-left) WW signal region and (top-right) WZ signal region, and for the low-purity (LP) category in the (bottom-left) WW signal region and (bottom-right) WZ signal region. Pre-fit HVT signal expectation at $m = 2$ TeV is overlaid. The background expectation is shown after the profile likelihood fit to the data. The band denotes the total statistical and systematic uncertainty on the background after the fit to the data. The lower panels show the ratio of the observed data to the SM background estimation.
Figure 3: Observed and expected 95% CL upper limits on the production cross section times the branching fraction for HVT $Z' \to WW$, as a function of the resonance mass. The theoretical cross sections for the signal models A and B are also shown. The inner (green) and outer (yellow) bands around the expected limits represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively.

Figure 4: Observed and expected 95% CL upper limits on the production cross section times the branching fraction for HVT $W' \to WZ$, as a function of the resonance mass. The theoretical cross sections for the signal models A and B are also shown. The inner (green) and outer (yellow) bands around the expected limits represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively.
Figure 5: Observed and expected 95% CL upper limits on the production cross section times the branching fraction to $WW$ for a narrow-width heavy Higgs boson with $gg \rightarrow H \rightarrow WW$, as a function of the resonance mass. The inner (green) and outer (yellow) bands around the expected limits represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively. The theoretical curves corresponding to the expectation for a scalar singlet, in the NDA (red) and unsuppressed (blue) hypotheses are also overlaid.

Figure 6: Observed and expected 95% CL upper limits on the production cross section times the branching fraction to $WW$ for a Randall-Sundrum bulk graviton with $gg \rightarrow G^* \rightarrow WW$, as a function of the resonance mass. The inner (green) and outer (yellow) bands around the expected limits represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively.
References


Figure 7: (Top) The reconstructed mass of the large-\( R \) jets in the signal region and sidebands summed together, for the high-purity (HP, left) and low-purity (LP, right) selections, respectively. (Bottom) Distribution of \( D^2_{\beta=1} \), as used to distinguish between the high- and low-purity regions. In all cases, post-fit normalization factors are used to normalize the expected background contributions. The band denotes the statistical and systematic uncertainty on the background after the fit to the data. The lower panels show the ratio of the observed data to the SM background estimation.
Figure 8: Event display for an event with high $m_{\ell\nu J}$ in the muon channel, in the low-purity signal region, found in the 2016 data. The event contains a muon with $p_T = 269$ GeV, a large-$R$ jet with mass = 72 GeV and transverse momentum $p_T = 812$ GeV, $E_T^{\text{miss}} = 458$ GeV and $m_{\ell\nu J} = 1.56$ TeV. A second large-$R$ jet is also present, with $p_T = 241$ GeV. On the left-hand side, two views of the detector are shown, with the muon indicated by the red line, the direction of the missing transverse energy vector by the yellow line and the large-$R$ jets by the white cones. On the right-hand side, a detailed look at the large-$R$ jets (yellow bars) is provided, with the muon indicated by the red line and the missing transverse energy by the dashed white line.