Search for resonant diboson production in the $WW/WZ \rightarrow \ell\nu jj$ decay channels with the ATLAS detector at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Abstract

A search for resonant diboson production using a data sample corresponding to $4.7$ fb$^{-1}$ of integrated luminosity collected by the ATLAS experiment at the Large Hadron Collider in $pp$ collisions at $\sqrt{s} = 7$ TeV is presented. The search for a narrow resonance in the $WW$ or $WZ$ mass distribution is conducted in a final state with an electron or a muon, missing transverse momentum and at least two jets. No significant excess is observed and limits are set using three benchmark models: $WW$ resonance masses below $940$ GeV and $710$ GeV are excluded at 95% confidence level for spin-2 Randall–Sundrum and bulk Randall–Sundrum gravitons, respectively; $WZ$ resonance masses below $950$ GeV are excluded at 95% confidence level for a spin-1 Extended Gauge Model $W'$ boson.
Search for resonant diboson production in the $WW/WZ \rightarrow \ell\nu jj$ decay channels with the ATLAS detector at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration
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I. INTRODUCTION

Many extensions to the Standard Model (SM) predict new massive particles that can decay to $WW$, $WZ$ or $ZZ$ final states [1–3]. In some extensions, the branching ratios of the new particles to these diboson final states greatly exceed their branching ratios to light fermions or photons [4–6]. An analysis of $WW$, $WZ$ and $ZZ$ events is therefore a central element in the search for physics beyond the SM.

This article describes a search for a narrow resonance decaying to either a $WW$ or $WZ$ diboson intermediate state with subsequent decays to an $\ell\nu jj$ final state, i.e. a charged lepton (electron or muon), large missing transverse momentum ($E_{T}^{\text{miss}}$) and at least two jets. Data corresponding to 4.7 fb$^{-1}$ collected by the ATLAS experiment at the Large Hadron Collider (LHC) in $pp$ collisions at $\sqrt{s} = 7$ TeV are used. The search is complementary to other direct searches by the ATLAS Collaboration for a $WW$ or $WZ$ resonance using events from the $\ell\ell\nu\nu$ or $\ell\ell\ell\ell$ final state and has the additional advantage of the hadronically decaying $W$ or $Z$ boson in the final state, which leads to a higher branching ratio. Also, the $\ell\nu jj$ final state allows the reconstruction of the invariant mass of the system, under certain assumptions for neutrino momentum from a $W$ boson decay. Such a reconstruction is not possible in the $\ell\ell\nu\nu$ final state due to the presence of two neutrinos in each event. A separate search for a $ZZ$ resonance has been performed using events with a $\ell\ell\ell\ell$ or $\ell\ell jj$ final state at $\sqrt{s} = 7$ TeV [6].

Three benchmark signal models are used to interpret the $\ell\nu jj$ results. A spin-2 Randall–Sundrum graviton ($G^*$) is used to model a narrow resonance decaying to $WW$ in two distinct warped extra-dimension models: the original Randall–Sundrum (RS) model [1] (commonly called RS1) and the bulk RS model [10] which allows all SM particles to propagate into the extra dimension. The $WZ$ resonance is modeled by a Sequential Standard Model (SSM) $W'$ boson with the $W'WWZ$ coupling strength set by the Extended Gauge Model (EGM) [11].

In the EGM model, the $WWZ$ coupling is equal to the SM $WWZ$ coupling strength scaled by a factor $c_{\text{EGM}} \times (m_W/m_{W'})^3$, producing a partial width proportional to $m_{W'}$. In the nominal EGM, the coupling strength scaling factor $c_{\text{EGM}}$ is set to one. However, this analysis derives exclusion limits for a range of values of this parameter as a function of the invariant mass of the $\ell\nu jj$ system. This particle is referred to as the EGM $W'$ boson below.

Gauge Model (EGM) [11]. In the EGM model, the $WWZ$ coupling is equal to the SM $WWZ$ coupling strength scaled by a factor $c_{\text{EGM}} \times (m_W/m_{W'})^2$ with $c_{\text{EGM}}$ set to 1, thereby producing a partial width proportional to $m_{W'}$. This particle is referred to as the EGM $W'$ boson throughout the text.

The aforementioned direct $WW$ resonance search by the ATLAS Collaboration using $\ell\ell\nu\nu$ final-state events in 4.7 fb$^{-1}$ $pp$ collision data at $\sqrt{s} = 7$ TeV excludes an RS1 graviton with mass less than 1.23 TeV and a bulk RS graviton with mass below 840 GeV [7]. Previous searches for a $WW$ resonance by the D0 Collaboration in Run II at the Tevatron exclude an RS1 graviton with mass less than 760 GeV [12]. Similar searches, mentioned above, for a $ZZ$ resonance by the ATLAS Collaboration exclude an RS1 graviton with mass below 845 GeV [9]. The CMS Collaboration reports a $ZZ$ resonance search in the $\ell\ell jj$ final state and excludes an RS1 graviton with mass below 945 TeV [13]. Previous direct searches for a $WZ$ resonance at $\sqrt{s} = 7$ TeV by the ATLAS and CMS Collaborations exclude the EGM $W'$ benchmark with mass below 760 GeV [8] and 1143 GeV [14], respectively.

II. THE ATLAS DETECTOR

ATLAS [15] is a general-purpose particle detector used to investigate a broad range of different physics processes. Its cylindrical construction is forward-backward symmetric and provides nearly complete hermeticity. The de-
tector is composed of three main subsystems: the inner detector, the calorimeter system and the muon spectrometer. The inner detector (ID) is used for tracking and measuring the momentum of charged particles within the pseudorapidity range $|\eta| < 2.5$ and is composed of a silicon pixel detector, a silicon microstrip detector and, for $|\eta| < 2.0$, a transition radiation tracker. A uniform 2 T magnetic field is provided by a superconducting solenoid surrounding the ID. The calorimeter system forms the next layer of the detector, spanning the region $|\eta| < 4.9$ and providing three-dimensional reconstruction of particle showers. The inner calorimeter is a high-granularity lead–liquid-argon (LAr) electromagnetic (EM) sampling calorimeter covering $|\eta| < 3.2$. Surrounding the EM calorimeter is an iron–scintillator–tile sampling calorimeter providing hadronic coverage in the range $|\eta| < 1.7$, extended to $|\eta| < 3.2$ with copper–LAr technology. The EM and hadronic calorimeters both have LAr-based forward detectors reaching up to $|\eta| = 4.9$. Outside the calorimeters, the muon spectrometer (MS) is used to identify muons and measure their momenta. The MS is composed of three large air-core superconducting toroid systems (one barrel and two endcaps) each with eight azimuthally symmetric superconducting coils. Three layers of precision tracking chambers, consisting of drift tubes and cathode strip chambers, allow muon track reconstruction for $|\eta| < 2.7$, and fast resistive plate and thin-gap trigger chambers provide trigger signals in the region $|\eta| < 2.4$.

The ATLAS detector uses a three-level trigger system to select events for offline analysis. For this search, events are required to have at least one lepton satisfying trigger requirements, the details of which are presented in section IV.

### III. MONTE CARLO SIMULATION

Monte Carlo (MC) simulations are used to model the benchmark signal samples and most SM background processes. The RS1 $G^*$ and EGM $W'$ boson production and decay are simulated using PYTHIA 6.4 [17] with the modified leading-order (LO*) parton distribution function (PDF) set MRST2007LO* [18]. RS1 $G^*$ samples are generated for resonance masses between 500 GeV and 1500 GeV in 250 GeV steps. In these samples the warping parameter, $k \equiv k / M_{PPl}$, is set to 0.1, where $M_{PPl} = m_{Pl} / \sqrt{8\pi}$ is the reduced Planck mass. EGM $W'$ samples are generated with resonance masses from 500 GeV to 1500 GeV in 100 GeV steps, and the production cross-sections are calculated at next-to-next-to-leading order (NNLO) in $\alpha_s$ using ZWPRPROD [19]. The EGM coupling strength scaling factor $c_{EGM}$ is set to 1.0 in these samples, which produces a resonance width of $0.032 \times m_{W'}$ GeV.

The bulk RS model is implemented in CALCHEP [20], allowing simulation of the $2 \rightarrow 4$ production and decay of the graviton with transfer of spin information to the final-state particles. The CTEQ6L LO PDF set [21] is used for these events. Because the bulk RS $G^*$ graviton has negligible coupling to light fermions, only gluonic initial states are considered. These events are processed with PYTHIA to simulate the parton shower, hadronization and underlying event. Samples are generated with $k$ of 1.0 and resonance masses from 500 GeV to 1500 GeV in 100 GeV steps, with cross-sections taken from the CALCHEP calculation. For three representative resonance masses, the production cross-sections times branching ratios to $WW/WW$ for each sample are given in Table I.

Templates with 50 GeV spacing in the mass of the $t\bar{t}jj$ system, $m_{t\bar{t}jj}$, are constructed to ensure a signal prediction if no signal MC sample is generated at that mass. These templates are created by first fitting the fully simulated $m_{t\bar{t}jj}$ distribution with a Crystal Ball function [22]. The shape parameters from these fits are interpolated across the mass range 500–1500 GeV and used to construct Crystal Ball functions, the signal templates, at the intermediate mass points. The acceptances for these signal templates are also interpolated from fits to the acceptances of the fully simulated samples.

For SM background processes, the production of a $W$ or $Z$ boson in association with jets is simulated with ALPGEN [23] using the CTEQ6L LO PDF set. These events are processed with HERWIG [24] for parton showering and hadronization, and JIMMY [25] to simulate the underlying event. The samples are initially normalized to the NNLO production cross-section computed with FOWZ [26, 27]. The prediction of the $W$ boson transverse momentum, $p_T$, by ALPGEN is reweighted to agree with the shape predicted by SHERPA [28], which is observed to agree more closely with data at high $p_T$ [29]. Single top quark ($tb$, $tqb$, $tW$) and top quark pair ($tt$) production are simulated with the next-to-leading-order (NLO) generator MC@NLO [30–32] interfaced to HERWIG and JIMMY and using the CT10 [33] NLO PDF set. A sample of $t\bar{t}$ events generated with POWHEG [34, 36] interfaced to HERWIG and JIMMY is used to cross-check the MC@NLO $t\bar{t}$ production model, and a POWHEG $tt$ sample interfaced to PYTHIA is generated to study the

<table>
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<tr>
<th>Mass [GeV]</th>
<th>$\sigma \times BR$ [pb]</th>
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<td>500</td>
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<tr>
<td>1000</td>
<td>0.23</td>
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<tr>
<td>1500</td>
<td>0.017</td>
</tr>
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</table>

TABLE I: Production cross-sections times branching ratios for $G^* \rightarrow WW$ or $W' \rightarrow WZ$ for the RS1 $G^*$, bulk RS $G^*$, and the EGM $W'$, for resonance masses equal to 500 GeV, 1000 GeV, and 1500 GeV. All cross-sections are given in picobarns.
dependence on the parton shower and hadronization model. The ACERMC event generator [33] interfaced with PYTHIA is employed to study the effect of initial- and final-state radiation in $t\bar{t}$ events. Both $t\bar{t}$ and single top quark samples are generated assuming a top quark mass, $m_t$, of 172.5 GeV, but two MC@NLO $t\bar{t}$ samples are generated with $m_t = 170$ GeV and 175 GeV to determine the dependence of the background prediction on the top quark mass. The $t\bar{t}$ cross-section is normalized to the approximate NNLO value [38, 39]. Single top quark production cross-sections are taken from an NNLO calculation for the $tb$ process [40], and approximate NNLO calculations for the $t\bar{t}p$ and $tW$ processes [41]. SM diboson production ($WW, WZ, ZZ$) is modeled using HERWIG and normalized to the NLO production cross-sections computed by MCFM [42, 43] with the MRST2007LO* PDF set. In all samples, PHOTOS [44] is employed to simulate final-state photon radiation and TAUOLA [45] to take into account polarization in $\tau$ lepton decays.

All MC samples include the effect of multiple $pp$ interactions (pile-up) per bunch crossing and are reweighted so as to match the distribution of the number of interactions per bunch crossing to that observed in the data. The detector response is simulated using a GEANT4-based model [46] of the ATLAS detector [47]. Finally, events are reconstructed using the same software used for collision data.

IV. OBJECT RECONSTRUCTION AND EVENT SELECTION

The events recorded by the ATLAS detector for this analysis are selected by single-electron or single-muon triggers. The electron trigger requires an electron-like object [48] with transverse energy ($E_T$) greater than 20 GeV or 22 GeV depending on the LHC instantaneous luminosity. The muon trigger requires a muon candidate with $p_T > 18$ GeV. The data sample used, collected in 2011, corresponds to an integrated luminosity of 4.7 fb$^{-1}$ [49, 50] after applying data-quality requirements [51]. MC events must satisfy the same trigger selection requirements.

All triggered events must have at least one reconstructed vertex formed by the intersection of at least three tracks with $p_T > 400$ MeV [52]. From the list of all vertices satisfying this requirement, the vertex with the largest sum of squared $p_T$ of the associated tracks is assumed to be the primary hard-scatter vertex (PV).

Electrons are reconstructed from energy clusters in the calorimeter with an electromagnetic shower profile consistent with that expected for an electron, and must have a matching ID track. Electron candidates must have $E_T > 30$ GeV and be found within the fiducial region defined by $|\eta| < 2.47$, excluding the region $1.37 < |\eta| < 1.52$ which corresponds to the poorly instrumented transition between the barrel and endcap calorimeters. The longitudinal impact parameter of the electron track with respect to the PV ($|z_0|$) must be less than 1 mm, and the significance of its transverse impact parameter with respect to the PV ($|d_0|/\sigma_{d_0}$) must be less than 10.

Electron candidates must also be isolated from other activity in the calorimeter, such that the sum of calorimeter transverse energy in a cone of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.3$ around the electron, corrected for pile-up contributions and the electron energy, is less than 6 GeV. The energy scale and resolution for electrons in MC events are corrected to match that in $Z \rightarrow e^+e^-$ events [53] measured in data.

Muons are reconstructed from the combination of tracks formed from hits in the MS and the ID [54, 55]. The combined muon track must have $p_T > 30$ GeV and $|\eta| < 2.4$. The muon track must have $|z_0| < 10$ mm and $|d_0|/\sigma_{d_0} < 10$. The difference in $|z_0|$ requirements between the electron and muon tracks results from the higher fraction of misreconstructed electrons due to QCD multi-jet events.

Furthermore, muon candidates must be isolated from other tracks and calorimeter activity: the sum of track transverse momenta surrounding the muon track in a cone of radius $\Delta R = 0.3$ must be less than 15% of the muon $p_T$; the calorimeter transverse energy, corrected for pile-up contributions, in a cone of radius $\Delta R = 0.3$ must be less than 14% of the muon $p_T$. The muon $p_T$ scale and resolution in MC events are adjusted to match that in $Z \rightarrow \mu^+\mu^-$ events measured in data [56].

Jets are reconstructed using the anti-$k_T$ sequential recombination clustering algorithm [57, 58], with radius set to 0.4. The inputs to the reconstruction algorithm are topological energy clusters [59] calibrated at the EM energy scale, appropriate for the energy deposited by electrons or photons [59]. These jets are then calibrated to the hadronic energy scale, using $p_T$- and $\eta$-dependent correction factors obtained from simulation. The uncertainty on these correction factors is determined from control samples in data. Jets originating from the PV are selected by requiring that at least 75% of the $p_T$ sum of tracks matched to the jet belongs to tracks originating from the PV. If a reconstructed electron and jet candidate overlap within $\Delta R = 0.3$, the jet is rejected. Finally, jets must have $p_T > 40$ GeV and $|\eta| < 2.8$.

Jets originating from $b$-quarks are identified by exploiting the long lifetimes of bottom hadrons, which lead to observable decay lengths in the detector. The SV0 secondary vertex $b$-tagger [60, 61] is used at an operating point yielding an average $b$-jet-tagging efficiency of 50% in simulated $t\bar{t}$ events and an average light-quark jet rejection factor of 200.

The missing transverse momentum ($E_T^{\text{miss}}$) is defined as the negative vector sum of transverse energies or momenta of all objects in the event. The ATLAS $E_T^{\text{miss}}$ algorithm [62] combines the $p_T$ of muons reconstructed in the
MS with the transverse energies measured in calorimeter
cells associated either to physics objects (such as jets or
leptons) or to topological clusters not associated with
physics objects. Calorimeter cells used in the \(E_T^{\text{miss}}\) calculation
are calibrated individually according to the physics
object to which they are associated. Cells in topological
energy clusters that are not associated with any recon-
structed high-\(p_T\) object are calibrated separately using
the local hadronic calibration scheme \[63\].

In the initial selection, events must contain exactly one
electron or muon, and must have \(E_T^{\text{miss}} > 40\) GeV. Events
are also required to contain at least two jets, with the
requirement that the highest-\(p_T\) jet has \(p_T > 100\) GeV.
In the following, events with an electron are labeled \(e\nu jj\) and muon events are labeled \(\mu\nu jj\). To reduce the
QCD multi-jet background, two triangular veto regions
are constructed in the plane defined by the \(E_T^{\text{miss}}\) and
\(\Delta \phi (\ell, E_T^{\text{miss}})\), the difference in azimuthal angle between
the lepton and \(E_T^{\text{miss}}\) directions. The first region, defined by
\(| \Delta \phi | < 1.5 - 1.5 \times (E_T^{\text{miss}}/75\) GeV), corresponds to
events where the lepton and \(E_T^{\text{miss}}\) directions are aligned.
Back-to-back event topologies populate the second re-
region defined by \(| \Delta \phi | > 2.0 + (\pi - 2) \times (E_T^{\text{miss}}/75\) GeV).
Events falling in either of these two regions are rejected.
The selection cuts described above define the preselection
criteria.

V. BACKGROUND ESTIMATION

Background sources are classified into two categories
based on the origin of the charged lepton in the
event. The first category includes backgrounds where
the charged lepton is produced in the decay of a \(W\) or
\(Z\) boson. The second category corresponds to all other
sources, including both events with a misidentified lep-
ton, e.g. where a jet with a large electromagnetic energy
fraction passes the electron selection requirements, and
events with a true lepton produced in a hadron decay.

Backgrounds from the first category, which include
\(W/Z + \) jets, \(t\bar{t}\), single top quark, and diboson produc-
tion, are modeled with MC events and are normalized to
the product of the production cross-section for that back-
ground and the total integrated luminosity of the dataset.
The normalization of the \(W + \) jets and \(t\bar{t}\) backgrounds is
further tested using data as described in Section VI.

Backgrounds in the second category are modeled with
independent samples of collision data based on the follow-
ing prescriptions. In the \(e\nu jj\) channel, the sample is se-
lected by inverting the calorimeter isolation requirement
for electron candidates that satisfy all other selection cri-
teria. This selects events that are likely to originate from
multi-jet production, but have kinematic properties that
are very similar to those multi-jet events that pass the
isolation requirement. In the \(\mu\nu jj\) channel, the primary
source of these backgrounds are semileptonic decays of
hadrons within a jet. Events with muons that satisfy all
selection criteria except the transverse impact parameter
significance cut are used to model this background. Kin-
eumatic variable templates are derived from these samples
after subtracting the contributions from backgrounds in
the first category.

The data-driven backgrounds in the second category,
henceforth labeled “fake” lepton backgrounds, are then
normalized together with the \(W + \) jets background
through a likelihood fit to the data in a region with
negligible signal contamination. This is done separately
for the \(e\nu jj\) and \(\mu\nu jj\) channels using the lepton trans-
verse mass distribution, \(m_T \equiv \sqrt{2p_T E_T^{\text{miss}} (1 - \cos(D\phi))}\),
which distinguishes events with charged leptons from a
\(W\) boson decay from events with a “fake” lepton. The
normalization of all other backgrounds, from the first cat-
egory, remains fixed in the fit.

The distributions of the lepton \(p_T\), \(E_T^{\text{miss}}\) and the lead-
ing jet \(p_T\) in data and for the predicted backgrounds, after
applying the event preselection criteria, are shown in
Fig. \[1\]. In this figure, the associated errors are com-
bination of the systematic and statistical uncertainties.
Table \[II\] shows the yields for each background and for
the data. The total estimated background and the data
agree within the expected total uncertainty at this stage
of the selection.

VI. SELECTION OF SIGNAL AND CONTROL
REGIONS

The \(WW\) or \(WZ\) mass, \(m_{\ell\nu jj}\), is calculated as the
invariant mass of the \(\ell\nu jj\) system. To reconstruct
this quantity, the \(x\) and \(y\) components of the neu-
trino momentum vector, \(p_x\) and \(p_y\), are set equal to
\(E_T^{\text{miss}} \cos(\phi_{\text{miss}})\) and \(E_T^{\text{miss}} \sin(\phi_{\text{miss}})\), respectively, with
\(\phi_{\text{miss}}\) corresponding to the direction of the \(E_T^{\text{miss}}\) vec-
tor in the transverse plane. The neutrino \(p_z\) is obtained
by imposing the \(W\) boson mass constraint in the momen-
tum conservation equation. It is defined as either the real
component of the complex $p_z$ solution or the minimum of the two real solutions. In events with three or more jets, the two jets with the highest transverse momenta are considered.

In signal events, the $p_T$ of each boson peaks near half of the resonance mass, and the dijet mass distribution, $m_{jj}$, is characterized by a peak close to the $W$ or $Z$ boson mass. Since this analysis searches for resonant masses larger than 500 GeV, the signal region is defined by requiring the reconstructed $p_T$ of the dijet system and of the lepton–$E_T^{\text{miss}}$ system to be greater than 200 GeV and the reconstructed dijet mass to be within the window $65 < m_{jj} < 115$ GeV. Figure 2 compares the $m_{jj}$ distribution observed in data with those predicted for the backgrounds and an enhanced EGM $W'$ boson, with the signal cross-section enhanced by a factor of five, are shown for a resonance mass of 1 TeV.

Two control regions are created to test the $W +$ jets and $t\bar{t}$ background modeling of the $m_{\ell\nu jj}$ distribution. The $W +$ jets control region is identical to the signal region, except for the $m_{jj}$ requirement, which is inverted. Two independent sidebands are formed, $m_{jj} < 65$ GeV and $m_{jj} > 115$ GeV. A scale factor, defined as the number of data events divided by the total background prediction, is computed in each sideband and parameterized as a function of $m_{jj}$. The weighted average of the scale factors, found in the $m_{jj} < 65$ GeV and $m_{jj} > 115$ GeV sidebands, has a value of 1.012 and is used to normalize the $W +$ jets background prediction in the signal region. The difference between the individual scale factors is used as the uncertainty on this normalization. The two sidebands are combined in Fig. 3 which shows the $m_{\ell\nu jj}$ distribution for the $W +$ jets background control region after applying the $W +$ jets scale factors. Good agreement between the data and MC is observed.

The $t\bar{t}$ control region is created by selecting events with at least two $b$-tagged jets. The reconstructed $p_T$ of the dijet system is required to be greater than 200 GeV, and

FIG. 1: (color online) Data and background predictions for (a) the lepton $p_T$, (b) $E_T^{\text{miss}}$, and (c) leading jet $p_T$ for preselected events. Electron and muon events are combined in all plots. The right-most bin contains overflow events.

FIG. 2: (color online) Observed and predicted $m_{jj}$ distribution in all events satisfying the $p_T$ selection requirements of the reconstructed $W/Z$ bosons. Predictions for an EGM $W'$ boson, with the signal cross-section enhanced by a factor of five, are shown for a resonance mass of 1 TeV.

FIG. 3: (color online) The $m_{\ell\nu jj}$ distribution for the data and the background predictions for events in the $W +$ jets background control region. The right-most bin contains overflow events.
VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties that affect the predicted signal acceptance and background rate are grouped into three independent categories: uncertainties due to the limited precision of theoretical calculations, experimental uncertainties on the event reconstruction efficiencies and resolutions, and the determination of the integrated luminosity. Uncertainties from the first and third categories impact the signal and all of the backgrounds except $W$ + jets and “fake” lepton backgrounds which are estimated from data. The integrated luminosity uncertainty is 3.9% \cite{49, 50}.

Several sources of theoretical uncertainty on the $t\bar{t}$ background rate are considered. The largest of these is the $+^{17}_{-10}\%$ \cite{38, 39} uncertainty on the production cross-section. Additionally, the magnitudes of the following systematic uncertainties affecting the $t\bar{t}$ background distribution vary with $m_{\ell\nu jj}$. The largest deviation from the $t\bar{t}$ prediction for all $m_{\ell\nu jj}$ values is presented below. The nominal MC@NLO model for $t\bar{t}$ production differs from the POWHEG model by at most 3%. A 1–2% variation is measured when the top quark mass is varied by $\pm 2.5$ GeV using MC@NLO MC samples. The difference between the nominal HERWIG parton shower model and the PYTHIA model in POWHEG generated events is at most 2%. Finally, the uncertainty due to the initial-state radiation (ISR) and final-state radiation (FSR) model in PYTHIA is estimated to be at most 3% for all $m_{\ell\nu jj}$ values.

For the remaining, smaller backgrounds modeled with MC simulation, only theoretical uncertainties due to limited knowledge of their production cross-sections are considered. The production rate of $WW$ and $ZZ$ dibosons is known to 5% accuracy, while that for $WZ$ production is known to within 7% \cite{43}. The uncertainty on the $Z$ + jets production rate is estimated to be 5%, primarily due to limited knowledge of the $u$- and $d$-quark PDFs \cite{19}. The production of $s$-channel single top quarks ($tb$) is known to 6% \cite{40} while $t$-channel ($tqb$) and $tW$ production are known to $\pm 4\%$ and 9% \cite{41}, respectively.

For the signals, the PDF uncertainty is estimated by comparing signal events generated with MRST2007LO* and CTEQ6L PDFs and a maximum difference of 5% is measured in the acceptance. The ISR and FSR uncertainty is determined to be 5% using the same procedure as that for $t\bar{t}$ events.

The largest experimental uncertainties come from the determination of the jet energy scale (JES) \cite{59} and resolution (JER) \cite{64}. The JES uncertainty includes effects due to uncertainties in jet flavor composition, overlapping jets, and pile-up effects. The overall JES uncertainty on each background process as well as the signal is determined by varying all jet energies within their uncertainties. The impact of this uncertainty varies with $m_{\ell\nu jj}$, and the largest deviation from the nominal prediction is found to be between 1% and 3% for all signal and background samples.

Additional uncertainties arise from the differences between data and MC simulation in the reconstruction efficiencies and energy or momentum resolution for electrons, muons, and $E_T^{miss}$. The electron energy scale and resolution uncertainties are derived by comparing $Z \rightarrow e^+e^-$ events in data and MC samples. The combined uncertainty is 2–3% depending on $m_{\ell\nu jj}$. The corresponding uncertainty for muons is at most 2% for any $m_{\ell\nu jj}$ value. The primary contribution to the $E_T^{miss}$ scale uncertainty is pile-up, but the impact on the $m_{\ell\nu jj}$ distribution above 500 GeV is less than 1% for all backgrounds. The combined uncertainty on the signal acceptance ranges from 7% at low $m_{\ell\nu jj}$ to 20% at high $m_{\ell\nu jj}$.

The distributions from the “fake” lepton and $W$+jets backgrounds are normalized to the number of events in data control regions, and are therefore not affected by systematic uncertainties in the relative reconstruction efficiency in data and MC events, nor uncertainties in their respective production cross-sections. The “fake” lepton background normalization uncertainty is estimated by...
TABLE III: Estimated background yields, number of data events, and predicted signal yield after applying the signal selection criteria. Quoted uncertainties are statistical plus systematic as described in text.

<table>
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<th>Process</th>
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<th>µνjj</th>
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<td>590 ± 60</td>
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<td>Fake Lepton</td>
<td>20 ± 16</td>
<td>15 ± 15</td>
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<tr>
<td>RS1 G* (mG* = 1 TeV)</td>
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<td>Bulk G* (mG* = 1 TeV)</td>
<td>4 ± 0.4</td>
<td>3.5 ± 0.3</td>
</tr>
<tr>
<td>EGM W' (mW' = 1 TeV)</td>
<td>29 ± 2</td>
<td>24 ± 2</td>
</tr>
</tbody>
</table>

TABLE IV: Expected and observed 95% CL lower mass limits (GeV) for the RS1 G*, bulk RS G*, and the EGM W' boson using evjj events, µνjj events and the combined channels.

<table>
<thead>
<tr>
<th>Process</th>
<th>evjj</th>
<th>µνjj</th>
<th>ℓνjj</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Limits [GeV]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS1 G*</td>
<td>930</td>
<td>900</td>
<td>950</td>
</tr>
<tr>
<td>Bulk RS G*</td>
<td>740</td>
<td>710</td>
<td>750</td>
</tr>
<tr>
<td>EGM W'</td>
<td>950</td>
<td>930</td>
<td>970</td>
</tr>
<tr>
<td>Observed Limits [GeV]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS1 G*</td>
<td>910</td>
<td>920</td>
<td>940</td>
</tr>
<tr>
<td>Bulk RS G*</td>
<td>760</td>
<td>650</td>
<td>710</td>
</tr>
<tr>
<td>EGM W'</td>
<td>930</td>
<td>930</td>
<td>950</td>
</tr>
</tbody>
</table>

This method uses a ratio of the p-values of the signal-plus-background and background-only hypotheses called CLs. For a 95% CL exclusion, the signal production cross-section (σ95%) is adjusted until CLs = 0.05, and the resonance mass limit (m95%) is defined by the mass for which σ(m95%) = σ95%. The excluded production cross-sections times the branching ratios to the WW or WZ final state are shown in Fig. 6 with the evjj and µνjj channels combined, for the three signal hypotheses. The expected and observed limits on the resonances are shown in Table IV for the evjj and µνjj channels separately, as well as their combination.

Limits are also set on the EGM W' boson coupling strength scaling factor cEGM within the EGM framework. The EGM W' boson limits shown in Fig. 6 correspond to cEGM = 1. For cEGM > 10, the resonance width exceeds the experimental resolution, thus only values less than 10 are considered. Limits on cEGM are derived as a function of mW' as shown in Fig. 7.

VIII. RESULTS AND INTERPRETATION

The numbers of expected and observed events after the final signal selection are reported in Table III. A total of 1453 evjj and 1328 µνjj events are observed with background predictions of 1425 ± 100 and 1195 ± 85 events, respectively. The mevjj distributions for data, predicted background samples and an EGM W' boson signal with mass mW' = 1 TeV are shown in Fig. 5.

These distributions are used to construct a log-likelihood ratio (LLR) test statistic to compute the statistical significance of any excess over expectation using a modified frequentist approach. Pseudo-experiments that treat all systematic uncertainties as Gaussian-sampled nuisance parameters are used to generate the distribution of possible LLR values for the background-only (b) and signal-plus-background (s+b) hypotheses. Confidence levels (CL) for each hypothesis are defined as the fraction of experiments with LLR evaluated on the data.

The statistical significance of an observed signal is quantified by giving, for each mass point, the p-value (p = 1 − CLb) of the background-only hypothesis. The greatest deviations from the background prediction occur at mevjj = 1300 GeV and 1500 GeV with p = 0.12 and 0.11, respectively.

Lacking evidence for new phenomena, limits on the signal rate are determined using the CLs method.

IX. CONCLUSION

We report the results of a search for resonant WW and WZ production in the ℓνjj decay channels using an integrated luminosity of 4.7 fb−1 of pp-collision data at √s = 7 TeV collected in 2011 by the ATLAS detector at the Large Hadron Collider. A set of event selections for the RS1 G*, the bulk RS G*, and the EGM W' boson signals are derived using simulated events. No evidence for resonant diboson production is observed and 95% CL upper bounds on the two graviton and EGM W' boson production cross-sections are determined. Resonance masses below 940 GeV, 710 GeV, and 950 GeV are excluded at 95% CL for the spin-2 RS1 graviton, the spin-2 bulk RS graviton and the spin-1 EGM W' boson, respectively.
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[16] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, Φ) are used in the transverse plane, Φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = −ln tan(θ/2). The transverse energy ET is defined as E sin θ, where E is the energy associated to the calorimeter cell or energy cluster. Similarly, pT is the momentum component transverse to the beam line.


[63] ATLAS Collaboration,.


FIG. 5: (color online) Observed and predicted $m_{\ell\nu jj}$ distributions shown for all (a) $e\nu jj$ and (b) $\mu\nu jj$ events satisfying the signal selection requirements. Predictions for an EGM $W'$ boson are shown for a resonance mass of 1 TeV. The right-most bin contains overflow events.

FIG. 6: (color online) Observed and expected 95% CL upper limits on $\sigma(pp \to G^*) \times BR(G^* \to WW)$ for (a) an RS1 $G^*$ and (b) a bulk RS $G^*$, and on $\sigma(pp \to W') \times BR(W' \to WZ)$ for (c) an EGM $W'$ boson.
FIG. 7: (color online) The 95% CL observed and expected excluded regions of the EGM coupling strength scaling factor $c_{\text{EGM}}$ as a function of $m_{W'}$. The green and yellow band correspond to the ±1 and ±2σ intervals, respectively.
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