Search for resonant diboson production in the WW/WZ → ℓνjj decay channels with the ATLAS detector at √s = 7 TeV


DOI: 10.1103/PhysRevD.87.112006

Publication date: 2013

Document Version: Final published version

Published in: Physical Review D. Particles, Fields, Gravitation, and Cosmology

Citation for published version (APA):
Search for resonant diboson production in the $WW/WZ\to \ell\nu jj$ decay channels with the ATLAS detector at $\sqrt{s} = 7$ TeV

G. Aad et al.*
(ATLAS Collaboration)
(Received 1 May 2013; published 17 June 2013)

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 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.

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 [4–7]. 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 $W$ or $WZ$ diboson intermediate state with subsequent decays to a $\ell\nu jj$ 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 $\ell\ell\ell\ell$ [8] or $\ell\ell\ell\nu$ [9] 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 $\ell\ell\nu\ell$ 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 [10].

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 [11] which allows all SM particles to propagate into the extra dimension. The $WZ$ resonance is modeled by a sequential standard model $W'$ boson with the $W'WZ$ coupling strength set by the extended gauge model (EGM) [12]. In the EGM model, the $W'WZ$ coupling is equal to the SM $WWZ$ coupling strength scaled by a factor $c_{\text{EGM}} \times (m_W/m_{W'})^2$, 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.

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 [8]. 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 [13]. Similar searches, mentioned above, for a $ZZ$ resonance by the ATLAS Collaboration exclude an RS1 graviton with mass below 845 GeV [10]. 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 [14]. 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 [9] and 1143 GeV [15], respectively.

II. THE ATLAS DETECTOR

ATLAS [16] 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 detector 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 $|\eta| < 2.5$ [17] 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 Sec. 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 [18] with the modified leading-order (LO*) parton distribution function (PDF) set MRST2007LO* [19]. RS1 $G^*$ samples are generated for resonance masses between 500 and 1500 GeV in 250 GeV steps. In these samples the warping parameter, $\tilde{k} = k/M_{p_1}$, is set to 0.1, where $M_{p_1} = M_{p_1}/\sqrt{8\pi}$ is the reduced Plank mass. EGM $W'$ samples are generated with resonance masses from 500 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 ZWPROD [20]. The EGM coupling strength scaling factor $c_{\text{EGM}}$ 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 [21], 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 [22] 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 $\tilde{k}$ of 1.0 and resonance masses from 500 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 $WW/ZZ$ for each sample are given in Table I.

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>RS1 $G^*$</th>
<th>Bulk RS $G^*$</th>
<th>EGM $W'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>13.0</td>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td>1000</td>
<td>0.23</td>
<td>0.023</td>
<td>0.10</td>
</tr>
<tr>
<td>1500</td>
<td>0.017</td>
<td>0.0011</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Templates with 50 GeV spacing in the mass of the $\ell vjj$ system, $m_{\ell vjj}$, 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 $m_{\ell vjj}$ distribution with a crystal ball function [23]. 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 [24] using the CTEQ6L LO PDF set. These events are processed with HERWIG [25] for parton showering and hadronization, and JIMMY [26] to simulate the underlying event. The samples are initially normalized to the NNLO production cross section computed with FELZ [27,28]. The prediction of the $W$ boson transverse momentum, $p_T$, by ALPGEN is reweighted to agree with the shape predicted by SHERPA [29], which is observed to agree more closely with data at high $p_T$ [30]. Single top quark ($t\bar{b}$, $tq\bar{b}$, $tW$) and top quark pair ($t\bar{t}$) production are simulated with the next-to-leading-order (NLO) generator MC@NLO [31–33] interfaced to HERWIG and JIMMY and using the CT10 [34] NLO PDF set. A sample of $t\bar{t}$ events generated with POWHEG [35–37] interfaced to HERWIG and JIMMY is used to cross-check the MC@NLO $t\bar{t}$ production model, and a POWHEG $t\bar{t}$ sample interfaced to PYTHIA is generated to study the dependence on the parton shower and hadronization model. The ACERMC event generator [38] 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

112006-2
172.5 GeV, but two MC@NLO $t\bar{t}$ samples are generated with $m_t = 170$ 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 [39,40]. Single top quark production cross sections are taken from an NNLO calculation for the $tb$ process [41], and approximate NNLO calculations for the $tq\bar{b}$ and $tW$ processes [42]. SM diboson production ($WW$, $WZ$, $ZZ$) is modeled using HERWIG and normalized to the NLO production cross sections computed by MCFM [43,44] with the MRST2007LO* PDF set. In all samples, PHOTOS [45] is employed to simulate final-state photon radiation and TAUOLA [46] to take into account polarization in $\tau$ lepton decays.

All MC samples include the effect of multiple $pp$ interactions (pileup) 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 [47] of the ATLAS detector [48]. 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 electronlike object [49] with transverse energy ($E_T$) greater than 20 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$^{-1}$ [50,51] after applying data-quality requirements [52]. 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 [53]. 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 pileup 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 [54] measured in data.

Muons are reconstructed from the combination of tracks formed from hits in the MS and the ID [55,56]. 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 multijet 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 pileup 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 [57].

Jets are reconstructed using the anti-$k_t$ sequential recombination clustering algorithm [58,59], with radius set to 0.4. The inputs to the reconstruction algorithm are topological energy clusters [60] calibrated at the EM energy scale, appropriate for the energy deposited by electrons or photons [60]. 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 [61,62] 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 [63] 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 reconstructed high-$p_T$ object are calibrated separately using the local hadronic calibration scheme [64].

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 \(\text{evjj}\) and muon events are labeled \(\mu\nu j j\). To reduce the QCD multijet 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 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 lepton, 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, \(n\bar{n}\), single top quark, and diboson production, are modeled with MC events and are normalized to the product of the production cross section for that background and the total integrated luminosity of the data set. The normalization of the W + jets and \(n\bar{n}\) backgrounds is further tested using data as described in Sec. VI.

Backgrounds in the second category are modeled with independent samples of collision data based on the following prescriptions. In the evjj channel, the sample is selected by inverting the calorimeter isolation requirement for electron candidates that satisfy all other selection criteria. This selects events that are likely to originate from multijet production but have kinematic properties that are very similar to those multijet 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. Kinematic 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 evjj and \(\mu\nu jj\) channels using the lepton transverse mass distribution, \(m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos(\Delta \phi))}\), 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 category, remains fixed in the fit.

The distributions of the lepton \(p_T\), \(E_T^{\text{miss}}\) and the leading 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 a combination 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.

![Graphs](image.png)

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 rightmost bin contains overflow events.

<p>|</p>
<table>
<thead>
<tr>
<th>Process</th>
<th>evjj channel</th>
<th>(10^3) events</th>
<th>(10^3) events</th>
</tr>
</thead>
<tbody>
<tr>
<td>W + jets</td>
<td>38.0 ± 4.1</td>
<td>46.0 ± 4.8</td>
<td></td>
</tr>
<tr>
<td>Z + jets</td>
<td>1.3 ± 0.1</td>
<td>1.8 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td>15.0 ± 1.4</td>
<td>16.0 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>Diboson</td>
<td>0.5 ± 0.1</td>
<td>0.5 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Fake lepton</td>
<td>0.9 ± 0.2</td>
<td>0.5 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>56.0 ± 4.3</td>
<td>65.0 ± 5.1</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>55.2</td>
<td>64.2</td>
<td></td>
</tr>
</tbody>
</table>
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 neutrino 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 \( E_T^{\text{miss}} \) vector in the transverse plane. The neutrino \( p_z \) is obtained by imposing the W boson mass constraint in the momentum 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 dijet and lepton–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' signal after the requirements on the reconstructed dijet and lepton–miss \( p_T \) values but without the dijet mass window requirement.

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 parametrized as a function of \( m_{\ell\nu jj} \). 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 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 events are required to have \( m_{jj} < 65 \) GeV or \( m_{jj} > 115 \) GeV to avoid overlap with the signal region. Figure 4 shows \( m_{\ell\nu jj} \) for all events in the \( t\bar{t} \) control region. In this control region, 587 \( \pm \) 87 \( t\bar{t} \) events and 42 \( \pm \) 6 events from other backgrounds are expected and 602 data events are observed. Given the agreement observed in the \( t\bar{t} \) control region, no normalization correction is applied to the \( t\bar{t} \) background prediction in the signal region.
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% [50,51].

Several sources of theoretical uncertainty on the $t\bar{t}$ background rate are considered. The largest of these is the $+7\% \rightarrow 10\%$ [39,40] uncertainty on the production cross section. Additionally, the magnitudes of the following systematic uncertainties affecting the $t\bar{t}$ background distribution vary with $m_{t\bar{t}}$jj. The largest deviation from the $t\bar{t}$ prediction for all $m_{t\bar{t}}$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% uncertainty 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 POWHEG generated events is at most 2%. The uncertainty due to the limited knowledge of their production cross sections are considered. The uncertainty on the $Z + \text{jets}$ production rate is estimated to be 5%, primarily due to limited knowledge of the $u$- and $d$-quark PDFs [20]. The production of $s$-channel single top quarks ($tb$) is known to 5% accuracy, while that for $WZ$ production is known to within 7% [44]. The uncertainty on the $Z + \text{jets}$ production rate is estimated to be 5%, primarily due to limited knowledge of the $u$- and $d$-quark PDFs [20]. The production of $s$-channel single top quarks ($tb$) is known to 5% accuracy, while that for $WZ$ production is known to within 7% [44]. The uncertainty on the $Z + \text{jets}$ production rate is estimated to be 5%, primarily due to limited knowledge of the $u$- and $d$-quark PDFs [20]. The production of $s$-channel single top quarks ($tb$) is known to 5% accuracy, while that for $WZ$ production is known to within 7% [44].

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) [60] and resolution (JER) [65]. The JES uncertainty includes effects due to uncertainties in jet flavor composition, overlapping jets, and pileup 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 $m_{t\bar{t}}$jj, and the largest deviation from the nominal prediction is presented. For the background samples, this ranges from 8% for single top quark events to 13% for diboson events. For the signal events samples, the largest deviation from the nominal prediction for all $m_{t\bar{t}}$jj values is 4%. An equivalent procedure is applied to evaluate the JER uncertainty, 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 $m_{t\bar{t}}$jj. The corresponding uncertainty for muons is at most 2% for any $m_{t\bar{t}}$jj value. The primary contribution to the $E_T^{miss}$ scale uncertainty is pileup, but the impact on the $m_{t\bar{t}}$jj distribution above 500 GeV is less than 1% for all backgrounds. The combined uncertainty on the signal acceptance ranges from 7% at low $m_{t\bar{t}}$jj to 20% at high $m_{t\bar{t}}$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 using the distributions of $E_T^{miss}$ and the scalar sum of the lepton $p_T$ and $E_T^{miss}$ to determine the fake lepton normalization, and quoting the maximum deviation from the $m_{t\bar{t}}$jj-fitted value. This results in an 80 (100)% uncertainty on events with electrons (muons). The W + jets normalization uncertainty is defined as the difference between the low-$m_{jj}$ and high-$m_{jj}$ control region scale factors, resulting in an uncertainty of 9%.

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 $\mu\nu jj$ events are observed with

<table>
<thead>
<tr>
<th>Process</th>
<th>$evjj$</th>
<th>$\mu\nu jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W + \text{jets}$</td>
<td>700 ± 65</td>
<td>590 ± 60</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>15 ± 2</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>Top</td>
<td>615 ± 70</td>
<td>515 ± 65</td>
</tr>
<tr>
<td>Diboson</td>
<td>75 ± 9</td>
<td>60 ± 8</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>20 ± 16</td>
<td>15 ± 15</td>
</tr>
<tr>
<td>Total backgrounds</td>
<td>1425 ± 100</td>
<td>1195 ± 85</td>
</tr>
<tr>
<td>Data</td>
<td>1453</td>
<td>1328</td>
</tr>
<tr>
<td>RS1 $G^*(m_{G} = 1 \text{TeV})$</td>
<td>22 ± 2</td>
<td>18 ± 2</td>
</tr>
<tr>
<td>Bulk $G^*(m_{G} = 1 \text{TeV})$</td>
<td>4 ± 0.4</td>
<td>3.5 ± 0.3</td>
</tr>
<tr>
<td>EGM $W^*(m_{W} = 1 \text{TeV})$</td>
<td>29 ± 2</td>
<td>24 ± 2</td>
</tr>
</tbody>
</table>
background predictions of 1425 ± 100 and 1195 ± 85 events, respectively. The \( m'_{\nu jj} \) distributions for data, predicted background samples, and an EGM \( W' \) boson signal with mass \( m_{W'} = 1 \) 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. Pseudoexperiments that treat all backgrounds...
TABLE IV. Expected and observed 95% C.L. lower mass limits (GeV) for the RS1 \textit{G}′, bulk RS \textit{G}′, and the EGM \textit{W}′ boson using \textit{evjj} events, \textit{\mu vjj} events and the combined channels.

<table>
<thead>
<tr>
<th>Process</th>
<th>evjj</th>
<th>(\mu vjj)</th>
<th>(\ell vjj)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Limits [GeV]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS1 \textit{G}′</td>
<td>930</td>
<td>900</td>
<td>950</td>
</tr>
<tr>
<td>Bulk RS \textit{G}′</td>
<td>740</td>
<td>710</td>
<td>750</td>
</tr>
<tr>
<td>EGM \textit{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 \textit{G}′</td>
<td>910</td>
<td>920</td>
<td>940</td>
</tr>
<tr>
<td>Bulk RS \textit{G}′</td>
<td>760</td>
<td>650</td>
<td>710</td>
</tr>
<tr>
<td>EGM \textit{W}′</td>
<td>930</td>
<td>930</td>
<td>950</td>
</tr>
</tbody>
</table>

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 (C.L.) for each hypothesis are defined as the fraction of experiments with LLR greater than or equal to the LLR evaluated on the data.

The statistical significance of an observed signal is quantified by giving, for each mass point, the value \(p = 1 - \text{CL}_{b}\) of the background-only hypothesis. The greatest deviations from the background prediction occur at \(m_{\ell vjj} = 1300\) 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 \[66,67\]. This method uses a ratio of the \(p\) values of the signal-plus-background and background-only hypotheses called CLs. For a 95% C.L. exclusion, the signal production cross section \(\sigma^{95\%}\) is adjusted until \(\text{CL}_{s} = 0.05\), and the resonance mass limit \(m^{95\%}\) is defined by the mass for which \(\sigma(m^{95\%}) = \sigma^{95\%}\). The excluded production cross sections times the branching ratios to the \textit{WW} or \textit{WZ} final state are shown in Fig. 6, with the \textit{evjj} and \textit{\mu vjj} channels combined, for the three signal hypotheses. The expected and observed limits on the resonances are shown in Table IV for the \textit{evjj} and \textit{\mu vjj} channels separately, as well as their combination.

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

![FIG. 7 (color online). The 95% C.L. observed and expected excluded regions of the EGM coupling strength scaling factor \(c_{\text{EGM}}\) as a function of \(m_{\text{W}'}\). The green and yellow band correspond to the \(\pm 1\) and \(\pm 2\sigma\) intervals, respectively.](image)

**IX. CONCLUSION**

We report the results of a search for resonant \textit{WW} and \textit{WZ} production in the \(\ell vjj\) decay channels using an integrated luminosity of 4.7 fb\(^{-1}\) of \(pp\)-collision data at \(\sqrt{s} = 7\) TeV collected in 2011 by the ATLAS detector at the Large Hadron Collider. A set of event selections for the RS1 \textit{G}′, the bulk RS \textit{G}′, and the EGM \textit{W}′ boson signals are derived using simulated events. No evidence for resonant diboson production is observed and 95% C.L. upper bounds on the two graviton and EGM \textit{W}′ boson production cross sections are determined. Resonance masses below 940, 710, and 950 GeV are excluded at 95% C.L. for the spin-2 RS1 graviton, the spin-2 bulk RS graviton and the spin-1 EGM \textit{W}′ boson, respectively.

**ACKNOWLEDGMENTS**

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva,
search for resonant diboson production in \ldots

Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[17] 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 \( \eta = -\ln \tan (θ/2) \). The transverse energy \( E_T \) is defined as \( E \sin θ \), where \( E \) is the energy associated with the calorimeter cell or energy cluster. Similarly, \( p_T \) is the momentum component transverse to the beam line.
SEARCH FOR RESONANT DIBOSON PRODUCTION IN ... PHYSICAL REVIEW D 87, 112006 (2013)

P. Grenier,143 J. Griffiths,8 N. Grigalashvili,64 A. A. Grillo,137 S. Grinstein,12 Ph. Gris,34 Y. V. Grishkevich,97 J.-F. Grivaz,115 E. Gross,172 J. Grosse-Knetter,54 J. Groth-Jensen,172 K. Grybel,141 D. Guest,176 C. Guichene,...
SEARCH FOR RESONANT DIBOSON PRODUCTION IN ... PHYSICAL REVIEW D 87, 112006 (2013)
SEARCH FOR RESONANT DIBOSON PRODUCTION IN...

PHYSICAL REVIEW D 87, 112006 (2013)

128State Research Center Institute for High Energy Physics, Protvino, Russia
129Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130Physics Department, University of Regina, Regina, Saskatchewan, Canada
131Ritsumeikan University, Kusatsu, Shiga, Japan
132aINFN Sezione di Roma I, Italy
132bDipartimento di Fisica, Università La Sapienza, Roma, Italy
133aINFN Sezione di Roma Tor Vergata, Italy
133bDipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134aINFN Sezione di Roma Tre, Italy
134bDipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
135aFaculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco
135bCentre National de l’Energie des Sciences Techniques Nucléaires, Rabat, Morocco
135cFaculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
135dFaculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
135eFaculté des sciences, Université Mohammed V-Adad, Rabat, Morocco
136DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
137Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
138Department of Physics, University of Washington, Seattle, Washington, USA
139Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140Department of Physics, Shinshu University, Nagano, Japan
141Fachbereich Physik, Universität Siegen, Siegen, Germany
142Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
143aSLM National Accelerator Laboratory, Stanford California
143bFaculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
143cDepartment of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
144aDepartment of Physics, University of Johannesburg, Johannesburg, South Africa
144bSchool of Physics, University of the Witwatersrand, Johannesburg, South Africa
144cDepartment of Physics, Stockholm University, Sweden
144dThe Oskar Klein Centre, Stockholm, Sweden
145Physics Department, Royal Institute of Technology, Stockholm, Sweden
146aDepartments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
146bDepartment of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
146cSchool of Physics, University of Sydney, Sydney, Australia
146dInstitute of Physics, Academia Sinica, Taipei, Taiwan
146eDepartment of Physics, Technion: Israel Institute of Technology, Haifa, Israel
146fRaymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
146gDepartment of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
146hInternational Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
146iGraduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
146jDepartment of Physics, Tokyo Institute of Technology, Tokyo, Japan
146kDepartment of Physics, University of Toronto, Toronto, Ontario, Canada
146lTRIUMF, Vancouver, British Columbia, Canada
146mDepartment of Physics and Astronomy, York University, Toronto, Ontario, Canada
146nFaculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
146oDepartment of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
146pCentro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
146qDepartment of Physics and Astronomy, University of California Irvine, Irvine, California, USA
146rINFN Gruppo Collegato di Udine, Italy
146sICTP, Trieste, Italy
146tDipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
146uDepartment of Physics, University of Illinois, Urbana, Illinois, USA
146vDepartment of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
146wInstituto de Fisica Corpuscular (IFIC) and Departamento de Fisica Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMM), University of Valencia and CSIC, Valencia, Spain
146xDepartment of Physics, University of British Columbia, Vancouver, British Columbia, Canada
146yDepartment of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
170 Department of Physics, University of Warwick, Coventry, United Kingdom

171 Waseda University, Tokyo, Japan

172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

173 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

175 Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany

176 Department of Physics, Yale University, New Haven, Connecticut, USA

177 Yerevan Physics Institute, Yerevan, Armenia

178 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Deceased.
b Also at Department of Physics, King’s College London, London, United Kingdom.
c Also at Laboratorio de Instrumentación e Física Experimental de Partículas-LIP, Lisboa, Portugal.
d Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
e Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
f Also at TRIUMF, Vancouver, British Columbia, Canada.
g Also at Department of Physics, California State University, Fresno, CA, USA.
h Also at Novosibirsk State University, Novosibirsk, Russia.
i Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
j Also at Department of Physics, UASLP, San Luis Potosi, Mexico.
k Also at Università di Napoli Parthenope, Napoli, Italy.
l Also at Institute of Particle Physics (IPP), Canada.
m Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
n Also at Louisiana Tech University, Ruston, LA, USA.
o Also at Dep Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
p Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
q Also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA.
r Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
s Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
t Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
u Also at Manhattan College, New York, NY, USA.
v Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
w Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
x Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
y Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
z Also at School of Physics, Shandong University, Shandong, China.
aa Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
ab Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France.
c Also at Section de Physique, Université de Genève, Geneva, Switzerland.
d Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
e Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
f Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
g Also at California Institute of Technology, Pasadena, CA, USA.
h Also at International School for Advanced Studies (SISSA), Trieste, Italy.
i Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
j Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
k Also at Nevis Laboratory, Columbia University, Irvington, NY, USA.
l Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
m Also at Department of Physics, Oxford University, Oxford, United Kingdom.
n Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
o Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
p Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.