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Search for new particles decaying to ZZ using final states with leptons and jets with the ATLAS detector in $\sqrt{s} = 7$ TeV proton–proton collisions ☆

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ABSTRACT

A search is presented for a narrow resonance decaying to a pair of Z bosons using data corresponding to 1.02 fb^{-1} of integrated luminosity collected by the ATLAS experiment from pp collisions at $\sqrt{s} = 7$ TeV. Events containing either four charged leptons ($\ell\ell\ell\ell$) or two charged leptons and two jets ($\ell\ell jj$) are analyzed and found to be consistent with the Standard Model background expectation. Lower limits on a resonance mass are set using the Randall–Sundrum (RS1) graviton model as a benchmark. Using both $\ell\ell\ell\ell$ and $\ell\ell jj$ events, an RS1 graviton with $k/\bar{m}_{\text{pl}} = 0.1$ and mass between 325 and 845 GeV is excluded at 95% confidence level. In addition, the $\ell\ell\ell\ell$ events are used to set a model-independent fiducial cross section limit of $\sigma_{\text{fid}}(pp \to X \to ZZ) < 0.92$ pb at 95% confidence level for any new sources of ZZ production with m_{ZZ} greater than 300 GeV.

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1. Introduction

The Standard Model (SM) of particle physics allows for resonant production of Z boson pairs (ZZ) solely through the production and decay of the Higgs boson. However, some extensions to the SM predict additional mechanisms for resonant ZZ production. For example, models of warped extra dimensions [1,2] predict two such resonances: excited states of the spin-2 graviton (G^*) and the spin-0 radion (R). Searches for such gravitons by the ATLAS Collaboration have excluded at 95% confidence level masses smaller than 1.63 TeV in dilepton final states [3] and smaller than 1.9 TeV in diphoton final states [4]; CMS has excluded masses below 1.84 TeV in diphoton final states [5]. Recent versions of these models [6] in which all SM fields propagate in these new dimensions predict enhanced coupling of the graviton to the ZZ final state and suppressed decay rates to light fermion and diphoton states. Observation of graviton production and decay to a pair of Z bosons would be striking evidence for physics beyond the Standard Model.

This Letter describes the search for a new particle decaying to the ZZ final state using the RS1 excited graviton (G^*) as a benchmark model [1]. This search uses 1.02 fb^{-1} of integrated luminosity collected between February and June 2011 by the ATLAS detector in $\sqrt{s} = 7$ TeV pp collisions at the Large Hadron Collider (LHC). Two final states of the ZZ decay are studied. The first, referred to as $\ell\ell jj$, where $\ell = e$ or μ, includes events in which one Z boson decays into electrons or muons, and the other Z boson decays into two jets. This channel is also sensitive to dijet decays of the W boson in association with a Z boson decaying to a lepton pair. For the second, referred to as $\ell\ell\ell\ell$, both Z bosons decay into electrons or muons. The final state with two pairs of oppositely charged same-flavor leptons, each pair with invariant mass near the Z boson mass, is used to search for anomalous ZZ production.

Below a graviton mass (m_{G^*}) of 500 GeV, the $\ell\ell\ell\ell$ channel dominates the combined $\ell\ell\ell\ell + \ell\ell jj$ sensitivity due to the extremely low background rate. Above 500 GeV, the background in $\ell\ell jj$ yield decreases rapidly with m_{G^*}, and this final state gains importance due to the larger branching fraction. Since no evidence for $G^* \to ZZ$ production is found in this analysis, 95% confidence level (CL) limits are presented using the RS1 graviton as a benchmark. Additionally, the simplicity of the $\ell\ell\ell\ell$ final state allows for the calculation of fiducial cross section limits which provide a model-independent bound on anomalous ZZ production.

The RS1 graviton has been used as a benchmark in earlier searches for a resonant structure in ZZ final states. The CDF Collaboration used $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with 2.9 fb^{-1} of integrated luminosity to exclude such a state with a mass less than 491 GeV [7] at 95% CL assuming $k/\bar{m}_{\text{pl}} = 0.1$, where k is the curvature scale of the warped extra dimension and $\bar{m}_{\text{pl}} \equiv m_{\text{pl}}/\sqrt{8\pi}$ is the reduced Planck mass. A more recent analysis by CDF using 6 fb^{-1} reports an excess of $\ell\ell\ell\ell$ events at high Z boson-pair invariant mass, clustered around 327 GeV [8], although this is not seen in $\ell\ell jj$ or $\ell\ell\nu\nu$ channels.

2. Detector

The ATLAS detector [9] is a multi-purpose detector with precision tracking, calorimetry and muon spectrometry. The detector

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covers almost the entire 4π solid angle surrounding the collision point at the center of a set of subdetectors. Starting at the collision point and moving outwards, the first subdetector reached is the silicon pixel detector followed by the silicon microstrip detector and the transition radiation tracker. These three systems comprise the inner detector (ID) and reconstruct charged particle tracks out to $|\eta| < 2.5$.[1] Particle momentum is measured by the curvature of the tracks as they are deflected in a peak 2T magnetic field provided by a solenoid surrounding the ID. The next subsystems reached are the electromagnetic (EM) and hadronic calorimeters. The EM calorimeter is a highly granular liquid argon (LAr) sampling calorimeter with lead absorber plates designed for electron and photon energy measurements. An iron scintillator tile calorimeter provides hadronic energy measurements in the barrel region ($|\eta| < 1.7$) while liquid argon with copper absorber plates is used in the endcap and forward regions. Together these detectors allow electromagnetic and hadronic energy measurements out to $|\eta| < 4.9$. Behind the calorimeters is the muon spectrometer (MS), which consists of gas-filled chambers and an air-core toroidal magnetic system. This detector measures both the muon momentum and charge out to $|\eta| < 2.7$.

To trigger readout [10], full event reconstruction and event storage by the data acquisition system, electron candidates must have transverse energy greater than 20 GeV. They must satisfy shower-shape requirements and correspond to an ID track. Muon candidates must have transverse momentum greater than 18 GeV and a consistent trajectory reconstructed in the ID and muon spectrometer. The full trigger chain uses signals from all muon detectors. These triggers reach their efficiency plateau at lepton p_T thresholds of 20 GeV for muons and 25 GeV for electrons.

3. Object reconstruction

Electrons are reconstructed from energy deposits in the EM calorimeter matched to tracks in the inner detector, and are required to satisfy the ‘medium’ identification requirements described in Ref. [11]. Electrons are required to have $E_T > 20(15)$ GeV in the $\ell\ell jj(\ell\ell\ell\ell)$ channel and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. For tracks with at least four hits in the pixel and silicon strip detectors, the angles η and ϕ are defined by the track, otherwise these quantities are computed from the calorimeter cluster position. Finally, all electrons must be isolated from other charged tracks to suppress jets, i.e. the scalar sum of track p_T for tracks with $p_T > 1$ GeV surrounding the electron track in a cone of radius $\Delta R = 0.2$, where ΔR is a distance measure in the η–ϕ plane defined as $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, must be less than 15% (10%) of the transverse energy of the electron in the $ee\ell\ell(eejj)$ channel.

Muons are reconstructed from hits in the muon spectrometer [12]. The track formed from these hits must match a track found in the ID. The ID track must have a hit in the innermost layer of the pixel detector to reduce backgrounds from heavy-flavor hadron decays. The muon track is constructed using information from the ID and MS tracks, and the muon p_T, η, and ϕ are defined from the properties of this combined track. Muons are required to have $p_T > 20(15)$ GeV in the $\ell\ell jj(\ell\ell\ell\ell)$ channel. The lower lepton p_T threshold is used for $\ell\ell\ell\ell$ to maintain acceptance at low Z boson pair mass; in $\ell\ell jj$ the background in this low-p_T region is very large. Finally, the muon must be isolated from nearby track activity such that the p_T sum of all tracks surrounding the muon track in a cone of radius $\Delta R = 0.2$ is less than 10% (15%) of the muon track p_T in the $\ell\ell jj(\ell\ell\ell\ell)$ channel.

For the $\ell\ell jj$ channel, jets are reconstructed from a collection of three-dimensional topological energy clusters using the anti-k_t sequential recombination clustering algorithm [13] implemented in the FastJet [14] package with a radius parameter equal to 0.4. A jet energy scale (JES) correction is applied to account for the energy response and non-uniformity of the EM and hadronic calorimeters [15]. Jets are required to have $p_T > 25$ GeV and $|\eta| < 2.8$. If an electron and jet overlap within $\Delta R < 0.3$, the jet candidate is removed from the event. The missing transverse momentum, E_T^{miss}, is the modulus of the vector sum of transverse energies of topological calorimeter clusters with $|\eta| < 4.5$, corrected for any high quality muons in the event. The $\ell\ell\ell\ell$ channel does not consider jets or missing transverse momentum. The $\ell\ell jj$ channel considers E_T^{miss} only for background studies.

All events must have at least one reconstructed vertex with at least three associated tracks with $p_T > 500$ MeV. The vertex with the largest sum of track p_T^2 is defined as the primary interaction vertex.

To ensure that they originate from the primary vertex, lepton candidates in the $\ell\ell\ell\ell$ and $\mu\mu jj$ channels are required to have a longitudinal impact parameter (distance of closest approach) with respect to the primary vertex of less than 10 mm and a transverse impact parameter significance (transverse impact parameter divided by its error) of less than 10. These requirements reduce contamination from both cosmic rays and leptons produced from hadron decays. In the $eejj$ channel this was found to give no improvement in sensitivity.

Scale factors are applied to the simulation to correct for differences in lepton reconstruction and identification efficiencies between simulation and data. These scale factors have values that differ from unity by 0.1%–2% for muons [16] and 1%–13% for electrons depending on the p_T (for muons) or E_T (for electrons); the larger corrections seen for electrons affect only the low-E_T region, and are due to mis-modeling of lateral shower shapes in simulation [17]. Systematic uncertainties on these scale factors are derived from efficiency measurements in the data. A small smearing is added to the muon p_T in the simulation [18] so that the $Z \to \mu\mu$ invariant mass distribution in data is correctly reproduced by the simulation; similarly, small corrections are applied to the calorimeter energy scale and resolution for electrons.

This analysis uses data collected by single and dilepton triggers during the 2011 LHC run at $\sqrt{s} = 7$ TeV with 50 ns bunch spacing. The efficiency of these triggers to select signal-like events is $99 \pm 1\%$. Additionally, only events recorded while all relevant subdetectors were operating properly are used. The total integrated luminosity for all results in this Letter is 1.02 ± 0.04 fb^{-1} [19,20].

4. Simulation

The signal and all backgrounds other than multi-jet production are modeled using simulated samples created by process-specific Monte Carlo (MC) event generators. Unless otherwise specified the events in these samples are normalized to the product of the production cross section, the final state branching ratio, and the recorded integrated luminosity. The detector response is simulated with GEANT4 [21,22] after which the event is reconstructed. The RS1 G^* signal events are generated primarily via gluon–gluon fusion with PYTHIA 6.421 [23] using MRST LO* [24] parton distribution functions for $m_{G^*} = 325$ and 500–1500 GeV in 250 GeV

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[1] 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 line. 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 line. The pseudorapidity is defined in terms of the polar angle θ ($z = r\cos\theta$) as $\eta = -\ln\tan(\theta/2)$. The transverse energy E_T is defined as $E\sin\theta$, where E is the energy associated to the calorimeter cell or energy cluster. Similarly, p_T is the momentum component transverse to the beam line.

steps. All samples assume the dimensionless coupling parameter $k/\bar{m}_{\rm pl} = 0.1$. The model described by PYTHIA generates events which are uniform in $\cos\theta^*$, where θ^* is the angle between the Z boson direction and the beam axis in the graviton rest frame, and does not have enhanced rates of longitudinal Z boson polarization.

Expected backgrounds from diboson production in the SM (WW, WZ, ZZ) are modeled using HERWIG and scaled to the next-to-leading order (NLO) production cross sections as computed by MCFM 6.0 with MRST2007 LO* [24]. PHOTOS [25] is employed to simulate final state photon radiation and TAUOLA 2.4 [26] decays all tau leptons. Production of the background processes $W \to \ell\nu$ and $Z \to \ell\ell$ in association with jets is modeled using the ALPGEN [27] event generator with CTEQ6L1 [28] interfaced with HERWIG [29] for parton showering and JIMMY [30] to model the underlying event. The SHERPA [31] event generator is used to cross check the W and Z boson + jets events simulated by ALPGEN; the MCFM 6.0 [32] generator is also used to check the Z boson + jets background estimate. Both $W \to \ell\nu$ and $Z \to \ell\ell$ samples are scaled to their respective cross sections at next-to-next-to-leading-order (NNLO) in the strong coupling constant, α_S, as computed with FEWZ 2.0 [33, 34]. The top pair ($t\bar{t}$) and single top-quark (tb, tqb, tW) backgrounds are modeled with the MC@NLO 3.41 [35] generator interfaced with HERWIG and JIMMY. A sample of $t\bar{t}$ events generated with POWHEG [36] is used to cross check the MC@NLO model. Both $t\bar{t}$ and single top-quark samples are generated assuming a top-quark mass of 172.5 GeV. The SM cross section for $t\bar{t}$ production is known to approximate-NNLO accuracy as computed in Refs. [37–39]. Single top-quark production cross sections are calculated to next-to-next-to-leading-logarithm order in α_S for the tb process [40], and approximate NNLO order for the tqb and tW processes [41].

In order to describe properly the effects of multiple proton–proton interactions per bunch crossing, the Monte Carlo samples contain multiple interactions per beam-crossing, weighted to match the data. Additional interactions may produce low-energy deposits in the calorimeter, which leads to a systematic uncertainty in the reconstructed jet energy. Lepton identification and reconstruction efficiency is largely unaffected by multiple interactions, due to the use of track-based isolation. Many of the background models used are data-driven and so naturally account for multiple interactions.

5. $\ell\ell jj$ event selection

Events in the $\ell\ell jj$ channel must have exactly two isolated electrons or exactly two isolated muons, each with $p_{\rm T} > 20$ GeV accompanied by two or more jets, each with $p_{\rm T} > 25$ GeV. The lepton pair mass ($m_{\ell\ell}$) must be consistent with that of a Z boson ($m_{\ell\ell} \in [66, 116]$ GeV); the size of this mass window reflects the non-negligible natural width of the Z boson as well as the lepton momentum resolution. A requirement that the leptons have opposite charge is applied only to dimuon events, where the charge mis-measurement rate is negligible.

Two signal regions are chosen to maximize the sensitivity to a low-mass ($m_{G^*} < 500$ GeV) and high-mass ($m_{G^*} \geqslant 500$ GeV) signal. In the low-mass region, the $p_{\rm T}$ of the lepton pair system is required to be greater than 50 GeV, and similarly the system formed by the two highest $p_{\rm T}$ jets is required to have $p_{\rm T}$ greater than 50 GeV. In the high-mass region, both $p_{\rm T}$ thresholds are raised to 200 GeV. In both regions, a signal will manifest itself as a peak in the $\ell\ell jj$ invariant mass. The signal definition requires that the two jets result from the decay of a Z boson and therefore have an invariant mass near the Z boson pole mass. The dijet mass, m_{jj}, is thus required to be between 65 GeV and 115 GeV for both low- and high-mass signals. This m_{jj} range was chosen to optimize sensitivity.

5.1. Backgrounds

The primary background with this event selection is production of a Z/γ^* boson with associated jets. Secondary backgrounds are $t\bar{t}$ and diboson production (WZ, ZZ).

Sidebands surrounding the dijet mass window (below 65 GeV and above 115 GeV) are used to normalize the Z boson + jets background separately for the low- and high-mass signal regions. The normalization factor, defined as the ratio of data to Z boson + jets ALPGEN MC prediction, is 93% (75%) in the low(high)-mass signal region. These factors agree within 20% with those obtained from Z boson + jets events simulated with SHERPA and scaled to the data in the sidebands.

The uncertainty of the background prediction in the high-mass selection sample is dominated by Z boson + jets background modeling; the main contribution comes from the uncertainty assigned as a relative deviation of the Z boson + jets normalization factor from unity due to limited m_{jj} sideband statistics. This assigned uncertainty, which leads to an uncertainty of 40% on the Z boson + jets background normalization, is combined with an additional uncertainty obtained as the difference between the ALPGEN and SHERPA predictions in the signal region after sideband normalization, leading to a total uncertainty of 43%. The Z boson + jets background uncertainty in the low-mass selection sample, which amounts to 6%, is obtained solely from the scale factor differences between the two m_{jj} sidebands. The Z boson + jets normalization factors are checked by repeating this study with NLO $\ell\ell jj$ invariant mass distributions in simulated Z boson + jets events generated with MCFM6.0 and scaled to the data in the sidebands. The JES uncertainty varies between 12–14% for the background estimate and the signal acceptance [15].

The observed event yield in a $t\bar{t}$-dominated region, low-mass sidebands with the additional requirement of $E_{\rm T}^{\rm miss} > 80$ GeV, is found to agree with the Monte Carlo prediction. The top-quark pair background uncertainty is determined to be 25% from a comparison of event yields between MC@NLO and POWHEG together with an evaluation of the sensitivity of the background prediction to the amount of initial state and final state radiation. The uncertainty associated with the theoretical production cross section is estimated to be 10% [42]. The uncertainty due to lepton energy and $p_{\rm T}$ resolution and reconstruction efficiency contribute less than 3% to the total uncertainty. The trigger selection efficiency and integrated luminosity contribute 1% and 3.7% [19,20] relative uncertainties, respectively.

Production of a W boson with associated jets and single top-quark production are found to give rise to negligible backgrounds. A sample of data events with two low-quality electron candidates (which fail at least one of the requirements above) or two non-isolated muon candidates is used to model the shape of the multijet background. The normalization of this background is determined by a fit to the dilepton mass spectrum using the multijet-like sample as one template and the sum of all other Monte Carlo-based backgrounds as the other template. The multijet background within the dilepton mass range ($m_{\ell\ell} \in [66, 116]$ GeV) is determined to be less than 1% (0.1%) for $eejj$ ($\mu\mu jj$) events.

Table 1 shows the number of events passing the full selection in the data and expected for each background, and for the RS1 graviton with $m_{G*} = 350$ and 750 GeV. No additional scale factors are applied to diboson background events. Fig. 1 shows the predicted and observed $m_{\ell\ell jj}$ distributions for both low- and high-mass signal selections.

Table 1
Expected numbers of $\ell\ell jj$ events in 1.02 fb^{-1} for each background for the low- and high-mass signal selection regions. The predicted signal yields for 350 and 750 GeV graviton signals ($k/\bar{m}_{\text{pl}} = 0.1$) and the observed number of events are also shown. Uncertainties are systematic and statistical.

Process	Low-mass selection	High-mass selection
Z + jets	3530 ± 190	60 ± 27
Top	81 ± 25	0.4 ± 0.3
Diboson	92 ± 14	4 ± 1
W + jets	9 ± 5	1 ± 1
Multijet	14 ± 14	0.2 ± 0.2
Background sum	3720 ± 200	66 ± 27
Graviton signal		
$m_{G^*} = 350$ GeV	680 ± 120	
$m_{G^*} = 750$ GeV		21 ± 4
Data	3515	85

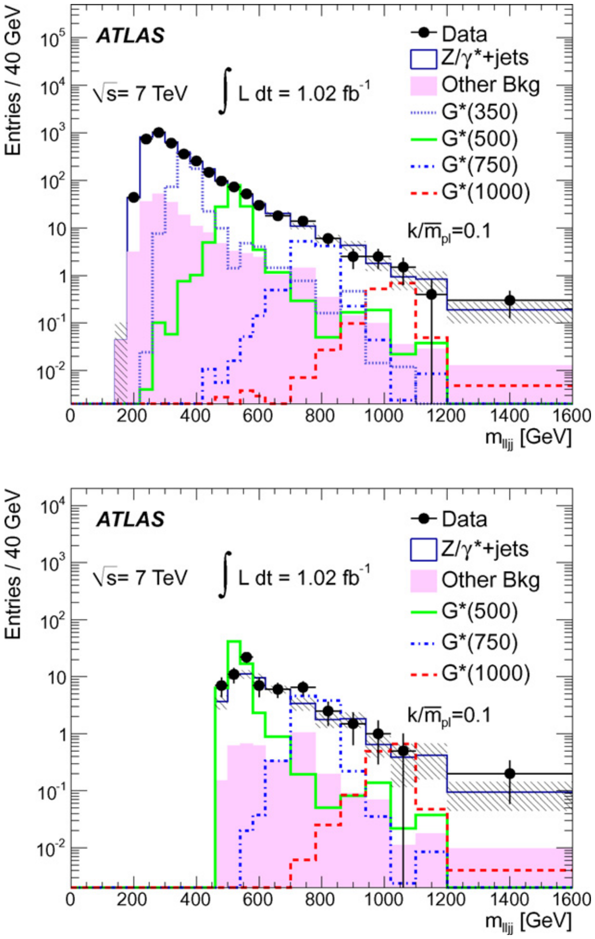

Fig. 1. Distribution of $\ell\ell jj$ invariant mass for events satisfying the low-mass signal selection (upper) and high-mass signal selection (lower). These distributions contain both $eejj$ and $\mu\mu jj$ events. The hatched area shows the uncertainty on the background prediction.

6. $\ell\ell\ell\ell$ event selection

Events in the $\ell\ell\ell\ell$ final state are characterized by at least four high-p_{T}, isolated electrons or muons. Events are required to have passed either a single-muon or single electron trigger which have thresholds of $p_{\text{T}} > 18$ GeV and $p_{\text{T}} > 20$ GeV, respectively. To minimize the systematic uncertainty on the trigger efficiency, at least one of the selected muons (electrons) is required to have $p_{\text{T}} > 20$ ($E_{\text{T}} > 25$) GeV, above which the trigger efficiency dependence on p_{T} (E_{T}) is small. The trigger efficiency for selected events is consistent with 100% with an uncertainty of 0.04%.

Same-flavor, oppositely-charged lepton pairs are combined to form Z boson candidates. When more than one such pairing exists, the set with the smallest value of the sum of the two $|m_{\ell\ell} - m_Z|$ values is chosen. Both Z boson candidates are required to have a dilepton invariant mass $m_{\ell\ell} \in [66, 116]$ GeV; events with two electrons and two muons are categorized as $e^+e^-\mu^+\mu^-$ ($\mu^+\mu^-e^+e^-$) if $m_{e^+e^-}$ ($m_{\mu^+\mu^-}$) is closer to m_Z than $m_{\mu^+\mu^-}$ ($m_{e^+e^-}$). The invariant mass of the *ZZ* diboson system must be greater than 300 GeV. No requirement is made of the p_{T} of the individual Z bosons, nor on the p_{T} of the *ZZ* system.

The dominant systematic uncertainties arise from electron identification and muon reconstruction efficiency which range from 3.1% to 6.6% and 1.0% to 2.0%, respectively, depending on the final state.

6.1. Backgrounds

The primary SM source of events with four charged leptons is $(Z/\gamma^*)(Z/\gamma^*)$ production, which we abbreviate as *ZZ*. Other sources are Z (or W) boson production in association with additional jets or photons ($W/Z + X$), and top-quark pair production. The jets might be misidentified as electrons or contain electrons, photons or muons from in-flight decays of pions, kaons, or heavy-flavored hadrons; photons might be misidentified as electrons. Only a small minority of these background ("misidentified") leptons survive the isolation requirement. This background is estimated directly from the data.

To estimate the background contribution to the selected sample from events in which one lepton originates from such misidentified jets, a sample of data events containing three leptons passing all selection criteria plus one 'lepton-like jet' is identified; such events are denoted $\ell\ell\ell F$. For muons, the lepton-like jets are muon candidates that fail the isolation requirement. For electrons, the lepton-like jets are clusters in the electromagnetic calorimeter matched to ID tracks that fail either the full electron quality requirements or the isolation requirement or both. The events are otherwise required to pass the full event selection, treating the lepton-like jet as if it were a fully identified lepton. This event sample is dominated by Z boson + jets events. The background is estimated by scaling the $\ell\ell\ell F$ control sample by a measured factor f (η and p_{T} dependent and treated as uncorrelated in the two variables) which is the ratio of the probability for a jet to satisfy the full lepton criteria to the probability to satisfy the lepton-like jet criteria. The background in which two selected leptons originate from jets is treated similarly, by identifying a data sample with two leptons and two lepton-like jets; such events are denoted $\ell\ell FF$. To avoid double counting in the background estimate, and to account for the expected *ZZ* contribution in the control region, $N(ZZ)$, the total number of background events $N(\text{BG})$ is calculated as:

$$N(\text{BG}) = N(\ell\ell\ell F) \times f - N(\ell\ell FF) \times f^2 - N(ZZ). \qquad (1)$$

The factor f is measured in a sample of data selected with single-lepton triggers with cuts applied to suppress isolated leptons from W and Z bosons, and corrected for the remaining small contribution of true leptons from W and Z boson decays using simulation. The negative contribution proportional to f^2 is used to correct for double-counting in the term proportional to f. A similar analysis is performed on Monte Carlo simulation of background processes of heavy-flavor and light-flavor multi-jet production; the difference between data and simulation is taken as the systematic uncertainty in each p_{T} (or η) bin. This results in an average systematic uncertainty of ~30% for each $p_{\text{T}}(\eta)$ bin except for the

Table 2

Expected background contributions (*ZZ* and misidentified lepton) and observed events inside the *ZZ* control region in 1.02 fb^{-1}, for events with two opposite-sign same-flavor pairs, each with mass $m_{\ell\ell} \in [66, 116]$ GeV, and the four lepton mass $m_{\ell\ell\ell\ell} < 300$ GeV. The first quoted uncertainty is statistical; the second systematic.

Process	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^- + \mu^+\mu^-e^+e^-$
ZZ	$1.3 \pm 0.1 \pm 0.1$	$2.5 \pm 0.1 \pm 0.1$	$3.6 \pm 0.1 \pm 0.1$
Mis. lep.	$0.01^{+0.02}_{-0.01}\,{}^{+0.02}_{-0.01}$	$0.3^{+0.9}_{-0.3} \pm 0.2$	$0.0^{+1.0}_{-0.0}\,{}^{+0.8}_{-0.0}$
Total bkg.	$1.3 \pm 0.1 \pm 0.1$	$2.7^{+0.9}_{-0.3} \pm 0.3$	$3.6^{+1.0}_{-0.1}\,{}^{+0.8}_{-0.1}$
Data	2	6	1

lowest p_T bin (15–20 GeV), for which there is nearly a 100% systematic uncertainty.

In some cases, the control regions from which the background estimate is extrapolated ($\ell\ell\ell F$ or $\ell\ell FF$) contain zero observed events. In such cases, the 68% CL upper limit on the mean of a Poisson distribution from which zero events are observed is $N < 1.29$. We consider the number of events in these regions to be $N = 0.0^{+1.3}_{-0.0}$, and the estimate of the misidentified lepton background uses the value of the lepton misidentification rate f in the lowest p_T bin (15–20 GeV), which has the largest misidentification rate. This is less likely to happen in electron final states ($e^+e^-e^+e^-$ or $e^+e^-\mu^+\mu^-$), which have two ways for the electron candidate to fail the full selection but still enter the control region, whereas muons are allowed only to fail the isolation requirement. For example, in final states with a muon this leads to $N(\ell\ell\ell F) \times f = 0.0^{+1.3}_{-0.0} \times 0.8 = 0^{+1.0}_{-0.0}$. When multiple final states are combined, this technique is applied to the combined final state, rather than adding the individual final states in quadrature. The systematic uncertainty in such cases is evaluated using the misidentification rate uncertainty in the lowest p_T bin.

Modeling of the *ZZ* and non-*ZZ* SM backgrounds is verified in two data subsamples. To validate the modeling of the *ZZ* background, events with two opposite-sign same-flavor (OS–SF) pairs, both within a dilepton invariant mass window of $m_{\ell\ell} \in [66, 116]$ GeV, are examined. Requiring two OS–SF pairs inside the chosen *Z* boson mass window results in an almost pure sample of *ZZ* events. To be orthogonal to the signal region for the graviton search, $m_{\ell\ell\ell\ell} < 300$ GeV is required. A comparison between the SM *ZZ* expectation and the observation shows agreement within statistics (see Table 2), indicating satisfactory modeling of the SM *ZZ* production.

Requiring four leptons and fewer than two OS–SF pairs but applying the same dilepton mass window used for *ZZ* pairs to the dilepton pair masses rejects nearly all of the SM *ZZ* production, so that one may test the misidentified lepton background estimate. This region is orthogonal to the $G^* \to ZZ$ signal regions. The expected *ZZ* contribution is $0.15 \pm 0.01 \pm 0.01$, while the misidentified lepton background is $0.0^{+1.3}_{-0.0}\,{}^{+0.8}_{-0.0}$. No events are observed in this region, demonstrating an agreement between data and the modeling of misidentified leptons within the available statistics.

Table 3 shows the expected yield in the $m_{\ell\ell\ell\ell} > 300$ GeV region. A total of $1.9^{+1.0}_{-0.1}\,{}^{+0.8}_{-0.1}$ events are expected from SM processes. Three events are observed, see Fig. 2. Due to the asymmetry of the uncertainties, three events corresponds to the median expected number of observed events from SM processes.

7. Statistical analysis

To test for possible resonances we search for an excess in the full spectrum using the BUMPHUNTER algorithm [43]. No significant excess is found in the $\ell\ell\ell\ell$, low-mass $\ell\ell jj$ or high-mass $\ell\ell jj$ spectra. The largest excesses have p-values of 0.07, 0.08, and 0.08 respectively, corresponding to significances of 1.5σ, 1.4σ, 1.4σ, respectively.

Table 3

Background estimates in 1.02 fb^{-1} of data in the $m_{\ell\ell\ell\ell} > 300$ GeV signal region. Also shown are expected yields for $G^* \to ZZ$ samples for a coupling of $k/\bar{m}_{\text{pl}} = 0.1$. The first quoted uncertainty is statistical; the second systematic.

Process	Total
ZZ	$1.9 \pm 0.1 \pm 0.1$
Mis. lep.	$0.02^{+1.0}_{-0.01}\,{}^{+0.8}_{-0.02}$
Total bkg.	$1.9^{+1.0}_{-0.1}\,{}^{+0.8}_{-0.1}$
Data	3
G^*(325 GeV)	$590 \pm 40 \pm 30$
G^*(350 GeV)	$71 \pm 3 \pm 4$
G^*(500 GeV)	$12 \pm 0.5 \pm 0.6$
G^*(750 GeV)	$1.5 \pm 0.1 \pm 0.1$
G^*(1000 GeV)	$(2.7 \pm 0.2 \pm 0.1) \times 10^{-1}$
G^*(1250 GeV)	$(6.6 \pm 0.4 \pm 0.3) \times 10^{-2}$
G^*(1500 GeV)	$(1.9 \pm 0.1 \pm 0.1) \times 10^{-2}$

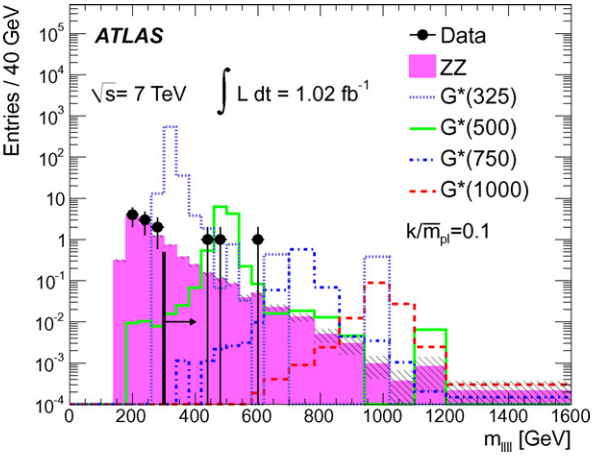

Fig. 2. Distribution of the four lepton invariant mass for the selected events. The misidentified lepton background is negligible and not shown. Hypothetical graviton signal distributions are overlaid. The hatched area shows the uncertainty on the background prediction. The region with $m_{\ell\ell\ell\ell} < 300$ GeV, to the left of the solid black line, serves as a *ZZ* control region; the signal region, indicated by the arrow, is $m_{\ell\ell\ell\ell} > 300$ GeV. Overflow events are shown in the highest mass bin. Numerical values are given in Table 3.

Observing no significant excess, we calculate limits on the production cross section times branching ratio for a narrow *ZZ* resonance from the $\ell\ell\ell\ell$ channel and the $\ell\ell jj$ channels separately, as well as for the combined channel. In the $\ell\ell jj$ channel, the background falls quickly and the resonance is expected to be fairly narrow; statistical analysis for each hypothesized mass is therefore done as a counting experiment using a single bin that surrounds the hypothesized mass. The mass windows are chosen to optimize the expected limit in the background-only hypothesis. In the $\ell\ell\ell\ell$ channel, the background is very low and the knowledge of the mass dependence of the misidentified lepton background is limited by the small number of events in the sample used to estimate its contribution. Hence, a single wide window, $m_{\ell\ell\ell\ell} > 300$ GeV, is used. Limits are evaluated at a specific set of mass points and interpolated between them, as the background levels and signal acceptance are smoothly varying.

Limits are set using the CLs method [44,45], a modified frequentist approach. In this method a log-likelihood ratio (LLR) test statistic is formed using the Poisson probabilities for estimated background yields, the signal acceptance, and the observed number of events for all *ZZ* resonance mass hypotheses, accounting

Table 4
Mass windows (in GeV) for statistical analysis of the $\ell\ell jj$ channel at each of the generated graviton masses (in GeV), with the expected numbers of background, graviton ($k/\bar{m}_{\mathrm{pl}} = 0.1$), and observed events. For a resonance mass of 350 GeV, the low-mass selection is used; at the remaining mass values the high-mass selection is used. Uncertainties are statistical and systematic added in quadrature.

Resonance mass	Mass window		Expected background	Expected signal	Obs.
350	330–360	$eejj$	116^{+20}_{-15}	161^{+36}_{-14}	109
		$\mu\mu jj$	163^{+28}_{-23}	165^{+19}_{-16}	147
500	480–530	$eejj$	6^{+4}_{-2}	27^{+3}_{-4}	8
		$\mu\mu jj$	8^{+5}_{-2}	23^{+2}_{-3}	6
750	730–830	$eejj$	4^{+2}_{-1}	$6.5^{+0.6}_{-0.9}$	6
		$\mu\mu jj$	$1.2^{+0.9}_{-0.5}$	$6.9^{+0.6}_{-0.7}$	2
1000	900–1090	$eejj$	$2.1^{+1.3}_{-0.9}$	1.2 ± 0.2	2
		$\mu\mu jj$	$1.2^{+0.8}_{-0.5}$	1.2 ± 0.1	3
1250	$\geqslant 1150$	$eejj$	$0.4^{+0.4}_{-0.3}$	0.18 ± 0.01	1
		$\mu\mu jj$	$0.5^{+0.5}_{-0.4}$	0.21 ± 0.01	1
1500	$\geqslant 1300$	$eejj$	0.1 ± 0.1	0.04 ± 0.01	0
		$\mu\mu jj$	0.4 ± 0.4	0.04 ± 0.01	1

for systematic uncertainties on the background estimate and signal acceptance. Pseudo-experiments are drawn from a Poisson distribution whose mean is drawn from a bifurcated Gaussian and truncated at zero; a bifurcated Gaussian has distinct positive and negative widths to represent asymmetric uncertainties. Confidence levels are derived by integrating the LLR in pseudo-experiments using both the signal plus background hypotheses (CL_{s+b}) as well as the background only hypothesis (CL_b). In the modified frequentist approach, the production cross section excluded at 95% CL is computed as the cross section for which CL_s, defined as CL_{s+b}/CL_b, is equal to 0.05.

7.1. $\ell\ell jj$ limits

For the statistical analysis of the $\ell\ell jj$ data, mass windows are chosen surrounding each of the generated graviton masses to perform a counting experiment, as shown in Table 4. The mass windows are chosen to optimize the expected limit in the background-only hypothesis. For a resonance mass of 350 GeV, the low-mass selection described above is as the initial selection; at the remaining mass values the high-mass selection described above is used. Observed limits are shown in Table 6 for the individual $eejj$ and $\mu\mu jj$ channels. The combined limits for the $\ell\ell jj$ channel are shown in Fig. 3.

The acceptance times efficiency including the mass window cuts is 5.6% (5.3%, 13.1%, 12.9%, 8.6%, and 6.0%) for 350 (500, 750, 1000, 1250 and 1500) GeV graviton signal with Z boson decays to e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$; the uncertainty is 15%, relative. The acceptance drop at high mass is due to highly boosted Z bosons producing a single merged jet.

7.2. $\ell\ell\ell\ell$ limits

The analysis of the $\ell\ell\ell\ell$ data is done using a single mass-independent counting experiment. The median expected upper limit on the number of $\ell\ell\ell\ell$ events from a new source with $m_{\ell\ell\ell\ell} > 300$ GeV is $N_{ZZ} < 5.7$ events at 95% CL. The observed three events leads to an upper limit of $N_{ZZ} < 5.7$ events at 95% CL.

We define a $ZZ \to \ell\ell\ell\ell$ fiducial region, which contains events with four charged leptons (e or μ) each with $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.5$ forming two OS–SF pairs each with $m_{\ell\ell} \in [66, 116]$ GeV and $m_{\ell\ell\ell\ell} > 300$ GeV. Within this fiducial region, the efficiency of the $\ell\ell\ell\ell$ selection is nearly independent of the graviton mass for the RS1 graviton benchmark model, as shown in Table 5.

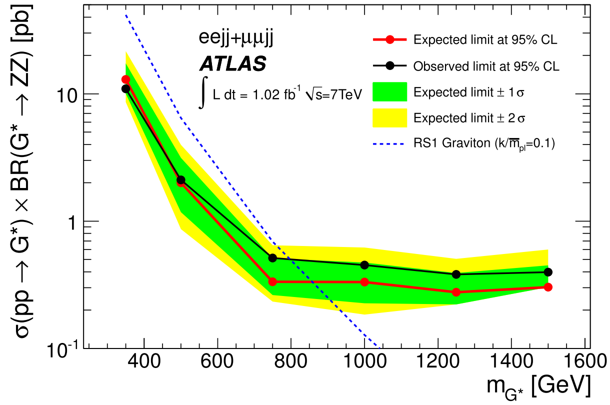

Fig. 3. Expected and observed 95% CL limits for $G^* \to ZZ$ for the combined $\ell\ell jj$ channel. The leading-order theoretical prediction is also shown for $k/\bar{m}_{\mathrm{pl}} = 0.1$. Theoretical predictions scale with $(k/\bar{m}_{\mathrm{pl}})^2$.

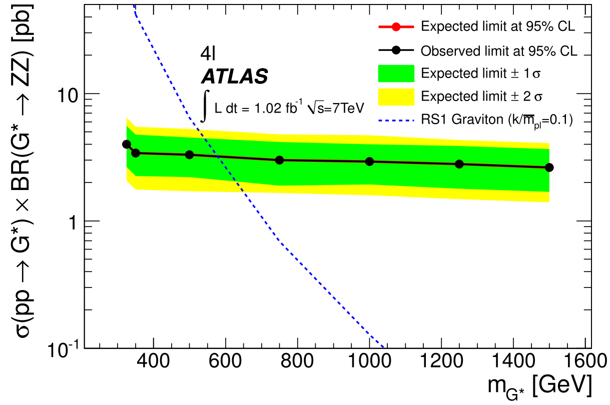

Fig. 4. Expected and observed 95% CL limits for $G^* \to ZZ$ using the $ZZ \to \ell\ell\ell\ell$ fiducial cross section upper limit, and the fraction of the produced events which fall into the fiducial region, see Table 5. The median expected result from pseudo-experiments drawn from the SM hypothesis is shown; the observed limit corresponds to $N_{obs} = 3$. The leading-order theoretical prediction is also shown for $k/\bar{m}_{\mathrm{pl}} = 0.1$. Theoretical predictions scale with $(k/\bar{m}_{\mathrm{pl}})^2$.

The lowest selection efficiency (61%) is used to set limits on all mass points. The corresponding ZZ fiducial limit on the production of new sources of high-mass ZZ pairs is

$$\sigma_{ZZ,\mathrm{fid}} < \frac{N_{ZZ}}{\epsilon_{ZZ} \times \mathrm{B}(ZZ \to \ell\ell\ell\ell) \times \mathcal{L}} = \frac{5.7}{0.61 \times 0.010 \times 1.02\ \mathrm{fb}^{-1}} = 0.92\ \mathrm{pb},$$

which can be applied to our benchmark model of RS1 gravitons using the fiducial acceptance, see Fig. 4 and Table 5, but may be extended to a larger class of models that hypothesize resonances with branching fraction (B) to ZZ different than that in the RS1 model.

The fiducial efficiency is relative to all ZZ decays to charged leptons, including τ leptons, and therefore $\mathrm{B}(ZZ \to \ell\ell\ell\ell) = 0.010$ also includes τ lepton decays.

7.3. Combined limits

The limits obtained from combinations of channels are calculated using the same technique, keeping each channel separate but with a coherent signal hypothesis and including the correlations

Table 5
For spin-2 RS1 graviton models, the theoretical prediction of $\sigma(pp \to G^* \to ZZ)$ using a coupling of $k/\bar{m}_{\rm pl} = 0.1$; acceptance of the $G^* \to ZZ \to \ell\ell\ell\ell$ fiducial region defined in the text, and the efficiency of the selection described in the text; the median expected and observed 95% CL upper limits on $\sigma(pp \to G^* \to ZZ)$ using the fiducial cross-section limit. We use $\mathrm{B}(G^* \to ZZ) = 4.5\%$ [46] and $\sigma(pp \to G^*)$ at leading order from PYTHIA with $k/\bar{m}_{\rm pl} = 0.1$; predictions scale as $(k/\bar{m}_{\rm pl})^2$. As is done with the $\ell\ell\ell\ell$ fiducial limit, the lowest selection efficiency (61%) is used to set limits on all mass points.

Graviton mass (GeV)	Theory $k/\bar{m}_{\rm pl} = 0.1$ (pb)	Fid. acc.	Sel. eff.	Exp. limit (pb)	Obs. limit (pb)
325	950	23%	61%	4.0	4.0
350	42	27%	61%	3.3	3.3
500	6.5	28%	63%	3.2	3.2
750	0.69	31%	66%	2.9	2.9
1000	0.13	32%	66%	2.8	2.8
1250	0.03	33%	67%	2.7	2.7
1500	0.01	35%	66%	2.6	2.6

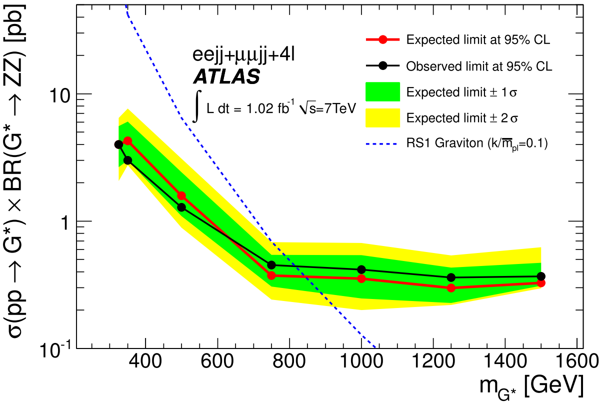

Fig. 5. Expected and observed 95% CL limits for $G^* \to ZZ$ for the combined $\ell\ell jj + \ell\ell\ell\ell$ channels. The leading-order theoretical prediction is also shown for $k/\bar{m}_{\rm pl} = 0.1$. Theoretical predictions scale with $(k/\bar{m}_{\rm pl})^2$.

Table 6
Upper limits at 95% CL on $\sigma(pp \to G^*) \times \mathrm{B}(G^* \to ZZ)$ in the individual channels $eejj$, $\mu\mu jj$ and $\ell\ell\ell\ell$ as well as the combined $\ell\ell jj$ ($eejj$ and $\mu\mu jj$) and $\ell\ell\ell\ell + \ell\ell jj$ ($eejj$, $\mu\mu jj$ and $\ell\ell\ell\ell$) channels.

Graviton mass (GeV)	$eejj$ (pb)	$\mu\mu jj$ (pb)	$\ell\ell jj$ (pb)	$\ell\ell\ell\ell$ (pb)	$\ell\ell\ell\ell + \ell\ell jj$ (pb)
325	–	–	–	4.0	4.0
350	8.9	11.6	10.9	3.3	3.0
500	2.3	1.8	2.1	3.3	1.3
750	0.9	0.5	0.5	2.9	0.5
1000	0.6	0.7	0.5	2.8	0.4
1250	0.7	0.6	0.4	2.8	0.4
1500	0.7	0.9	0.4	2.6	0.4

between the systematics where appropriate. The dominant uncertainties in the $\ell\ell\ell\ell$ channel are due to the misidentified-lepton estimate; the degree of correlation with uncertainties in the $\ell\ell jj$ channel is small. The combined limits are shown in Fig. 5 and given in Table 6.

We exclude an RS1 graviton in the mass range of 325 to 845 GeV at 95% CL for $k/\bar{m}_{\rm pl} = 0.1$.

8. Conclusions

We report the results of a search for narrow resonances such as Randall–Sundrum gravitons decaying to ZZ pairs, using $\ell\ell jj$ and $\ell\ell\ell\ell$ final states collected by the ATLAS detector from $\sqrt{s} = 7$ TeV LHC pp collisions. No excess is seen above the expected SM backgrounds, and upper limits are set on the cross section of graviton production times the branching fraction to ZZ. We exclude an RS1 graviton in the mass range of 325 to 845 GeV at 95% CL for $k/\bar{m}_{\rm pl} = 0.1$.

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