Search for new phenomena in the $WW \rightarrow l\nu l'\nu'$ final state in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

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ARTICLE INFO

ABSTRACT

This Letter reports a search for a heavy particle that decays to WW using events produced in pp collisions at $\sqrt{s} = 7$ TeV. The data were recorded in 2011 by the ATLAS detector and correspond to an integrated luminosity of 4.7 fb^{-1}. $WW \rightarrow \ell\nu\ell'\nu'$ ($\ell, \ell' = e$ or μ) final states are considered and the distribution of the transverse mass of the WW candidates is found to be consistent with Standard Model expectations. Upper limits on the production cross section times branching ratio into W boson pairs are set for Randall–Sundrum and bulk Randall–Sundrum gravitons, which result in observed 95% CL lower limits on the masses of the two particles of 1.23 TeV and 0.84 TeV, respectively.

The existence of new phenomena can be probed by studying heavy gauge boson pair production. Heavy particles that can decay to gauge boson pairs are predicted in many scenarios of physics beyond the Standard Model (SM), including the Extended Gauge Model (EGM) [1], Extra Dimensions [2–6], and Technicolor models [7–9]. This Letter describes a search for resonant WW production in the $WW \rightarrow \ell\nu\ell'\nu'$ ($\ell, \ell' = e$ or μ) decay channel using a data sample corresponding to an integrated luminosity of 4.7 fb^{-1}, collected by the ATLAS detector during 2011 at a center-of-mass energy of 7 TeV. A spin-2 Randall–Sundrum (RS) graviton model [2] and one of its extensions, the bulk RS graviton model [10], are used as benchmarks to interpret the analysis result.

The original RS model (RS1) was proposed to solve the hierarchy problem. It postulates a warped 5-dimensional universe, where the SM particles are localized on the TeV brane and the graviton is located on the Planck brane. In this model gravitons can propagate in the extra dimension, leading to a Kaluza–Klein tower of states which can be detected as massive spin-2 resonances that couple to all SM particles. The resonance with the lowest mass is known as the RS graviton G^*. The model has two parameters: the graviton mass m_{G^*}, and the dimensionless coupling $\kappa/\bar{M}_{\mathrm{pl}}$, where κ is the curvature of the warped fifth dimension and $\bar{M}_{\mathrm{pl}} = M_{\mathrm{pl}}/\sqrt{8\pi}$ is the reduced Planck mass.

The RS1 model introduces higher-dimensional operators that give excessively large contributions to flavour changing neutral current (FCNC) processes and to observables related to SM electroweak precision tests. An extension of the RS1 model, the bulk RS model, has been proposed to address this issue. In this model, the SM fields are also allowed to propagate in the extra dimension: the first and second generation fermions are chosen to be localized near the Planck brane, while the top-quark and the Higgs boson are localized near the TeV brane to account for the large top-quark Yukawa coupling. In this scenario, FCNCs and contributions to electroweak observables from higher-dimensional operators are suppressed, the graviton (here denoted by G^*_{bulk}) production and decay via light fermion channels is highly suppressed, the probability for the graviton to decay into photons is negligible, and the coupling to heavy particles, such as top-quark, W, Z and Higgs bosons is strongly enhanced. In this model the branching ratio of $G^*_{\mathrm{bulk}} \rightarrow WW$ is about 15%.

Direct searches for a heavy WW resonance have been performed by the CDF and D0 Collaborations at the Tevatron. The D0 Collaboration explored diboson resonant production using the $\ell\nu\ell'\nu'$ and $\ell\nu jj$ final states [11]; these searches excluded an RS graviton with a mass between 300 GeV and 754 GeV, assuming $\kappa/\bar{M}_{\mathrm{pl}} = 0.1$. The CDF Collaboration also searched for resonant WW production in the $e\nu jj$ final state, resulting in a lower limit of 607 GeV on the mass of an RS graviton [12], assuming the same coupling strength $\kappa/\bar{M}_{\mathrm{pl}} = 0.1$. No previous work on searches for G^*_{bulk} has been published.

The ATLAS detector [13] is a multi-purpose particle physics detector with forward–backward symmetric cylindrical geometry [14]. The inner tracking detector (ID) covers the region $|\eta| < 2.5$, and consists of a silicon pixel detector, a silicon microstrip detector, and a straw tube tracker with transition radiation detection capability. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. A high-granularity lead/liquid-argon (LAr) sampling calorimeter measures the energy and the position of electromagnetic

showers with $|\eta| < 3.2$. LAr sampling calorimeters are also used to measure hadronic showers in the end-cap ($1.5 < |\eta| < 3.2$) and forward ($3.1 < |\eta| < 4.9$) regions, while an iron/scintillator tile calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$). The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting air-core toroids, each with eight coils, a system of precision tracking chambers ($|\eta| < 2.7$), and fast tracking chambers for triggering. A three-level trigger system selects events to be recorded for offline analysis.

The data used in this analysis were recorded in 2011 at a centre-of-mass energy of 7 TeV, selected by a single-lepton (e or μ) trigger, with a threshold applied to the electron transverse energy, E_T, and to the muon transverse momentum, p_T. The single-muon trigger required a muon $p_T > 18$ GeV, while for the single-electron trigger the threshold was raised from 20 GeV to 22 GeV for later data. The trigger object quality requirements were tightened progressively throughout the data-taking period to cope with the increasing instantaneous luminosity. After the application of data-quality requirements, the data set corresponds to a total integrated luminosity of 4.7 fb^{-1} with an uncertainty of 3.9% [15,16].

The search for resonant WW production is performed in the fully leptonic decay channel. Events are required to contain two oppositely-charged leptons (either electrons or muons) and large missing transverse momentum E_T^{miss} due to the presence of neutrinos in the final state. Henceforth this final state is denoted by $\ell\ell' + E_T^{miss}$.

Events originating from pp collisions are selected by requiring a reconstructed primary interaction vertex with at least three tracks with $p_T > 0.4$ GeV. Electron candidates are selected from clustered energy deposits in the electromagnetic calorimeter with $E_T > 25$ GeV and within the ID fiducial region $|\eta| < 2.47$, excluding the transition region between barrel and endcap calorimeters $1.37 < |\eta| < 1.52$. A set of electron identification criteria based on the calorimeter shower shape, track quality and track-matching with the calorimeter cluster, referred to as *tight* [17], is applied. Muon candidates must be reconstructed in both the ID and the MS, and have $p_T > 25$ GeV and $|\eta| < 2.4$. A minimum number of silicon strip and pixel hits associated to the ID muon track is also required. To ensure good reconstruction quality even for very high-p_T muons, the charge-to-momentum ratio of the muon tracks reconstructed in the ID and MS have to be compatible within five standard deviations. Both electron and muon candidates are required to be isolated: the transverse energy deposited in the calorimeter in a $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ cone around the lepton track, excluding the energy associated to the lepton itself, must be less than 0.14 times the E_T (p_T) of the electron (muon); and the scalar sum of the transverse momentum of all tracks with $p_T > 1$ GeV reconstructed within $\Delta R = 0.3$ around the lepton track, must be less than 0.13 (0.15) times the E_T (p_T) of the electron (muon). Corrections are applied to account for electron energy leakage and energy deposition inside the isolation cone due to additional pp collisions occurring in the same or neighbouring bunch crossings. To ensure the leptons originate from the primary interaction vertex each candidate's longitudinal impact parameter is required to be less than 1 mm, and the transverse impact parameter divided by its resolution is required to be less than ten for electrons and less than three for muons. Any electron reconstructed in a $\Delta R = 0.1$ cone around a muon track is discarded.

Jets tagged as originating from a b-quark are used in this analysis to suppress the top background. Jets are reconstructed from noise-suppressed three-dimensional topological clusters of calorimeter cells [18] using the anti-k_t algorithm [19] with radius parameter $R = 0.4$. Topological clustering extends up to $|\eta| < 4.9$, and clusters are seeded by calorimeter cell deposits exceeding the cell noise level by at least four standard deviations. Neighbouring cells exceeding the cell noise level by at least two standard deviations are then added to the clusters. At least 75% of the scalar sum of the p_T of all the tracks associated to each jet must belong to tracks associated to the same primary vertex.

Jet energies are calibrated using E_T- and η-dependent correction factors based on Monte Carlo (MC) simulation, and validated by collision data studies [20]. Jets are identified as originating from b-quarks using an algorithm that combines information about the impact parameter significance of tracks in the jet with the topology of semi-leptonic b- and c-hadron decays [21]. The chosen operating point has an efficiency of 85% for tagging b-jets in a MC sample of $t\bar{t}$ events, and a mis-tag rate of less than 5% for jets from light quarks, c-quarks and gluons. A scale factor is applied to the b-tagging efficiency and to the light- and c- to b-quark jets mis-tag rate of the MC simulation to reproduce the ones measured in the data. The fiducial kinematic region for well-reconstructed b-jets is $p_T > 20$ GeV and $|\eta| < 2.5$. In order to remove electrons reconstructed as jets, b-jet candidates that lie within a $\Delta R = 0.3$ cone around an electron track are discarded.

The E_T^{miss} is determined by the energy collected by the electromagnetic and hadronic calorimeters, and by muon tracks reconstructed in the MS and the ID [22].

Candidate WW events are required to have exactly two oppositely-charged leptons with dilepton invariant mass greater than 106 GeV to reduce the background contamination from Z boson production. Three different final states are considered based on the lepton flavour, namely ee, $\mu\mu$, and $e\mu$. To cope with different background compositions, a different requirement on the E_T^{miss} is applied to each final state, which is $E_T^{miss} > 30$, 60 and 65 GeV for $e\mu$, ee and $\mu\mu$, respectively. To reject top-quark backgrounds, events with any reconstructed b-jets are discarded.

The SM processes that can mimic the $\ell\ell' + E_T^{miss}$ signature are: electroweak diboson pair production, namely WW, which is an irreducible background, WZ/ZZ when only two leptons are reconstructed in the final state, and $W\gamma$ when the photon is reconstructed as a lepton; top-pair and single-top production, when the b-jets in the final state are not identified; W/Z production in association with jets, when either one jet is reconstructed as a lepton as for W + jets events, or fake E_T^{miss} is generated from the mismeasurement of the p_T of the leptons or jets; and QCD multi-jet production, when two jets are reconstructed as leptons.

The expected background contributions from SM diboson, single-top and $t\bar{t}$ production are estimated using the MC simulation [23]. MC samples are generated at $\sqrt{s} = 7$ TeV using a GEANT4 [24] simulation of the ATLAS detector. To improve the agreement between data and simulation, selection efficiencies are measured in both data and simulation, and correction factors are applied to the simulation. Furthermore, the simulation is tuned to reproduce the muon momentum scale and the muon momentum and electron energy resolutions observed in data. The MC predictions are normalized to the data sample integrated luminosity, except for W/Z + jets processes, whose contributions are estimated from data. WW and $t\bar{t}$ production are simulated using the next-to-leading-order (NLO) generator MC@NLO 3.4 [25], interfaced to HERWIG 6.510 [26] for hadronization and parton showering. The gg2ww [27] program is used to simulate at next-to-next-to-leading order (NNLO) the WW production via gluon fusion, which is not implemented in MC@NLO; HERWIG 6.510 and ALPGEN 4 [28] are used to simulate at leading order (LO) the WZ/ZZ and $W\gamma$ processes respectively, and NLO corrections computed using