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

The ATLAS Collaboration

Abstract

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The ATLAS Collaboration
(Dated: December 27, 2012)

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 $\mu)$ 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.

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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, 3], and Technicolor models [7–9]. This paper describes a search for resonant $WW$ production in the $WW \rightarrow \ell \nu \ell' \nu'$ ($\ell, \ell' = e$ or $\mu$) 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 $\kappa/M_{pl}$, where $\kappa$ is the curvature of the warped fifth dimension and $M_{pl} = M_{pl}/\sqrt{8\pi}$ 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 $G^*_\text{bulk}$) 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 $G^*_\text{bulk} \rightarrow WW$ 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 $W W$ and $\ell\nujj$ final states [11]; these searches excluded an RS graviton with a mass between 300 GeV and 754 GeV, assuming $\kappa/M_{pl} = 0.1$. The CDF collaboration also searched for resonant $WW$ production in the $\ell\nujj$ final state, resulting in a lower limit of 607 GeV on the mass of an RS graviton [12], assuming the same coupling strength $\kappa/M_{pl} = 0.1$. No previous work on searches for $G^*_\text{bulk}$ 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% [13, 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 [15] 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 $E_T^\text{miss}$ and $\eta$-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 $tt$ 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 eμ. 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. The MC simulation correctly models the production cross section. The number of observed events in the top enal region, and completely dominated by top-quark pair production. The ratio $R$ of $Z$+jets events in the signal region to those in the control region is estimated using the MC simulation. The number of data events observed in the $Z$+jets control region, after having subtracted the non-$Z$+jets events contribution using MC expectations, is scaled by $R$ to estimate the $Z$+jets background contribution in the signal region. The ratio $R$ from $Z$+jets events generated with ALPGEN, is found to be $0.040^{+0.005}_{-0.006}$ in the $ee$ channel and $0.046^{+0.019}_{-0.015}$ in the $\mu\mu$ channel. The non-$Z$+jets events contribution in the $Z$+jets control region is 12% in the $ee$ channel and 16% in the $\mu\mu$ channel.

The $W$+jets process contributes to the final selected sample when one or more hadrons in a jet decay to, or are misidentified as, a charged lepton. Since the probability for a jet to be identified as a lepton may not be well modelled in the MC simulation, a data-driven method is used to estimate this contribution. A data control sample is selected by requiring one lepton which passes all the quality criteria in the lepton selection described above and a second lepton-like object. The muon-like objects are those reconstructed as muons but failing the isolation requirement. The electron-like objects are those reconstructed as electrons [17] but failing both the isolation and the tight quality requirements. These lepton-like objects are most likely jets reconstructed as leptons. To obtain the expected number of $W$+jets events contaminating the signal region, the number of events in this $W$+jets dominated control sample is then scaled by a pass-to-fail ratio $f$, defined as the number of lepton-like objects passing the full lepton selection requirements divided by the number that fail. The non-$W$+jets events in the control region are subtracted using MC expectations. The factor $f$ is measured from data for electrons and muons separately, using two control samples dominated by dijet events. The di-jet samples are selected by tagging events with one jet and one back-to-back lepton-like object without any isolation requirement (and no tight requirement for the electrons) after suppressing the lepton contribution from $W/Z$ bosons. The ratio $f$ is measured as a function of the jet $p_T$, and its value is found to be between 0.3 and 1.0 for electrons, and between 0.02 and 0.15 for muons.

The background contribution from QCD di-jet events in the signal region is estimated in a similar way to the $W$+jets contribution, but in this case the control sample is selected by requiring two lepton-like jets, and the ratio $f$ is applied to both of them. This background contribution is found to be negligible.

The simulation of the RS $G^*$ signal is based on the LO matrix element implemented in PYTHIA [32] 6.421 event generator, with the modified LO [33] parton distribution function (PDF) set MRST2007LO$^*$ [34]. The
coulpling $\kappa/\bar{N}_{f,b} = 0.1$ is assumed. A separate MC sample is generated for each of seven graviton masses $m_{G^*} = 200, 350, 500, 750, 1000, 1250$ and 1500 GeV. The production cross section times branching ratio $\sigma(pp \rightarrow G^*) \times BR(G^* \rightarrow WW \rightarrow \ell\bar{\nu}\ell'\nu') (\ell, \ell' = e, \mu$ or $\tau)$ decreases from 108 pb to 1.8 fb when the simulated $m_{G^*}$ increases from 200 GeV to 1500 GeV. The $G^*_{\text{bulk}}$ signal is simulated at LO using CTEQ6L1 PDF set [36], interfaced to PYTHIA for parton showering and hadronization. Thirteen signal samples with $G^*_{\text{bulk}}$ masses between 300 GeV and 1500 GeV in 100 GeV mass steps are generated, with the predicted $\sigma(pp \rightarrow G^*_{\text{bulk}}) \times BR(G^*_{\text{bulk}} \rightarrow WW \rightarrow \ell\bar{\nu}\ell'\nu') (\ell, \ell' = e, \mu$ or $\tau)$ decreasing from 8.6 pb to 0.22 fb. The ATLAS fast simulation [37] is used to simulate the detector response for both $G^*$ and $G^*_{\text{bulk}}$ samples. Events with $W$ bosons decaying to $\tau$ leptons are also considered as part of the signal if electrons or muons are present in the final state. The overall acceptance times trigger, reconstruction and selection efficiencies $(A \times \epsilon)$, defined as the number of signal events passing the full event selection divided by the number of generated events, increases from 3.0% at $m_{G^*} = 200$ GeV to 40.9% at $m_{G^*} = 1500$ GeV for $G^*$. The corresponding $A \times \epsilon$ for $G^*_{\text{bulk}}$ increases from 16.8% at $m_{G^*_{\text{bulk}}} = 300$ GeV to 58.8% at $m_{G^*_{\text{bulk}}} = 1500$ GeV. The difference in $A \times \epsilon$ between the two models is due to different production mechanisms and the treatment of the $W$ boson polarization in its decay, which is properly taken into account by CALCHEP but not by PYTHIA. PYTHIA is chosen to simulate the RS $G^*$ samples, even though it does not properly account for the $W$ boson polarization, in order to allow direct comparison with previous search results, which used the same PYTHIA implementation to simulate this process.

Table I shows the number of events selected in data and the estimated background contributions with combined statistical and systematic uncertainties. The expected numbers of events for an RS $G^*$ with a mass of 750 GeV and 1000 GeV, and for a $G^*_{\text{bulk}}$ with a mass of 600 GeV and 1000 GeV are also reported. A total of 1384 $\ell\ell' + E_T^{\text{miss}}$ candidates are observed in data, while the expected number of events from SM processes is $1280 \pm 13(\text{stat}) \pm 200(\text{syst})$.

Several sources of systematic uncertainty on the signal and background estimates are considered. The first is related to the correction scale factors applied to MC samples in order to account for the difference in the performance of object reconstruction, identification, isolation and trigger efficiency between data and MC simulation. The uncertainty on the single-lepton trigger efficiency scale factor is 1%, while the electron and muon reconstruction and identification efficiency scale factor uncertainties are less than 1.0% and 0.4% respectively, evaluated with tag-and-probe methods using $Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$ and $J/\psi \rightarrow \ell\ell$ events. A slight degradation of the muon reconstruction efficiency is observed at high $p_T$ in simulated MC samples. An uncertainty of the order 1% for muons with $p_T > 1$ TeV, corresponding to the magnitude of this effect, is included. The lepton isolation efficiency scale factor is determined with an uncertainty of 1% and 0.3% for electrons and muons, respectively.

The MC simulation is also corrected to reproduce the lepton energy scale and resolution, with residual uncertainties < 1% and < 0.1% on the energy scale, and < 0.6% and < 5% on the resolution, for electrons and muons, respectively. Uncertainties on the jet energy scale and resolution are found to be typically 3% at high $E_T^{\text{miss}}$, relevant for this analysis, varying between 2-9% [18]. The uncertainties on the lepton and jet energy scale and resolution are propagated to the $E_T^{\text{miss}}$, which also receives contributions from energy deposits due to additional $pp$ collisions in the same or neighbouring bunch crossings, and from energy deposits not associated to any reconstructed object. The total systematic uncertainty on the $E_T^{\text{miss}}$ energy scale is 3.5% [18]. The uncertainties on the $b$-tagging efficiency for heavy-quark jets and mis-tag rate for light- and $c$-quark jets are measured in data, and are 6–15% and up to 21%, respectively [21]. The effect of all these sources of detector uncertainty on the shape of the distribution used to set the final cross-section limit is taken into account.

The uncertainty on the normalization of the backgrounds estimated using MC simulation includes the integrated luminosity uncertainty of 3.9% [15, 16], and the theoretical uncertainty on the inclusive cross sections of SM processes, namely 10% for $t\bar{t}$ [39], 9% for single-top [40, 41], 5% for $W/Z+jets$, 5% for $WW$, 7% for $WZ$ and 5% for $ZZ$ [29], which arises from the choice of PDFs, from factorization and renormalization scale dependence, and from strong coupling constant $(\alpha_s)$ variations. The uncertainty on the estimate of the $W$+jets background includes the uncertainty on the non-$W$+jets events subtraction in the control region, and the uncertainty on the ratio $f$. The uncertainty on the non-$W$+jets background events is 10%. The uncertainty on $f$ varies between 10% and 30% depending on lepton $p_T$, and mainly comes from differences in the kinematics and flavour composition of the di-jet events used to determine the ratio $f$ with respect to the $W$+jets events to which $f$ is applied.

The uncertainty on the data-driven normalization of the $Z$+jets background in the $ee$ and $\mu\mu$ due to the non-$Z$+jets events subtraction in the control region is negligible, while the main contribution comes from the uncertainty on the factor $R$. This is evaluated accounting for possible uncertainties on the dilepton mass shape due to initial and final state radiation modeling, and on the $E_T^{\text{miss}}$ shape due to parton shower and hadronization modeling, both determined using PYTHIA and ALPGEN $Z$+jets simulations. The effect of lepton scale and resolution, and $E_T^{\text{miss}}$ resolution are also taken into account. Further systematic uncertainties on the $t\bar{t}$ background
are estimated, including the difference between event
generators, parton shower models and initial- and final-
state radiation models. The dominant contribution (up
to 40%) is due to the parton shower model, arising from
the b-jet requirement. The systematic uncertainties on
the modelling of the kinematics of the SM WW process
have been evaluated by comparing different MC genera-
tors; the local differences in the distributions are found
to be smaller than 10%.

The effect on the signal acceptance due to the choice
of the PDF set used to simulate the signal samples is
also considered. It is estimated to be 1% by comparing
predictions of the nominal PDF set MRST2007 LO* with
those of two NNPDF LO* 2.1[42] sets with values of
\( \alpha_s = 0.119, 0.130 \), and that of the CT09MCS[43] PDF
set, using the standard LHAPDF framework [44].

No significant excess in the overall number of
selected WW events is observed in data. The transverse
mass of the WW candidates, defined as

\[
m_{T}^{WW} = \sqrt{\left( \sum_{i=1}^{2} p_{T}^{i} + E_{T}^{\text{miss}} \right)^{2} - \left( \sum_{i=1}^{2} p_{x}^{i} + E_{x}^{\text{miss}} \right)^{2} - \left( \sum_{i=1}^{2} p_{y}^{i} + E_{y}^{\text{miss}} \right)^{2}}
\]

is examined for any resonant structure, where \( p_{T}^{i}(p_{x}, p_{y}) \) is
the \( p_{T} \) (\( p_{x}, p_{y} \)) of the \( i \)-th lepton, and \( E_{T}^{\text{miss}} \), \( E_{x}^{\text{miss}} \), \( E_{y}^{\text{miss}} \) is the \( x(y) \) component of the \( E_{T}^{\text{miss}} \). The \( m_{T}^{WW} \) distribution
of the WW system for the three analysed channels is presented
in Fig. [45] for data and background expectations together
with the expected signal contributions from RS graviton
and bulk RS graviton models. Due to the small numbers
of MC events, a convolution of a Gaussian with an
exponential function is used to fit the \( m_{T}^{WW} \) distribution
of each SM background. The functional form is then
used to predict the background contribution in the region
\( m_{T}^{WW} > 300 \) GeV, and the uncertainty on the fit
parameters is treated as an additional systematic
uncertainty on the final \( m_{T}^{WW} \) shape.

The \( m_{T}^{WW} \) distribution is used to build a log-likelihood
ratio (LLR) test statistic [45] to assess the compatibility
of the data with the presence of a signal in addition to
the background in a modified frequentist approach [46].
Confidence levels (CL) for the signal plus background hy-
pothesis, \( CL_{s+b} \), and background-only hypothesis, \( CL_{b} \),
are computed by integrating the LLR distributions ob-
tained from simulated pseudo-experiments using Poisson
statistics, and their ratio \( CL_{s} \) is used to set the limits.
Systematic uncertainties on the expected numbers of sig-
nal and background events are treated as nuisance pa-
rameters. The three analysed channels are treated sepa-
rateley and then combined by summing up the LLR val-
ues over all bins. All correlations are maintained among
channels and between signal and background. Due to the
large residual Z+Jets background contamination in the
\( \mu\mu \) channel, caused by the worse muon resolution at high
\( p_{T} \), this channel has a poorer sensitivity than the other
two channels.

No excess is observed in data and the \( p \)-value of the
background-only hypothesis, defined as the probability
for the background to produce an excess of equal or larger
size than the observed one, is found to be greater than
0.08 in all \( m_{T}^{WW} \) regions. Upper limits are therefore de-
ferred on the production cross section times branching ra-
tio \( (\sigma \times BR) \) for RS gravitons and bulk RS gravitons
decaying to WW. The observed (expected) 95% CL upper
limits on \( \sigma(pp \rightarrow G*_{\text{bulk}}) \times BR(G^*_{\text{bulk}} \rightarrow WW) \)
as a function of \( m_{G^*} \) and \( m_{G^*_{\text{bulk}}} \) are shown in Fig. [47]
and reported in Tables [11] and [13] corresponding to an
observed (expected) 95% CL lower limit of 1.23 (1.13) TeV
and 0.84 (0.74) TeV on the masses of the \( G^* \) and \( G^*_{\text{bulk}} \),
respectively. Tables [11] and [13] also report the \( A \times \epsilon \) values
for each signal sample.

In conclusion, a generic search for resonant production
of a pair of W bosons in two opposite sign leptons and large
\( E_{T}^{\text{miss}} \) final state has been performed using 4.7 fb\(^{-1}\)
of data collected with the ATLAS detector in \( pp \) colli-
sions at \( \sqrt{s} = 7 \) TeV at the LHC. No significant excess
of events is observed and upper limits on the production
cross section times branching ratio are set for two bench-
mark models: RS \( G^* \) and bulk RS \( G^* \). The observed
(expected) 95% CL lower limit on the masses of the two
particles is found to be 1.23 (1.13) TeV for \( G^* \) and 0.84
(0.74) TeV for \( G^*_{\text{bulk}} \), assuming the coupling \( \kappa/M_{\text{pl}} = 0.1 \).

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<td>Data</td>
<td>$258$</td>
<td>$249$</td>
<td>$877$</td>
</tr>
<tr>
<td>RS $G^*$ ($m = 750$ GeV)</td>
<td>$28.9 \pm 1.7$</td>
<td>$29.3 \pm 1.7$</td>
<td>$73.0 \pm 3.9$</td>
</tr>
<tr>
<td>RS $G^*$ ($m = 1000$ GeV)</td>
<td>$6.4 \pm 0.4$</td>
<td>$6.4 \pm 0.4$</td>
<td>$15.3 \pm 0.8$</td>
</tr>
<tr>
<td>Bulk RS $G^*$ ($m = 600$ GeV)</td>
<td>$26.3 \pm 1.5$</td>
<td>$25.7 \pm 1.5$</td>
<td>$73.6 \pm 3.9$</td>
</tr>
<tr>
<td>Bulk RS $G^*$ ($m = 1000$ GeV)</td>
<td>$1.4 \pm 0.1$</td>
<td>$1.2 \pm 0.1$</td>
<td>$3.2 \pm 0.1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$</td>
<td>$258$</td>
</tr>
</tbody>
</table>

TABLE I: Estimated background yields, observed number of data events, and predicted signal yield for different graviton mass points for the three analysed channels. The quoted uncertainties are the combined statistical and systematic uncertainties.
TABLE III: Expected and observed 95% CL upper limits on the cross section times branching ratio $\sigma \times BR$ for (a) the RS graviton $\sigma(pp \to G^*) \times BR(G^* \to WW)$ and (b) the bulk RS graviton $\sigma(pp \to G^*_{\text{bulk}}) \times BR(G^*_{\text{bulk}} \to WW)$, with the theoretical predictions at LO (dotted line). The inner and outer bands represent respectively the $1\sigma$ and $2\sigma$ uncertainty on the expected limit.

<table>
<thead>
<tr>
<th>$m_{G^*}$ [GeV]</th>
<th>$A \times \epsilon$ [%]</th>
<th>Expected [pb]</th>
<th>Observed [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>16.8 ± 0.1</td>
<td>17.6</td>
<td>20.3</td>
</tr>
<tr>
<td>350</td>
<td>18.6 ± 0.5</td>
<td>18.8</td>
<td>5.1</td>
</tr>
<tr>
<td>500</td>
<td>24.4 ± 0.7</td>
<td>13.0</td>
<td>1.46</td>
</tr>
<tr>
<td>800</td>
<td>30.7 ± 0.9</td>
<td>0.315</td>
<td>0.264</td>
</tr>
<tr>
<td>1000</td>
<td>36.3 ± 1.0</td>
<td>0.130</td>
<td>0.084</td>
</tr>
<tr>
<td>1250</td>
<td>39.0 ± 1.1</td>
<td>0.085</td>
<td>0.062</td>
</tr>
<tr>
<td>1500</td>
<td>40.9 ± 1.1</td>
<td>0.079</td>
<td>0.061</td>
</tr>
</tbody>
</table>

TABLE II: Expected and observed 95% CL upper limits on the cross section times branching ratio $\sigma \times BR(G^* \to WW)$ as a function of the RS graviton mass. For each mass point, $A \times \epsilon$ is also reported with the combined statistical and systematic uncertainty.

<table>
<thead>
<tr>
<th>$m_{G^*_{\text{bulk}}}$ [GeV]</th>
<th>$A \times \epsilon$ [%]</th>
<th>Expected [pb]</th>
<th>Observed [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>16.8 ± 0.5</td>
<td>4.73</td>
<td>5.48</td>
</tr>
<tr>
<td>400</td>
<td>26.5 ± 0.8</td>
<td>1.81</td>
<td>2.13</td>
</tr>
<tr>
<td>500</td>
<td>33.6 ± 1.0</td>
<td>0.814</td>
<td>0.910</td>
</tr>
<tr>
<td>600</td>
<td>39.0 ± 1.1</td>
<td>0.398</td>
<td>0.405</td>
</tr>
<tr>
<td>700</td>
<td>42.3 ± 1.2</td>
<td>0.212</td>
<td>0.189</td>
</tr>
<tr>
<td>800</td>
<td>44.2 ± 1.2</td>
<td>0.134</td>
<td>0.102</td>
</tr>
<tr>
<td>900</td>
<td>46.1 ± 1.3</td>
<td>0.083</td>
<td>0.056</td>
</tr>
<tr>
<td>1000</td>
<td>47.3 ± 1.3</td>
<td>0.060</td>
<td>0.040</td>
</tr>
<tr>
<td>1100</td>
<td>48.9 ± 1.4</td>
<td>0.044</td>
<td>0.029</td>
</tr>
<tr>
<td>1200</td>
<td>49.2 ± 1.4</td>
<td>0.037</td>
<td>0.025</td>
</tr>
<tr>
<td>1300</td>
<td>50.1 ± 1.4</td>
<td>0.030</td>
<td>0.022</td>
</tr>
<tr>
<td>1400</td>
<td>50.4 ± 1.4</td>
<td>0.028</td>
<td>0.019</td>
</tr>
<tr>
<td>1500</td>
<td>50.8 ± 1.4</td>
<td>0.027</td>
<td>0.020</td>
</tr>
</tbody>
</table>

TABLE III: Expected and observed 95% CL upper limits on the cross section times branching ratio $\sigma(pp \to G^*_{\text{bulk}}) \times BR(G^*_{\text{bulk}} \to WW)$ as a function of the bulk RS graviton mass. For each mass point, $A \times \epsilon$ is also reported with the combined statistical and systematic uncertainty.
nates $(R, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as 
\[
\eta = -\ln \tan(\theta/2).
\]


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