Abstract

This note reports on a search for narrow high-mass resonances decaying into dilepton final states. The data, recorded by the ATLAS experiment in $pp$ collisions at $\sqrt{s} = 7$ TeV at the Large Hadron Collider, correspond to a total integrated luminosity of 4.9 (5.0) fb$^{-1}$ in the $e^+ e^-$ ($\mu^+ \mu^-$) channel. No statistically significant excess above the Standard Model expectation is observed, and upper limits are set at the 95% confidence level on the cross section times branching fraction of $Z'$ resonances and Randall-Sundrum gravitons decaying into dileptons as a function of the resonance mass. A lower limit of 2.21 TeV on the mass of the Sequential Standard Model $Z'$ boson is set. A Randall-Sundrum graviton with coupling $k/M_{Pl} = 0.1$ is excluded at 95% confidence level for masses below 2.16 TeV.
1 Introduction

This note describes a search for narrow high-mass resonances decaying into $e^+e^−$ or $μ^+μ^−$ pairs using 7 TeV $pp$ collision data recorded with the ATLAS detector [1] at the Large Hadron Collider (LHC). Such resonances, which are predicted by several extensions of the Standard Model (SM), include new heavy spin-1 neutral gauge bosons such as $Z'$ [2, 3, 4] and $Z^*$ [5], techni-mesons [6, 7, 8], as well as spin-2 Randall-Sundrum gravitons, $G^*$ [9].

The benchmark models considered for the $Z'$ are the Sequential Standard Model (SSM) [3], with the same couplings to fermions as the Z boson, and the $E_6$ Grand Unified symmetry group [2], broken into SU(5) and two additional U(1) groups, leading to new neutral gauge fields $ψ$ and $χ$. The particles associated with the additional fields can mix in a linear combination to form the $Z'$ candidate: $Z'(θ_{E_6}) = Z'_ψ \cos θ_{E_6} + Z'_χ \sin θ_{E_6}$, where $θ_{E_6}$ is the mixing angle between the two gauge bosons. The pattern of spontaneous symmetry breaking and the value of $θ_{E_6}$ determine the $Z'$ couplings to fermions; six choices of $θ_{E_6}$ [2, 3] lead to the specific $Z'$ states named $Z'_ψ, Z'_N, Z'_µ, Z'_τ, Z'_3$ and $Z'_4$.

Other models predict additional spatial dimensions as a possible explanation for the gap between the electroweak symmetry breaking scale and the gravitational energy scale. The Randall-Sundrum (RS) model [9] predicts excited Kaluza-Klein modes of the graviton, which appear as spin-2 resonances. These modes have a narrow intrinsic width when $k/\overline{M}_{Pl} < 0.1$, where $k$ is the spacetime curvature in the extra dimension, and $\overline{M}_{Pl} = M_{Pl}/\sqrt{8π}$ is the reduced Planck scale.

Previous searches have set direct and indirect constraints on the mass of the $Z'$ and $G^*$ resonances [10, 11]. The Tevatron experiments [12, 13] excluded a $Z'_SSM$ with a mass lower than 1.071 TeV [13]. Recent measurements by the ATLAS and CMS collaborations based on 1 fb$^{-1}$ of data excluded a $Z'_SSM$ with a mass lower than 1.83 TeV [14] and 1.94 TeV [15], respectively. In addition, indirect constraints from LEP [16, 17, 18, 19] have set a limit of 1.787 TeV [11] on the $Z'_SSM$. Constraints on the mass of the RS graviton have been set by the ATLAS [14, 20], CMS [15, 21], CDF [22] and D0 [23] collaborations. Assuming $k/\overline{M}_{Pl}=0.1$, CDF and D0 excluded graviton masses below 1.058 TeV and 1.050 TeV respectively, with the dielectron and diphoton channels combined; CMS excluded masses below 1.84 TeV with the diphoton channel only using 2 fb$^{-1}$ of data, and masses below 1.78 TeV with the dielectron plus dimuon channels using 1 fb$^{-1}$ of data; the ATLAS lower limit was 1.95 TeV with the combination of the dielectron and dimuon channels (using 1 fb$^{-1}$ of data) and of the diphoton channel (using 2 fb$^{-1}$ of data).

2 ATLAS detector, data selection and trigger

The ATLAS detector consists of an inner detector surrounded by a 2 T superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field. Charged particle tracks in the pseudorapidity$^1$ range $|η| < 2.5$ are reconstructed with the inner detector, which consists of silicon pixel, silicon strip, and transition radiation detectors. The superconducting solenoid is surrounded by a hermetic calorimeter that covers $|η| < 4.9$. For $|η| < 2.5$, the electromagnetic calorimeter is finely segmented and plays an important role in electron identification. Outside the calorimeter, air-core toroids provide the magnetic field for the muon spectrometer. Three stations of precision drift tubes (with cathode strip chambers for the innermost station for $|η| > 2.0$) provide an accurate measurement of the muon track curvature in the range $|θ| < 2.7$. Resistive-plate and thin-gap chambers provide muon triggering capability in the range $|η| < 2.4$.

The data sample used in this analysis, recorded during 2011, corresponds to a total integrated luminosity of 4.9 (5.0) fb$^{-1}$ in the dielectron (dimuon) channel. The trigger used in the electron channel

$^1$ATLAS uses a right-handed coordinate system with the $z$-axis along the beam pipe. The $x$-axis points to the center of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle. The pseudorapidity is defined in terms of the polar angle $θ$ as $η = −\ln \tan (θ/2)$. 
requires at least two electromagnetic clusters in the calorimeter, each with a transverse energy of at least 20 GeV. It was measured in data to be 99% efficient with respect to the event selection described below for dilepton masses above 100 GeV. For the muon channel, the trigger requires the presence of a single muon with a transverse momentum ($p_T$) threshold of 22 GeV; the single-muon trigger efficiency was measured in data to be 85% in the barrel for most of the data-taking period, and 86% in the endcaps for the entire dataset. The muon trigger efficiency is lower than the electron trigger efficiency because of the lower geometrical acceptance of the muon trigger detectors.

3 Event selection

The triggered events are required to have a primary vertex with at least three associated charged particle tracks with $p_T > 0.4$ GeV.

In the dielectron channel, two electron candidates are required with transverse energy $E_T > 25$ GeV and $|\eta| < 2.47$; the transition region $1.37 \leq |\eta| \leq 1.52$ between the barrel and the endcap calorimeters is excluded. Electron candidates are formed from clusters of cells reconstructed in the electromagnetic calorimeter associated with a charged particle track in the inner detector. Criteria on the transverse shower shape, the longitudinal leakage into the hadronic calorimeter, and the association with an inner detector track are applied to the cluster to define a so-called Medium electron [24]. The electron energy is obtained from the calorimeter measurement and its direction from the associated track. The calorimeter energy resolution is dominated at large $E_E$ by a constant term which is 1.2% in the barrel and 1.8% in the endcaps. A hit in the first active pixel layer is required to suppress background from photon conversions. To further suppress background from QCD multijet production, the higher $E_T$ electron must be isolated, requiring that $\Sigma E_T(\Delta R < 0.2) < 7$ GeV, where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ and $\Sigma E_T(\Delta R < 0.2)$ is the sum of the transverse energy deposition in the calorimeter around the electron direction. The core of the electron energy deposition is excluded and the sum is corrected for transverse shower leakage and pile-up from additional $pp$ collisions. Since the resolution on the dielectron mass is dominated by the calorimeter energy measurements, the two electron candidates are not required to have opposite charge, which to minimizes the losses due to charge mis-identification. For these selection criteria, the total signal acceptance for a $Z' \rightarrow e^+e^- (G^* \rightarrow e^+e^-)$ of mass 2 TeV is 71% (72%), approximately independent of mass above 600 GeV. These numbers account for the acceptance of all selection criteria and efficiencies, and reflect the differences in lepton angular distributions due to spin.

In the dimuon channel, two muon candidates of opposite charge are required, each satisfying $p_T > 25$ GeV. Muon tracks are reconstructed independently in both the inner detector and muon spectrometer, and their momenta are determined from a combined fit to these two measurements. To optimize the momentum resolution, each muon candidate is required to pass quality cuts in both the inner detector and the muon spectrometer. Most muons used in the analysis have at least three hits in each of the inner, middle, and outer layers of the muon spectrometer. To increase the reconstruction efficiency, muons reconstructed in only two layers of the muon spectrometer are also included in the search if they are in regions where the toroidal field is strong and the detector well aligned. Muons with hits in both the barrel and the endcap regions are discarded because of residual misalignment between these two parts of the muon spectrometer. The effects of misalignments and intrinsic position resolution are included in the simulation by applying a smearing to $q/p_T$, which reproduces the momentum resolution of the data. The $p_T$ resolution at 1 TeV for muons reconstructed combining the measurements in the inner detector and muon spectrometer ranges from about 10% to 25%.

To suppress background from cosmic rays, the $z$ position of the primary vertex is required to be within 200 mm of the centre of the detector, and the muon tracks are required to have a transverse impact parameter $|d_0| < 0.2$ mm and a distance along the beam-line to the primary vertex below 1 mm. To reduce background from jets, each muon is required to be isolated such that $\Sigma p_T(\Delta R < 0.3)/p_T(\mu) < 0.05$, and the endcap regions are discarded because of residual misalignment between these two parts of the detector.
where only tracks with $p_T > 1$ GeV, and not the muon track, enter the sum. The total signal acceptance is 43% (47%) for a $Z' \rightarrow \mu^+ \mu^- (G^* \rightarrow \mu^+ \mu^-)$ of mass 2 TeV, including 4% from events with one muon reconstructed in only two layers of the muon spectrometer. The lower acceptance compared to the electron channel is due to the stringent requirements on the muon selection criteria to improve the $p_T$ resolution.

4 Signal and background simulation

For both channels, the dominant and irreducible background is due to the $Z/\gamma^*$ (Drell-Yan) process, characterized by the same final state as the signal. Small contributions from $t\bar{t}$ and diboson ($WW$, $WZ$ and $ZZ$) production are also present in both channels. Semileptonic decays of $b$ and $c$ quarks in the dimuon sample and a mixture of photon conversions, semileptonic heavy quark decays, and hadrons misidentified as electrons in the $e^+e^-$ sample are backgrounds that are referred to below as QCD background or QCD multijet. Jets accompanying $W$ bosons ($W + \text{jets}$) may similarly produce lepton candidates in addition to the one from $W \rightarrow \ell \nu$ decay.

The expected signal and backgrounds, with the exception of the QCD multijet background, are evaluated with simulated samples and rescaled using the most precise available cross-section predictions. The $Z'$, $G^*$ and $Z/\gamma^*$ processes are generated with Pythia 6.425 [25] using MRST2007lomod [26] parton distribution functions (PDFs). Interference between the $Z/\gamma^*$ process and the $Z'$ resonance is expected to be small and therefore neglected. The diboson processes are generated with HERWIG 6.510 [27] using MRST2007lomod PDFs. The $W + \text{jets}$ background is generated with ALPGEN [28] using CTEQ6L1 [29] PDFs and the $t\bar{t}$ background with MC@NLO 3.41 [30] using CTEQ66 [31] PDFs. JIMMY 4.31 [32] is used for both processes to describe multiple parton interactions and HERWIG to describe the remaining underlying event and parton showers. Final-state photon radiation is handled with PHOTOS [33]. The samples are processed through a full ATLAS detector simulation [34] based on GEANT4 [35].

The $Z/\gamma^*$ cross section is calculated at next-to-next-to-leading order (NNLO) using PHOZPR [36] with MSTW2008 PDFs [37]. The ratio of this cross section to the leading-order cross section is used to determine a mass-dependent QCD K-factor which is applied to the results of the leading-order simulations. The same QCD K-factor is applied to the $Z'$ signal. It is 0.91 at 2 TeV and slowly increases towards lower masses. A different K-factor is applied to the $G^*$ signal. The calculated values vary between 1.6 and 1.8, depending on the graviton mass and on $k/M_{Pl}$ [38]; in practice, 1.75 is used above 750 GeV. Electroweak corrections including virtual heavy gauge-boson loops are calculated using HORACE [39, 40], yielding an effective electroweak K-factor which is only applied to the Drell-Yan background.

The $t\bar{t}$ cross section is predicted at approximately NNLO, with 10% uncertainty [41, 42]. The diboson cross sections are calculated at next-to-leading order (NLO) using MCFM [43]; the $W$ inclusive cross section from ALPGEN, including all possible final states with and without jets, is renormalised to the NNLO calculation of FEWZ [44]; these cross sections are assigned a 5% uncertainty each, from scale, PDF and $\alpha_s$ variations. In the dimuon channel, the $W + \text{jets}$ Monte Carlo yield is assigned an overall 30% systematic uncertainty from the sum of the cross sections of the ALPGEN samples with at least one parton with $E_T > 20$ GeV accompanying the $W$ boson. In the electron channel, this uncertainty is replaced by a data-driven uncertainty, as explained below.

The QCD multijet background in the dielectron sample is estimated from data using a “reversed electron identification” technique. Data with both electron candidates failing a subset of identification criteria (chosen not to affect kinematic distributions) are used to determine the QCD background distribution versus $m_{ee}$. Contributions from other backgrounds are estimated from simulated samples and subtracted. An empirical function, $f(x) = p_1 x^{p_2} + p_3 \log x$, fitted in the 110 - 800 GeV range, extrapolates the distribution to high $m_{ee}$. This QCD background shape and the sum of the $Z/\gamma^*$, diboson, $t\bar{t}$ and $W + \text{jets}$ backgrounds are fitted to the observed $m_{ee}$ distribution in a control region to determine the
normalization of the QCD contribution. This method provides the central QCD multijet estimate, and two other techniques are used to assign a systematic uncertainty. One is another shape-fitting procedure, this time on two-dimensional (leading and sub-leading electron) isolation distributions in bins of \( m_{ee} \). A third independent data-driven QCD multijet estimate is based on fake rates computed from jet-enriched samples obtained from jet triggers or from the electromagnetic-cluster trigger used for the signal. These estimates are compatible with the central method. Since these alternative methods provide combined estimates of the QCD and \( W + \text{jets} \) contributions, the central QCD multijet determination is summed with the Monte Carlo predicted \( W + \text{jets} \) yield for the comparison. The largest difference with the alternative methods is assigned as the global systematic uncertainty to the QCD plus \( W + \text{jets} \) yield in the dielectron channel.

The QCD background in the dimuon sample is evaluated from data using the reversed isolation method described in [45], based on the track isolation variable \( \Sigma p_T(\Delta R < 0.3)/p_T \).

The QCD and \( W + \text{jets} \) backgrounds are small for the electron channel and very small for the muon channel. Backgrounds from cosmic rays are negligible.

## 5 Results

The observed invariant mass distributions are compared to the SM expectation, given by the Monte Carlo simulation for all components except QCD multijet, which is taken from the data. For this purpose, the Drell-Yan, \( t\bar{t}, \) diboson and \( W + \text{jets} \) backgrounds from Monte Carlo simulation are scaled according to their respective cross sections and added to the data-driven QCD background. The simulated backgrounds are then rescaled so that the sum matches the observed number of data events in the normalization region, defined as the 70 - 110 GeV mass interval. The scaling factor is within 1.6% of unity. The number of events in the normalization region is 1237292 in the dielectron channel, and 985004 in the dimuon channel; the Drell-Yan component amounts to more than 99% of the total in both cases. The advantage of this approach is that the uncertainty on the integrated luminosity, and any mass-independent uncertainties on efficiencies, cancel between the \( Z' (G^+) \) and the Z boson in the limit computation presented below.

<table>
<thead>
<tr>
<th>( m_{ee} ) [GeV]</th>
<th>110 - 200</th>
<th>200 - 400</th>
<th>400 - 800</th>
<th>800 - 1200</th>
<th>1200 - 3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z/\gamma^* )</td>
<td>26300 ± 800</td>
<td>3080 ± 120</td>
<td>265 ± 14</td>
<td>12.2 ± 0.9</td>
<td>1.46 ± 0.18</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>1300 ± 70</td>
<td>403 ± 26</td>
<td>28 ± 4</td>
<td>1.0 ± 0.8</td>
<td>0.021 ± 0.021</td>
</tr>
<tr>
<td>Diboson</td>
<td>440 ± 17</td>
<td>147 ± 8</td>
<td>14.7 ± 2.2</td>
<td>1.0 ± 0.4</td>
<td>0.06 ± 0.06</td>
</tr>
<tr>
<td>( W + \text{jets} ) and QCD</td>
<td>2000 ± 400</td>
<td>420 ± 160</td>
<td>40 ± 40</td>
<td>1.8 ± 1.2</td>
<td>0.11 ± 0.08</td>
</tr>
<tr>
<td>Total</td>
<td>30000 ± 900</td>
<td>4050 ± 200</td>
<td>340 ± 40</td>
<td>16.0 ± 1.8</td>
<td>1.64 ± 0.21</td>
</tr>
<tr>
<td>Data</td>
<td>29993</td>
<td>4038</td>
<td>358</td>
<td>17</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1: The expected and observed numbers of events in the dielectron channel for various \( m_{ee} \) bins. The expected numbers are shown separately for each of the background components discussed in the text. The errors quoted include both statistical and systematic uncertainties.

Figure 1 presents the invariant mass (\( m_{\ell\ell} \)) distribution for the dielectron (top) and dimuon (bottom) final states after final selection. Figure 1 also displays the expected \( Z'_\text{SSM} \) signal for three mass hypotheses. Tables 1 and 2 show the number of data events and the estimated backgrounds in bins of reconstructed dielectron and dimuon invariant mass above 110 GeV. The dilepton invariant mass distributions are well
Table 2: The expected and observed numbers of events in the dimuon channel for various $m_{\mu^+\mu^-}$ bins. The expected numbers are shown separately for each of the background components discussed in the text. The errors quoted include both statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>$m_{\mu^+\mu^-}$ [GeV]</th>
<th>110 - 200</th>
<th>200 - 400</th>
<th>400 - 800</th>
<th>800 - 1200</th>
<th>1200 - 3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'/\gamma'$</td>
<td>21000 ± 900</td>
<td>2040 ± 90</td>
<td>174 ± 9</td>
<td>7.3 ± 0.5</td>
<td>0.90 ± 0.11</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>830 ± 80</td>
<td>254 ± 24</td>
<td>20.0 ± 2.1</td>
<td>0.59 ± 0.15</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Diboson</td>
<td>283 ± 15</td>
<td>98 ± 5</td>
<td>12.7 ± 1.0</td>
<td>0.83 ± 0.24</td>
<td>0.022 ± 0.028</td>
</tr>
<tr>
<td>$(W + \text{jets})$ and QCD</td>
<td>7 ± 4</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
<td>&lt; 0.05</td>
<td>&lt; 0.005</td>
</tr>
<tr>
<td>Total</td>
<td>22100 ± 900</td>
<td>2400 ± 90</td>
<td>206 ± 9</td>
<td>8.7 ± 0.6</td>
<td>0.92 ± 0.11</td>
</tr>
<tr>
<td>Data</td>
<td>21941</td>
<td>2293</td>
<td>197</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

The invariant mass distribution of the data is compared to templates of the background and of signals with pole masses in the search region, which extends from 0.13 to 3.0 TeV [14, 45]. A likelihood function is defined as the product of the Poisson probabilities over all mass bins in the search region. The Poisson probability in each bin is evaluated for the observed number of data events given the background and signal template expectation. The total signal acceptance as a function of mass is propagated into the expectation, and systematic uncertainties are incorporated in the likelihood via nuisance parameters [46].

The significance of a signal is summarized by a $p$-value, the probability of observing an excess at least as signal-like as the one observed in data, in the absence of signal. The outcome of the search is ranked against pseudo-experiments using a likelihood ratio, which is scanned as a function of $Z'$ cross section and $m_{Z'}$ over the full considered mass range. The data are consistent with the SM hypothesis, with global $p$-values of 13% and 82% for the dielectron and dimuon channels respectively.

In addition, the agreement between data and expectation is studied by computing the significance of the difference in each mass bin, with statistical and systematic errors taken into account [47]; the result is displayed in Figure 2. The largest positive local significance is ∼2.5σ in the electron channel and less than 2σ in the muon channel, and the largest negative significance is about −3σ in both channels.

Given the absence of any significant signal, an upper limit on the number of signal events is determined at the 95% confidence level (C.L.) using a Bayesian approach [46] with a flat, positive prior on the signal cross section.

6 Systematic uncertainties

Systematic uncertainties include the normalization to the $Z$-peak, PDF, QCD and electroweak corrections, as well as the trigger, reconstruction and identification efficiencies. For each source of uncertainty, the correlations across bins, as well as the correlations between signal and background, are taken into account.

Since the total background is normalized to the data in the region of the $Z \rightarrow \ell^+\ell^-$ mass peak, the residual systematic uncertainties (with the exception of the $Z$ cross section uncertainty) are small at the $Z$ pole and grow at higher mass. The dominant uncertainties are theoretical. The overall uncertainty due to PDF, $\alpha_S$, and scale variations is estimated to be 20% at 2 TeV, where the PDF contribution is dominant. The $\alpha_S$ and PDF uncertainties are evaluated using the MSTW2008NNLO eigenvector PDF sets and the PDF sets corresponding to variations of $\alpha_S$, at the 90% C.L. The spread of the variations covers the
Figure 1: The dielectron (top) and dimuon (bottom) invariant mass ($m_{\ell\ell}$) distribution after final selection, compared to the stacked sum of all expected backgrounds, with three example $Z'_{\text{SSM}}$ signals overlaid. The bin width is constant in $\log m_{\ell\ell}$.
Figure 2: The dielectron (left) and dimuon (right) invariant mass ($m_{\ell\ell}$) distributions after final selection, compared to the expected background. The bin width is the same as in Figure 1. The bottom part of each histogram shows the significance of the difference between data and expectation in each bin.

difference between the central values obtained with the CTEQ and MSTW PDF sets. The scale uncertainties are estimated by varying the renormalization ($\mu_R$) and factorization ($\mu_F$) scales independently up and down by a factor of two, but with the constraint $0.5 \leq \mu_F/\mu_R \leq 2$. The resulting maximum variations are taken as the uncertainties. Additionally, a systematic uncertainty of 4.5% is attributed to electroweak corrections [45].

The uncertainty on the $Z/\gamma^*$ cross section is 5%, which is applied as a systematic uncertainty on the signal yield. It replaces the uncertainty on the integrated luminosity due to the normalization to the data under the $Z \to \ell^+\ell^-$ mass peak.

The experimental systematic effects due to resolution and inefficiencies at high mass were also studied. The uncertainty on the energy resolution is measured to be negligible in the electron channel. In the muon channel, the uncertainty on the momentum resolution is due to residual misalignments and intrinsic position uncertainties in the muon spectrometer that propagate to a change in the observed width of the $Z'$ ($G^*$) line-shape. The simulation was adjusted to reproduce the data at high muon momentum. The residual uncertainty translates into an event yield uncertainty of less than 3%. The combined uncertainty on the muon trigger and reconstruction efficiency is estimated to be 6% at 2 TeV. This uncertainty is dominated by a conservative estimate of the impact of large energy loss from muon bremsstrahlung in the calorimeter on the muon reconstruction performance in the muon spectrometer. In the electron channel, a systematic uncertainty of 2% at 2 TeV is estimated for a possible identification inefficiency caused by the isolation requirement.

The dominant systematic uncertainties are summarized in Table 3. Uncertainties of 3% and less are neglected in the limit setting procedure described below, and no theory uncertainties are applied to the $Z'$ or $G^*$ signal.

7 Interpretation

The limit on the number of produced $Z'$ ($G^*$) events is converted into a limit on cross section times branching fraction $\sigma B$ by scaling with the observed number of $Z$ boson events and the theoretical value
Table 3: Summary of systematic uncertainties on the expected numbers of events at $m_{\ell^+\ell^-} = 2$ TeV. NA indicates that the uncertainty is not applicable, and "-" denotes a negligible entry.

<table>
<thead>
<tr>
<th>Source</th>
<th>Dielectrons</th>
<th></th>
<th>Dimuons</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>Background</td>
<td>Signal</td>
<td>Background</td>
</tr>
<tr>
<td>Normalization</td>
<td>5%</td>
<td>NA</td>
<td>5%</td>
<td>NA</td>
</tr>
<tr>
<td>PDF/\alpha_s/scale</td>
<td>NA</td>
<td>20%</td>
<td>NA</td>
<td>20%</td>
</tr>
<tr>
<td>Electroweak corrections</td>
<td>NA</td>
<td>4.5%</td>
<td>NA</td>
<td>4.5%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>-</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>W + jets and QCD background</td>
<td>NA</td>
<td>3.5%</td>
<td>NA</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>5%</td>
<td>21%</td>
<td>8%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Figure 3: The expected and observed 95% C.L. upper limits on $\sigma B$ as a function of mass for $Z'$ (left) and $G^*$ (right) models for the electron channel. The thickness of the $Z'_\text{SSM}$ (left) and the $G^*$ for $k/M_{Pl}=0.1$ (right) theory curves illustrate the theoretical uncertainties.

The expected exclusion limits are determined using pseudo-experiments containing only SM processes, by evaluating the 95% C.L. upper limits for each pseudo-experiment for each fixed value of $m_{Z'}$ ($m_{G^*}$). The median of the distribution of limits represents the expected limit. The ensemble of limits is used to find the 68% and 95% envelopes of the expected limits as a function of $m_{Z'}$ ($m_{G^*}$).

Figure 3 shows the 95% C.L. observed and expected exclusion limits on $\sigma B(Z' \to e^+ e^-)$ and on $\sigma B(G^* \to e^+ e^-)$. It also shows the theoretical cross section times branching fraction for the $Z'_\text{SSM}$ and for $E_6$-motivated $Z'$ models with the lowest and highest $\sigma B$. The same information is shown in Figure 4 for the muon channel. Figure 5 shows the combined dielectron and dimuon 95% C.L. observed and expected exclusion limits on $\sigma B(Z' \to ll)$ and on $\sigma B(G^* \to ll)$.

Figure 6 shows the ratio between the observed limit and the expected cross section times branching fraction as a function of the $Z'$ mass for the SSM model, for previous results at the Tevatron and in ATLAS, together with the results presented here. Mass limits obtained for the $Z'_\text{SSM}$ and $G^*$ (with $k/M_{Pl}=0.1$) are displayed in Table 4. The combined mass limits on the $E_6$-motivated models and the $G^*$ with various couplings are given in Table 5.

Figures 7 and 8 show event displays of the dielectron and dimuon candidates reconstructed with the highest invariant mass.
Figure 4: The expected and observed 95% C.L. upper limits on $\sigma B$ as a function of mass for $Z'$ (left) and $G^*$ (right) models for the muon channel. The thickness of the $Z'_\text{SSM}$ (left) and the $G^*$ for $k/\overline{M}_{Pl}=0.1$ (right) theory curves illustrate the theoretical uncertainties.

Table 4: The observed (expected) 95% C.L. mass lower limits in TeV on $Z'_\text{SSM}$ resonance and $G^*$ graviton (with $k/\overline{M}_{Pl}=0.1$), for the dielectron and dimuon channels separately and for their combination.

<table>
<thead>
<tr>
<th>Model</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$\ell^+\ell^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_\text{SSM}$</td>
<td>2.07 (2.14)</td>
<td>1.99 (2.01)</td>
<td>2.21 (2.26)</td>
</tr>
<tr>
<td>$G^*$</td>
<td>2.03 (2.05)</td>
<td>1.90 (1.92)</td>
<td>2.16 (2.17)</td>
</tr>
</tbody>
</table>

Table 5: The observed 95% C.L. lower limits on the masses of E$_6$-motivated $Z'$ bosons and RS gravitons $G^*$ for various values of the coupling $k/\overline{M}_{Pl}$. Both lepton channels are combined.

<table>
<thead>
<tr>
<th>Model/Coupling</th>
<th>$E_6$ $Z'$ models</th>
<th>RS graviton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass limit [TeV]</td>
<td>$Z'_0$</td>
<td>$Z'_N$</td>
</tr>
<tr>
<td></td>
<td>1.76</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>1.45</td>
</tr>
</tbody>
</table>

8 Conclusion

The ATLAS detector has been used to search for narrow, high-mass resonances in the dilepton invariant mass spectrum. Proton-proton collision data with integrated luminosities of 4.9 (5.0) fb$^{-1}$ in the dielectron (dimuon) channel have been used. The observed invariant mass spectra are consistent with the SM expectations. Limits are set on the cross section times branching fraction $\sigma B$. The resulting lower limits on the mass of a new resonance are 2.21 TeV for a Sequential Standard Model $Z'$, 1.76–1.96 TeV for various $E_6$-motivated $Z'$ bosons and 0.91 TeV–2.16 TeV for a Randall-Sundrum graviton with couplings $(k/\overline{M}_{Pl})$ in the range 0.01–0.1.
Figure 5: The expected and observed 95% C.L. upper limits on $\sigma B$ as a function of mass for $Z'$ (top) and $G^*$ (bottom) models. Both results show the combination of the electron and muon channels. The thickness of the $Z'_{SSM}$ (top) and the $G^*$ for $k/M_{Pl}=0.1$ (bottom) theory curves illustrate the theoretical uncertainties.
Figure 6: The ratio between the observed limit and the predicted cross section times branching ratio as a function of the $Z'$ mass for the SSM model. The results are shown for the most recent limits from the Tevatron [13, 12], the latest ATLAS published data [14] and the analysis presented here. No uncertainties on the theoretical prediction are applied.

References


Figure 7: Event display for the dielectron candidate with the highest reconstructed invariant mass ($m_{ee}=1.66$ TeV). Both electrons are in the calorimeter end-caps; their tracks are shown in green. The electron with highest transverse energy has an $E_T$ of 329 GeV and an $(\eta, \phi)$ of (2.00, 1.02). The subleading electron has an $E_T$ of 217 GeV and an $(\eta, \phi)$ of (-1.60, -1.83). The event missing transverse energy is 26 GeV.
Figure 8: Event display for the dimuon candidate with the highest reconstructed invariant mass ($m_{\mu\mu}=1.25$ TeV). The muon with highest momentum has a $p_T$ of 648 GeV and an ($\eta$, $\phi$) of (-0.75, 0.49). The subleading muon has a $p_T$ of 583 GeV and an ($\eta$, $\phi$) of (-0.36, -2.60). The event missing transverse energy is 67 GeV, with a $\phi_{MET}$ of -2.83.


[23] D0 Collaboration, Search for Randall-Sundrum gravitons in the dielectron and diphoton final states with 5.4 fb\(^{-1}\) of data from pp\(\bar{p}\) collisions at \(\sqrt{s} = 1.96\) TeV, Phys. Rev. Lett. 104 (2010) 241802.


[38] M. C. Kumar, P. Mathews, and V. Ravindran - Private Communication.


