Search for high-mass dilepton resonances in 6.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment

The ATLAS collaboration

Abstract

The ATLAS detector is used to search for heavy neutral gauge bosons ($Z'$) decaying to an electron-positron pair or a muon-antimuon pair. Results are presented based on the analysis of $pp$ collisions at a center-of-mass energy of 8 TeV corresponding to an integrated luminosity of approximately $5.9\ (e^+e^-) / 6.1\ (\mu^+\mu^-)\ fb^{-1}$. A $Z'$ with Standard Model $Z$ couplings to fermions is excluded at 95\% C.L. for masses below 2.39 TeV in the electron channel, 2.19 TeV in the muon channel, and 2.49 TeV in the two channels combined. The result is also interpreted in a Grand Unification model based on the $E_6$ gauge group.
1 Introduction

A search for high-mass resonances decaying into $e^+e^-$ or $\mu^+\mu^-$ pairs is presented based on an analysis of 8 TeV LHC pp collision data recorded with the ATLAS detector [1]. Among the possibilities for such resonances, this note focuses on new heavy neutral gauge bosons $Z'$ [2–4]; other hypothetical states like a Randall-Sundrum spin-2 graviton [5] or a spin-1 techni-meson [6–9] are not discussed here, though this search is also sensitive to them.

The benchmark model for $Z'$ bosons is the Sequential Standard Model (SSM) [2], in which the $Z'$ ($Z'_{\text{SSM}}$) has the same couplings to fermions as the $Z$ boson. A more theoretically-motivated model is a Grand Unification model in which the $E_6$ gauge group is broken into SU(5) and two additional $U(1)$ groups [10]. The lightest linear combination of the corresponding two neutral gauge bosons, $Z'_\phi$ and $Z'_\chi$, is considered the $Z'$ candidate: $Z'(\theta_{E_6}) = Z'_\phi \cos \theta_{E_6} + Z'_\chi \sin \theta_{E_6}$, where $0 \leq \theta_{E_6} < \pi$ is the mixing angle between the two gauge bosons. The pattern of spontaneous symmetry breaking and the value of $\theta_{E_6}$ determine the $Z'$ couplings to fermions; six different models [2, 10] lead to the specific $Z'$ states named $Z'_\chi, Z'_N, Z'_p, Z'_j, Z'_S$ and $Z'_\chi$, respectively. In this search, the resonances are assumed to have a narrow intrinsic width, comparable to the contribution from the detector mass resolution. The expected intrinsic width of the $Z'_{\text{SSM}}$ as a fraction of the mass is 3.1%, while for any $E_6$ model the intrinsic width is predicted to be between 0.5% and 1.3% [11].

Previous results from ATLAS using 2011 data at $\sqrt{s} = 7$ TeV in this search exclude a $Z'_{\text{SSM}}$ of 2.21 TeV at 95% C.L. [12]. The corresponding mass limit from CMS is 2.33 TeV [13] which has recently been extended to 2.59 TeV by including about 4 fb$^{-1}$ of 2012 data at $\sqrt{s} = 8$ TeV [14]. This note follows the analysis strategy presented in Ref. [12] but uses 6.1 fb$^{-1}$ of $\sqrt{s} = 8$ TeV ATLAS data from 2012. At this higher center-of-mass energy, the cross section for $Z'$ increases by roughly a factor of two for $M_{Z'} = 2.5$ TeV. In addition, the analysis benefits from substantial improvements to the electron reconstruction and identification, with respect to the 2011 analysis, to maintain good performance in high pile-up conditions.

2 ATLAS detector

The data used for this analysis were collected in 2012 using the ATLAS detector [1]. It consists of an inner tracking detector system (ID) surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer (MS). Charged particles in the pseudorapidity range $|\eta| < 2.5$ are reconstructed with the inner detector, which consists of layers of silicon pixel and strip detectors and a straw-tube transition-radiation tracker, the latter extending to $|\eta| < 2.0$. The ID is immersed in a homogeneous 2 T magnetic field provided by a superconducting solenoid. The superconducting solenoid is surrounded by a hermetic calorimeter that covers $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers using lead-liquid argon sampling for the electromagnetic compartment followed by a hadronic compartment which is based on iron-scintillating tiles sampling for $|\eta| < 1.7$ and on liquid argon sampling with copper or tungsten absorbers for $|\eta| > 1.5$. For $|\eta| < 2.5$, 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 sets of precision drift tubes and cathode strip chambers provide an accurate measurement of the muon track curvature in the region $|\eta| < 2.7$. Resistive-plate and thin-gap chambers provide muon triggering capability up to $|\eta| < 2.4$.

\[^{1}\text{ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the }z\text{-axis along the beam pipe. The }x\text{-axis points from the interaction point to the center of the LHC ring, and the }y\text{-axis points upward. Cylindrical coordinates (}r, \phi\text{) are used in the transverse plane, }\phi\text{ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle }\theta\text{ as }\eta = -\ln \tan(\theta/2).\]
3 Event selection

All candidate events must satisfy data-quality requirements, i.e. proper functioning of the ID, MS, solenoid, toroid, calorimeter and trigger subsystems, as well as being recorded during LHC stable beam periods. Each event must have at least one primary vertex with more than two tracks.

In the $e^+e^-$ channel, the events are required to have been triggered by a diphoton trigger with transverse energy threshold $E_T > 35$ GeV and $E_T > 25$ GeV for the leading and subleading candidate, respectively. The diphoton trigger is preferred over the dielectron trigger as the lack of requirements on the electron track is advantageous in the background-determination method. Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter that are associated to ID tracks. For the 2012 LHC data taking, the electron reconstruction algorithm has been improved with respect to 2011. The ATLAS track pattern recognition and global $\chi^2$ fit were updated to account for energy losses due to bremsstrahlung, and the track-to-cluster matching algorithm was improved to be less sensitive to bremsstrahlung losses. Electron candidates must have a well-reconstructed ID track and the cluster should satisfy a set of identification criteria [15], which were optimized to maintain good performance in high pile-up conditions and to take advantage of the new electron reconstruction. The identification criteria require the shower profiles to be consistent with those expected for electromagnetic showers as well as a minimum requirement on the amount of transition radiation. To suppress background from jets misidentified as electrons, the electron candidate with the higher $E_T$ is required to be isolated by requiring $\Sigma E_T(\Delta R < 0.2) < 7$ 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 energies around the electron direction in a cone of $\Delta R < 0.2$. The sum excludes the core of the electron energy deposition and is corrected for transverse shower leakage and pile-up from additional $pp$ collisions. The electron energy is obtained from the calorimeter measurements and its direction from the associated track. A hit in the first layer of the pixel detector is required (if an active pixel layer is traversed) to suppress background from photon conversions. At least two electron candidates with transverse energy $E_T > 40$ GeV and $E_T > 30$ GeV within $|\eta| < 2.47$ are required. The region $1.37 \leq |\eta| \leq 1.52$ is excluded because it corresponds to a transition region between the barrel and endcap calorimeters which has degraded energy resolution. Charge balance between the two electron candidates is not required because of possible charge mis-identification either due to bremsstrahlung or to the limited momentum resolution of the inner detector at very high transverse momentum ($p_T$). Using these selection criteria, the overall event acceptance including efficiency for a $Z' \rightarrow e^+e^-$ of mass 2 TeV is 70%, as determined from simulation.

In the $\mu^+\mu^-$ channel, the events are required to have been triggered by a single-muon trigger that uses combined tracking in the ID and MS. The trigger requires a transverse momentum of $p_T > 24$ GeV. The event is selected if it contains at least two muons within the trigger acceptance of $|\eta| < 2.4$. The muon candidates must be of opposite charge and each have $p_T > 25$ GeV. Muon tracks are reconstructed independently in both the inner detector and muon spectrometer. The momentum is taken from a combined fit to the measurements from both subsystems. To obtain optimal momentum resolution, the muons used in this analysis are required to have at least three precision hits (hits in the bending plane) in each of the inner, middle, and outer precision detectors of the muon system, and at least one hit in the non-bending plane. To suppress background from cosmic rays, the muons are also required to satisfy selections on the transverse impact parameter, $|d_0| < 0.2$ mm, and the coordinate with respect to the primary vertex (PV), $|z_0 - z(PV)| < 1$ mm. To reduce the background from jets, each muon is required to be isolated such that $\Sigma p_T(\Delta R < 0.3)/p_T(\mu) < 0.05$, where $\Sigma p_T(\Delta R < 0.3)$ is the sum of the $p_T$ of the other tracks in a cone $\Delta R < 0.3$ around the direction of the muon. The overall event acceptance is 39% for a $Z' \rightarrow \mu^+\mu^-$ of mass 2 TeV. The primary reason for the lower acceptance compared to the electron channel is the requirement that hits be observed in all three layers of muon chambers, which reduces coverage in some regions of $\eta$. 

2
4 Backgrounds

For both channels, the dominant and irreducible background is the $Z/\gamma^*$ (Drell-Yan) process. In the $e^+e^-$ channel, the next largest background arises from QCD multijet production including heavy flavor quarks and $\gamma + \text{jet}$ production, referred to below as dijet background. Other important backgrounds are $t\bar{t}$, $W + \text{jets}$ and diboson ($WW$, $WZ$ and $ZZ$) production. In the $\mu^+\mu^-$ channel, in order of dominance the backgrounds are Drell-Yan production, followed by $t\bar{t}$ and diboson production; the dijet and $W + \text{jets}$ backgrounds are negligible.

Expected signal and backgrounds, with the exception of the dijet background, are evaluated with simulated samples and normalized with respect to one another using the highest-order available cross-section predictions. The $Z'$ signal processes are derived using a Pythia 8 [16] Drell-Yan sample, generated using MSTW2008LO [17] parton distribution functions (PDF), by reweighting the sample to the desired invariant-mass shape.

An additional Drell-Yan sample for background modeling as well as inclusive $W$ and diboson samples are generated at next-to-leading order (NLO) using Powheg [18] with Pythia 8 and the CT10 PDF [19]. The $t\bar{t}$ background is modeled with MC@NLO [20] with Herwig [21, 22] using the CT10 PDF. For all samples, the final-state photon radiation is handled by PHOTOS [23] and the interaction of particles and the response of the detector are modeled using a full ATLAS detector simulation [24] based on Geant4 [25].

The $Z/\gamma^*$ cross section is calculated at next-to-next-to-leading order (NNLO) using ProZvr [26] with MSTW2008 parton distribution functions [17] with an uncertainty of 5%. The ratio of this cross section to the leading-order cross section (or next-to-leading order in the case of Powheg) is used to determine a mass-dependent QCD K-factor. Higher order weak corrections (beyond the photon radiation included in the simulation) are calculated using Horace [27, 28], yielding a weak K-factor due to virtual heavy gauge-boson loops. The weak K-factor is $\approx 0.925$ for a dilepton mass of 2 TeV. The weak K-factor is not applied to the $Z'$ signal since it is not universal, but depends on the unknown coupling of the $W$ and $Z$ bosons to the $Z'$ boson.

The diboson cross section is known to NLO with an uncertainty of 5%. The $W + \text{jets}$ cross section is calculated at NLO, and rescaled to the inclusive NNLO calculation resulting in a 28% uncertainty when at least one parton with $E_T > 20$ GeV accompanies the $W$ boson. The $t\bar{t}$ cross section is predicted at approximate-NNLO, with 8.3% uncertainty [29–31]. Cross-section uncertainties are estimated from PDF error sets and from variation of renormalization and factorization scales in the cross-section calculation.

To estimate the dijet background in the $e^+e^-$ sample, the “reversed electron identification” technique is used [32]. A sample of events in which both electron candidates fail the requirement on the matching between track and cluster is used to determine the shape of the dijet background as a function of the invariant mass $m_{ee}$, corrected for Drell-Yan, $W + \text{jets}$, $t\bar{t}$ and diboson contributions using Monte Carlo. The mass distributions of the dijet and non-dijet backgrounds are fit to the data in the $80 < m_{ee} < 200$ GeV range in order to determine their relative contributions. The dijet background shape is extrapolated to high invariant mass, i.e., above 500 GeV, via fits.

The dijet background in the dimuon sample is evaluated from data using the reversed isolation method described in Ref. [33], based on the track isolation variable $\Sigma p_T(\Delta R < 0.3)/p_T$. The contribution in the dimuon channel has been found to be negligible. Backgrounds from cosmic rays are also negligible.

The observed invariant mass distributions, $m_{ee}$ and $m_{\mu\mu}$, are compared to the expectation from the Standard Model backgrounds. To make this comparison, the sum of the Drell-Yan, $t\bar{t}$, diboson and $W + \text{jets}$ backgrounds (with the relative contributions fixed according to the respective cross sections) is scaled such that, when added to the data-driven dijet background, the result agrees with the observed number of data events in the 80 - 110 GeV mass interval. The advantage of this approach is that the
mass-independent uncertainties cancel between the $Z'$ boson and the $Z$ boson in the statistical analysis presented below.

Figure 1 and Table 1 present the dielectron invariant mass distribution after final selection and the number of events observed compared to expected background. Figure 2 and Table 2 reflect this information for the dimuon channel. Good agreement between the data and the Standard Model prediction is found.

Table 1: The expected and observed number of events in the dielectron channel. The errors quoted include both statistical and systematic uncertainties.

<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>36200 ± 1500</td>
<td>4330 ± 180</td>
<td>412 ± 20</td>
<td>21.6 ± 1.5</td>
<td>3.03 ± 0.35</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2190 ± 250</td>
<td>750 ± 130</td>
<td>53 ± 19</td>
<td>0.86 ± 0.18</td>
<td>0.041 ± 0.017</td>
</tr>
<tr>
<td>W + jets</td>
<td>470 ± 130</td>
<td>130 ± 40</td>
<td>10.6 ± 3.0</td>
<td>0.30 ± 0.09</td>
<td>0.026 ± 0.009</td>
</tr>
<tr>
<td>Diboson</td>
<td>482 ± 34</td>
<td>172 ± 22</td>
<td>21 ± 8</td>
<td>0.91 ± 0.05</td>
<td>0.117 ± 0.014</td>
</tr>
<tr>
<td>Dijet</td>
<td>720 ± 240</td>
<td>250 ± 120</td>
<td>34 ± 23</td>
<td>2.1 ± 2.0</td>
<td>0.4 ± 0.5</td>
</tr>
<tr>
<td>Total</td>
<td>40100 ± 1600</td>
<td>5620 ± 260</td>
<td>530 ± 40</td>
<td>25.8 ± 2.5</td>
<td>3.6 ± 0.6</td>
</tr>
<tr>
<td>Data</td>
<td>39875</td>
<td>5760</td>
<td>615</td>
<td>31</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 2: Dimuon invariant mass ($m_{\mu\mu}$) distribution with statistical uncertainties after final selection, compared to the stacked sum of all expected backgrounds, with two selected $Z'_{SSM}$ signals overlaid. The bin width is constant in log $m_{\mu\mu}$.

5 Systematic uncertainties

The treatment of systematic uncertainties in this analysis is simplified by the fact that the backgrounds are normalized to the data in the region of the $Z$ peak. This procedure makes the analysis insensitive to the uncertainty on the measurement of the integrated luminosity as well as other mass-independent systematic uncertainties. Instead, a flat systematic error of 5%, due to the uncertainty on the $Z'/\gamma^*$ cross section in the normalization region, is assigned to the signal expectation.

Mass-dependent systematic uncertainties include theoretical effects due to the PDF, QCD and electroweak corrections, as well as experimental effects, namely lepton efficiency and resolution. These uncertainties are correlated across all bins in the search region. The mass-dependent theoretical uncer-

Table 2: The expected and observed number of events in the dimuon channel. 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>27800 ± 1800</td>
<td>2800 ± 250</td>
<td>247 ± 27</td>
<td>12.4 ± 1.6</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1390 ± 170</td>
<td>470 ± 100</td>
<td>33 ± 15</td>
<td>0.68 ± 0.30</td>
<td>0.04 ± 0.04</td>
</tr>
<tr>
<td>Diboson</td>
<td>306 ± 25</td>
<td>107 ± 17</td>
<td>12 ± 6</td>
<td>0.47 ± 0.09</td>
<td>0.050 ± 0.020</td>
</tr>
<tr>
<td>Total</td>
<td>29500 ± 1800</td>
<td>3370 ± 270</td>
<td>293 ± 31</td>
<td>13.6 ± 1.6</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>Data</td>
<td>28516</td>
<td>3341</td>
<td>276</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 3: Summary of the main systematic uncertainties on the expected numbers of events at $m_{\ell^+\ell^-} = 2$ TeV. NA indicates that the uncertainty is not applicable.

<table>
<thead>
<tr>
<th>Source</th>
<th>Dielectrons</th>
<th>Dimuons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>Background</td>
</tr>
<tr>
<td>Normalization</td>
<td>5%</td>
<td>NA</td>
</tr>
<tr>
<td>PDF / $\alpha_s / \alpha_{em} / \text{scale}$</td>
<td>NA</td>
<td>20%</td>
</tr>
<tr>
<td>Electroweak corrections</td>
<td>NA</td>
<td>4.5%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$&lt; 3%$</td>
<td>$&lt; 3%$</td>
</tr>
<tr>
<td>Dijet and $W + \text{jets}$ background</td>
<td>NA</td>
<td>21%</td>
</tr>
<tr>
<td>Total</td>
<td>5%</td>
<td>30%</td>
</tr>
</tbody>
</table>

tainties are applied to the $Z/\gamma'$ background expectation only. We assume that the experimental uncertainties are correlated between signal and all types of backgrounds. All systematic uncertainties quoted below refer to narrow resonances with dilepton masses of 2 TeV.

The uncertainties on the PDF, $\alpha_s$, $\alpha_{em}$ and renormalization/factorization scale variations at 2 TeV are 20%, the largest contribution being the uncertainty on the PDF. The uncertainty on the PDF is obtained from variations of the error PDF sets of the MSTW2008, NNPDF2.1 [34], CT10, and CT10W and evaluating the envelope of the individual uncertainty bands. In addition, a systematic uncertainty of 4.5% is attributed to electroweak corrections for both channels. This contribution includes the effects of neglecting real boson emission, the difference in the electroweak scheme definition between PYTHIA and HORACE, and higher-order electroweak and $O(\alpha\alpha_s)$ corrections.

Experimental systematic uncertainties have been evaluated as well. In the electron channel, the largest systematic uncertainty is due to the estimate of the dijet and $W + \text{jets}$ backgrounds. The former is based on changes in the result under variations in the fit range and choices of the fit functions used for the extrapolations, as well as differences in the estimate based on two other independent methods [32]. The systematic uncertainty on the $W + \text{jets}$ backgrounds is dominated by the uncertainty on the cross section. Their total uncertainties are dominated by systematics and shown in Table 1.

Other experimental systematics in the electron channel include uncertainties due the electron reconstruction and identification efficiency at high $p_T$ ($< 3\%$) and systematic uncertainties due to the calorimeter energy calibration (0.5% - 1.5% depending on transverse energy and pseudorapidity). The uncertainty in the corrections applied to the simulation to reproduce the calorimeter resolution at high energy is found to be negligible.

For the muon channel, the combined uncertainty on the trigger and reconstruction efficiency is estimated to be 6% at 2 TeV. This uncertainty is dominated by a conservative estimate of the impact from large energy loss due to muon bremsstrahlung in the calorimeter, which may interfere with reconstruction in the muon spectrometer if this energy loss is not well contained within the calorimeter. In addition, the uncertainty on the resolution due to residual misalignments in the muon spectrometer propagates to a change in the observed width of the signal line-shape. However its effect on the final result has a negligible impact. Finally, the muon momentum scale is calibrated with a statistical precision of 0.1% using the $Z \rightarrow \mu^+\mu^-$ mass peak. As with the electron channel, the momentum calibration uncertainty has negligible impact in the muon channel search.

All systematic uncertainties estimated to have an impact $\leq 3\%$ on the expected number of events are neglected in the statistical analysis. A summary of systematic uncertainties relevant to this analysis is shown in Table 3.
Figure 3: Median expected (dashed line) and observed (solid red line) 95% C.L. limits on $\sigma B$ and expected $\sigma B$ for $Z'_\text{SSM}$ production and the two $E_6$-motivated $Z'$ models with lowest and highest $\sigma B$ for the dielectron (left) and dimuon channel (right). The inner and outer bands show the range in which the limit is expected to lie in 68% and 95% of pseudo-experiments, respectively. The thickness of the $Z'_\text{SSM}$ theory curve represents the theoretical uncertainty and holds for the other theory curves.

6 Signal significance

The significance of a signal is summarized by a $p$-value, the probability of observing an excess in the search region 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 from 110 GeV - 3 TeV. The data are consistent with the Standard Model hypothesis, with global $p$-values of 8.6% and 69% for the dielectron and dimuon channels, respectively.

7 Limits

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 [35] with a flat, positive prior on the signal cross section. 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 [35].

The limit on the number of produced $Z'$ events is converted into a limit on cross section times branching fraction, $\sigma B$. The expected exclusion limits are determined using simulated pseudo-experiments containing only Standard Model processes by evaluating the 95% C.L. upper limits for each pseudo-experiment for each fixed value of $M_{Z'}$. The median of the distribution of limits is chosen to represent the expected limit. The ensemble of limits is also used to find the 68% and 95% envelope of the expected limits as a function of $M_{Z'}$.

Figure 3 shows the 95% C.L. observed and expected exclusion limits on $\sigma B$ for the dielectron and dimuon channels. It also shows the theoretical cross section times branching ratio for the $Z'_\text{SSM}$ and for the two $E_6$-motivated $Z'$ models with the highest and lowest $\sigma B$. Figure 4 shows the 95% C.L. exclusion limit on $\sigma B$ for the combination of the electron and muon channels, assuming an equal branching ratio. The combination is performed by defining the likelihood function in terms of $\sigma B(Z' \to \ell^+ \ell^-)$ in both
channels.

Figure 4: Median expected (dashed line) and observed (solid red line) 95% C.L. limits on $\sigma B$ and expected $\sigma B$ for $Z'_{\text{SSM}}$ production and the two $E_6$-motivated $Z'$ models with lowest and highest $\sigma B$ for the combination of the electron and muon channels. The inner and outer bands show the range in which the limit is expected to lie in 68% and 95% of pseudo-experiments, respectively. The thickness of the $Z'_{\text{SSM}}$ theory curve represents the theoretical uncertainty and holds for the other theory curves.

The 95% C.L. limits on $\sigma B$ are used to set mass limits for each of the considered models. Mass limits obtained for the $Z'_{\text{SSM}}$ are displayed in Table 4. The combined mass limit for the $Z'_{\text{SSM}}$ is 2.49 TeV (observed) and 2.49 TeV (expected). The combined mass limits on the $E_6$-motivated models are given in Table 5.

Table 4: $e^+e^-$, $\mu^+\mu^-$ and combined 95% C.L. mass limits on $Z'_{\text{SSM}}$.

<table>
<thead>
<tr>
<th>$Z'_{\text{SSM}} \rightarrow e^+e^-$</th>
<th>$Z'_{\text{SSM}} \rightarrow \mu^+\mu^-$</th>
<th>$Z'_{\text{SSM}} \rightarrow \ell^+\ell^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed mass limit [TeV]</td>
<td>2.39</td>
<td>2.19</td>
</tr>
<tr>
<td>Expected mass limit [TeV]</td>
<td>2.39</td>
<td>2.17</td>
</tr>
</tbody>
</table>

Table 5: Combined mass limits at 95% C.L. on the $E_6$-motivated $Z'$ models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$Z'_S$</th>
<th>$Z'_N$</th>
<th>$Z'_I$</th>
<th>$Z'_S$</th>
<th>$Z'_S$</th>
<th>$Z'_I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed mass limit [TeV]</td>
<td>2.09</td>
<td>2.10</td>
<td>2.15</td>
<td>2.14</td>
<td>2.18</td>
<td>2.24</td>
</tr>
<tr>
<td>Expected mass limit [TeV]</td>
<td>2.07</td>
<td>2.08</td>
<td>2.14</td>
<td>2.13</td>
<td>2.17</td>
<td>2.23</td>
</tr>
</tbody>
</table>
8 Conclusions

In conclusion, the ATLAS detector has been used to search for narrow resonances in the dilepton invariant mass spectrum above the $Z$-boson pole with $5.9 \text{ fb}^{-1}$ ($6.1 \text{ fb}^{-1}$) in the $e^+e^-$ ($\mu^+\mu^-$) channel of proton-proton collision data at $\sqrt{s} = 8 \text{ TeV}$. The observed invariant-mass spectrum is consistent with the Standard Model expectation. The resulting mass limits are $2.49 \text{ TeV}$ for the $Z'_{\text{SSM}}$ and $2.09 - 2.24 \text{ TeV}$ for various $E_6$-motivated $Z'$ bosons.
References


Figure 5: Event display of the selected event with the highest dimuon invariant mass. The highest momentum muon has a $p_T$ of 289 GeV and an $\eta$ of 1.54. The subleading muon has a $p_T$ of 274 GeV and an $\eta$ of -1.35. The invariant mass of the pair is 1258 GeV.