Search for a heavy gauge boson decaying to a charged lepton in $pp$ collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector

The ATLAS Collaboration

Abstract

The ATLAS detector at the LHC is used to search for high-mass states, such as heavy charged gauge bosons ($W'$), decaying to a charged lepton (electron or muon) and a neutrino. Results are presented based on the analysis of $pp$ collisions at a center-of-mass energy of 7 TeV corresponding to an integrated luminosity of 1.04 fb$^{-1}$. No excess beyond Standard Model expectations is observed. A $W'$ with Sequential Standard Model couplings is excluded at the 95% confidence level for masses up to 2.15 TeV.

1. Introduction

The high-energy collisions at the CERN Large Hadron Collider provide new opportunities to search for physics beyond the Standard Model (SM) of strong and electroweak interactions. One extension common to many models is the existence of additional heavy gauge bosons $W'$, the charged ones commonly denoted $W'$. Such particles are most easily searched for in their decay to a charged lepton (electron or muon) and a neutrino.

This letter describes such a search performed using 7 TeV $pp$ collision data collected with the ATLAS detector covering 1.04 fb$^{-1}$ in 2011 and corresponding to a total integrated luminosity of 1.04 fb$^{-1}$. No $W'$ signal is observed, and the data are used to extend current limits on $\sigma B$ as a function of $W'$ mass. The significant improvement over the previous ATLAS result comes mostly from the increase in available integrated luminosity, but also reflects optimization of the event selection and increased acceptance in the muon channel. A lower limit on the mass of a $W'$ boson in the Sequential Standard Model (SSM), i.e. the extended gauge model of Ref. with $W'$ coupling to $WZ$ set to zero, is also reported. In this model, the $W'$ has the same couplings to fermions as the SM $W$ boson and thus a width which increases linearly with the $W'$ mass.

The analysis presented here identifies candidates in the electron and muon channels and sets separate limits for $W' \rightarrow e\nu$ and $W' \rightarrow \mu\nu$. In addition, combined limits are evaluated, assuming the same branching fraction for both channels. The kinematic variable used to identify the $W'$ is the transverse mass

$$m_{T} = \sqrt{2p_{T}E_{T}^{\text{miss}}(1 - \cos \varphi_{\nu})}.$$  \hspace{1cm} (1)

which displays a Jacobian peak that falls sharply above the resonance mass. Here $p_{T}$ is the lepton transverse momentum, $E_{T}^{\text{miss}}$ is the magnitude of the missing transverse momentum (missing $E_{T}$), and $\varphi_{\nu}$ is the angle between the $p_{T}$ and missing $E_{T}$ vectors. Throughout this letter, transverse refers to the plane perpendicular to the colliding beams, longitudinal means parallel to the beams, $\theta$ and $\varphi$ are the polar and azimuthal angles with respect to the longitudinal direction, and pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$.

The main background to the $W' \rightarrow e\nu$ signal comes from the high-$m_{T}$ tail of SM $W$ boson decay to the same final state. Other backgrounds are $Z$ bosons decaying into two leptons where one lepton is not reconstructed, $W$ or $Z$ decaying to $\tau$-leptons where a $\tau$ subsequently decays to an electron or muon, and diboson production. These are collectively referred to as the electroweak (EW) background. In addition, there is a background contribution from $t\bar{t}$ production which is most important for the lowest $W'$ masses considered here, where it constitutes about 10% of the background after event selection. Other strong-interaction background sources, where a light or heavy hadron decays semileptonically or a jet is misidentified as an electron, are estimated to be at most 10% of the total background in the electron channel and a negligible fraction in the muon channel. These are called QCD background in the following.

2. Data

The ATLAS detector has three major components: the inner tracking detector, the calorimeter and the muon spectrometer. Charged particle tracks and vertices are reconstructed with silicon pixel and silicon strip detectors covering $|\eta| < 2.5$ and transition radiation detectors covering $|\eta| < 2.0$, all immersed in a homogeneous 2 T magnetic field provided by a superconducting solenoid. This tracking detector is surrounded by a finely-segmented, hermetic calorimeter system that covers $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers. It uses liquid argon for the inner, electromagnetic compartment followed by a hadronic compartment based on...
scintillating tiles in the central region ($|\eta| < 1.7$) and additional liquid argon for higher $|\eta|$. Outside the calorimeter, there is a muon spectrometer with air-core toroids providing a magnetic field, whose integral averages about 3 Tm. The deflection of the muons in the magnetic field is measured with three layers of precision drift-tube chambers for $|\eta| < 2.0$ and one layer of cathode-strip chambers followed by two layers of drift-tube chambers for $2.0 < |\eta| < 2.7$. Additional resistive-plate and thin-gap chambers provide muon triggering capability and measurement of the $\varphi$ coordinate.

The data used in the electron channel are the events recorded with a trigger requiring the presence of an electron with $p_T > 20$ GeV. The efficiency of this trigger is 98%. For the muon channel, matching tracks in the muon spectrometer and inner detector with combined $p_T > 22$ GeV are used to identify events. Events are also recorded if a muon with $p_T > 40$ GeV is found in the muon spectrometer. The muon trigger efficiency is 80-90% in the regions of interest.

Each energy cluster reconstructed in the electromagnetic compartment of the calorimeter with $E_T > 25$ GeV and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ is considered as an electron candidate if it matches with an inner detector track. The electron direction is defined as that of the reconstructed track and its energy as that of the cluster, with a small $\eta$-dependent energy scale correction. The resolution of the energy measurement is 2% for $E_T \approx 50$ GeV and approaches 1% in the high-$E_T$ range relevant to this analysis. To discriminate against hadronic jets, requirements are imposed on the lateral shower shapes in the first two layers of the electromagnetic part of the calorimeter and the fraction of energy leaking into the hadronic compartment. A hit in the first pixel layer is required to reduce background from photon conversions in the inner detector material. These requirements give about 90% identification efficiency for electrons with $E_T > 25$ GeV and a $2 \times 10^{-4}$ probability to falsely identify jets as electrons before isolation requirements are imposed.

Muon tracks can be reconstructed independently in both the inner detector and muon spectrometer, and the muons used in this study are required to have matching tracks in both systems. The muons are required to have $p_T > 25$ GeV, where the momentum of the muon is obtained by combining the inner detector and muon spectrometer measurements. To ensure precise measurement of the momentum, muons are required to have hits in all three muon layers and are restricted to those $\eta$-ranges where the muon spectrometer alignment is best understood: approximately $|\eta| < 1.0$ and $1.3 < |\eta| < 2.0$. The average momentum resolution is currently about 15% at $p_T = 1$ TeV. About 80% of the muons in these $\eta$-ranges are reconstructed, with most of the loss coming from regions with limited detector coverage.

The missing $E_T$ in the electron channel is obtained from a vector sum over calorimeter cells associated with topological clusters and using local hadronic calibration:

$$E_{miss}^{topo} = \sum_{cell} E_{cell}^{topo}.$$  \hfill (2)

The topological clusters reduce contributions from electronic noise and additional $pp$ interactions. The $E_T$ of cells associated with the electron is corrected so their sum equals the electron $E_T$. Muons only deposit a small fraction of their energy in the calorimeter, and so, in the muon channel, the missing $E_T$ is obtained from

$$E_{miss}^{topo} = E_{Tcalo}^{miss} = p_T^\mu + E_{T}^{\mu,loss}.$$  \hfill (3)

The second term in this vector sum subtracts the muon transverse momentum and the last corrects for the transverse component of the energy deposited in the calorimeter by the muon, which is included in both of the first two terms. The energy loss is estimated by integrating the amount of material traversed and applying a calibrated conversion from path length to energy for each material type.

This analysis makes use of all the $\sqrt{s} = 7$ TeV data collected in March-June 2011 that satisfy data quality requirements which guarantee the relevant detector systems were operating properly. The integrated luminosity for the data used in this study is 1.04 fb$^{-1}$ in both the electron and muon decay channels. The uncertainty on this estimate is 3.7%.

3. Simulation

Except for the QCD background, which is estimated from data, expected signal and background levels are evaluated with simulated samples and normalized using calculated cross sections and the integrated luminosity of the data.

The $W'$ signal and the $W/Z$ boson backgrounds are generated with Pythia 6.421 [9] using MRST LO* [10] parton distribution functions (PDFs). The $t\bar{t}$ background is generated with MC@NLO 3.41 [11]. For all samples, final-state photon radiation is handled by Photos [12]. ATLAS full detector simulation [13] based on Geant4 [14] is used to propagate the particles and account for the response of the detector.

The Pythia signal model for $W'$ has $V - A$ SM couplings but does not include interference between $W$ and $W'$. Decays to channels other than $e\nu$ and $\mu\nu$, including $\tau\nu, ud, sc$ and $tb$ are included in the calculation of the $W'$ widths but are not explicitly included as signal or background. At high mass ($m_{W'} > 1$ TeV), the branching fraction to any of the lepton decay channels is 8.2%.

The $W \to \ell\nu$ events are reweighted to have the NNLO (next-to-next-to-leading-order QCD) mass dependence of ZWPROD [15] with MSTW2008 PDFs [16] and following the $G_{\rho}$ scheme [17]. Higher-order electroweak corrections (in addition to the photon radiation included in the simulation) are calculated using HORACE [17, 18]. In the high-mass region of interest, the electroweak corrections reduce
the cross sections by 11% at $m_{t\bar{t}} = 1$ TeV and by 18% at $m_{t\bar{t}} = 2$ TeV.

The $W \to \ell \nu$ and $Z \to \ell \ell$ cross sections are calculated at NNLO using FEWZ \cite{19, 20} with the same PDFs, scheme and electroweak corrections used in the ZWPROD event reweighting. The $W' \to \ell \nu$ cross sections are calculated in the same way, except the electroweak corrections beyond final-state radiation are not included because the calculation for the SM $W$ cannot be applied directly. The $t\bar{t}$ cross section is calculated at approximate-NNLO \cite{21, 22} assuming a top-quark mass of 172.5 GeV. The signal and most important background cross sections are listed in Table 1.

<table>
<thead>
<tr>
<th>Process</th>
<th>Mass [GeV]</th>
<th>$\sigma B$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W' \to \ell \nu$</td>
<td>500</td>
<td>17.25</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>8.27</td>
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<td>1000</td>
<td>0.837</td>
</tr>
<tr>
<td></td>
<td>1250</td>
<td>0.261</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>0.0887</td>
</tr>
<tr>
<td></td>
<td>1750</td>
<td>0.0325</td>
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<tr>
<td></td>
<td>2250</td>
<td>0.00526</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>0.00234</td>
</tr>
<tr>
<td>$W \to \ell \nu$</td>
<td>10460</td>
<td></td>
</tr>
<tr>
<td>$Z/\gamma \rightarrow \ell \ell$</td>
<td>989</td>
<td></td>
</tr>
<tr>
<td>$(m_{Z/\gamma} &gt; 60$ GeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \ell X$</td>
<td>89.4</td>
<td></td>
</tr>
</tbody>
</table>

Consistent results are obtained using the “inverted isolation” technique described in Ref. \cite{4}. In the higher mass bins ($m_{t\bar{t}} > 700$ GeV) where no events remain in the estimate, the QCD background level is set to zero and assigned an uncertainty equal to 10% of the total background level, a conservative upper limit based on the QCD contribution to the electron $E_T$ distribution.

The QCD background for the muon channel is evaluated using a non-isolated data sample following the same procedure used for the 2010 analysis \cite{4}. With the higher statistics now available, it is clear this background is less than 1% of the total background, so it is neglected in the following.

4. Event selection

Events are required to have their primary vertex reconstructed from at least three tracks with $p_T > 0.4$ GeV and longitudinal distance less than 200 mm from the center of the collision region. Due to the high luminosity, there were typically five additional interactions per event and the primary vertex is defined to be the one with the highest summed track $p_T^2$. Spurious tails in missing $E_T$ arising from calorimeter noise and other detector problems are suppressed by checking the quality of each reconstructed jet and discarding events where any jet has a shape indicating such problems, following Ref. \cite{22}. Events are required to have exactly one candidate electron or one candidate muon satisfying the requirements described above. In addition, the inner detector track associated with the electron or muon is required to be compatible with originating from the primary vertex, specifically to have transverse distance of closest approach $|d_0| < 1$ mm and longitudinal distance at this point $|z_0| < 5$ mm.

To suppress the QCD background, the lepton is required to be isolated. In the electron channel, the isolation energy is measured with the calorimeter in a cone $\Delta R < 0.4$ ($\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$) around the electron track, and the requirement is $\sum E_T^\text{miss} < 9$ GeV, where the sum includes all calorimeter energy clusters in the cone excluding the core energy deposited by the electron. The sum is corrected to account for additional interactions and leakage of the electron energy outside this core.

In the muon channel, the isolation energy is measured using inner detector tracks with $p_T^k > 1$ GeV in a cone $\Delta R < 0.3$ around the muon track. The isolation requirement is $\sum p_T^k < 0.05 p_T$, where the muon track is excluded from the sum. The scaling of the threshold with the muon $p_T$ reduces efficiency losses due to radiation from the muon at high $p_T$.

Finally, missing $E_T$ requirements are imposed to further suppress the QCD background. In both channels, a fixed threshold is applied: $E_T^\text{miss} > 25$ GeV. In the electron channel, where QCD jets may be misidentified as electrons, a threshold proportional to the electron $E_T$ is also applied: $E_T^\text{miss} > 0.6 E_T$.

In the electron channel, the QCD background is estimated from data using the ABCD technique \cite{27} with the isolation energy and missing $E_T$ serving as discriminants. Consistent results are obtained using the “inverted isolation” technique described in Ref. \cite{4}. In the higher mass bins ($m_{t\bar{t}} > 700$ GeV) where no events remain in the estimate, the QCD background level is set to zero and assigned an uncertainty equal to 10% of the total background level, a conservative upper limit based on the QCD contribution to the electron $E_T$ distribution.
The measurements in the two decay channels are combined assuming the same branching fraction for each. Equation (6) remains valid with the Poisson likelihood replaced by the product of the Poisson likelihoods for the two channels. The electron and muon integrated luminosity measurements are fully correlated. The selection efficiencies are uncorrelated and the background levels are partly correlated, including only the full correlation between the cross section uncertainties in the two channels. The effect of this correlation is small: if it is not included, the observed $σB$ limits for the lowest mass points improve by 2% and those for the high-mass points are unchanged.

Bayes theorem gives the posterior probability that the $W' \to ℓν$ has signal strength $σB$:

$$P_{\text{post}}(σB|N_{\text{obs}}) = \mathcal{N}(σB|N_{\text{obs}}|σB) P_{\text{prior}}(σB)$$ (7)

where $P_{\text{prior}}(σB)$ is the assumed prior probability, here chosen to be one (i.e. flat in $σB$) for $σB > 0$. The constant factor $N$ normalizes the total probability to one. The posterior probability is evaluated for each mass and each decay channel and their combination, and then used to assess discovery significance and set a limit on $σB$.

5. Statistical analysis

A Bayesian analysis is performed to determine if there is significant evidence for existence of a $W' \to ℓν$ signal above the SM background and to set limits on that process. For each candidate mass and decay channel, events are counted above an $m_T$ threshold, $m_T > m_{T\text{min}}$, with the threshold chosen to maximize sensitivity. The expected number of events in each channel is

$$N_{\text{exp}} = ε_{\text{sig}} L_{\text{int}} σB + N_{\text{bg}},$$ (4)

where $L_{\text{int}}$ is the integrated luminosity of the data sample and $ε_{\text{sig}}$ is the event selection efficiency, i.e. the fraction of events that pass event selection criteria and have $m_T$ above threshold. $N_{\text{bg}}$ is the expected number of background events. Using Poisson statistics, the likelihood to observe $N_{\text{obs}}$ events is

$$\mathcal{L}(N_{\text{obs}}|σB) = \frac{(L_{\text{int}} ε_{\text{sig}} σB + N_{\text{bg}})^{N_{\text{obs}}} e^{-(L_{\text{int}} ε_{\text{sig}} σB + N_{\text{bg})}}}{N_{\text{obs}}!}.$$ (5)

Uncertainties are handled by introducing Gaussian nuisance parameters $θ_i$, each with a probability density function (pdf) $g_i(θ_i)$, and integrating the product of the Poisson likelihood with the pdfs. The integrated likelihood is

$$\mathcal{L}_{\text{B}}(N_{\text{obs}}|σB) = \int \mathcal{L}(N_{\text{obs}}|σB) \prod g_i(θ_i)dθ_i.$$ (6)

The nuisance parameters are taken to be the explicit dependencies: $L_{\text{int}}$, $ε_{\text{sig}}$ and $N_{\text{bg}}$, with the latter evaluated at the central value of $L_{\text{int}}$. Correlations between the nuisance parameters are neglected. This is justified by the small effect that the nuisance parameters themselves have on the limits, as demonstrated below.

6. Parameter estimation and systematics

The inputs for the evaluation of $\mathcal{L}_B$ (and hence $P_{\text{post}}$) are $L_{\text{int}}$, $ε_{\text{sig}}$, $N_{\text{bg}}$, $N_{\text{obs}}$ and the uncertainties on the first three. Except for $L_{\text{int}}$ and its uncertainty, these inputs are all listed in Table 3. The uncertainties on $ε_{\text{sig}}$ and $N_{\text{bg}}$ account for all relevant experimental and theoretical effects except for the uncertainty on the integrated luminosity. The latter is included separately to allow for the correlation between signal and background. The table also lists the predicted numbers of signal events, $N_{\text{sig}}$, with their uncertainties accounting for the uncertainties in both $ε_{\text{sig}}$ and the cross-section calculation.

The maximum value for the signal selection efficiency is at $m_{W'} = 1500$ GeV. For lower masses, the efficiency falls because the relative $m_T$ threshold, $m_T/m_{W'}$, increases to reduce the background level. For higher masses, the efficiency falls because a large fraction of the cross section goes to off-shell production with $m_ℓν ≪ m_{W'}$.

The fraction of fully simulated signal events that pass the event selection and are above the $m_T$ threshold provides the initial estimate of $ε_{\text{sig}}$ for each mass. Small corrections are made to account for the difference in acceptance at NNLO (obtained from FEWZ) and that in the LO simulation. These vary from a 7% increase for $m_{W'} = 500$ GeV to a 10% decrease for $m_{W'} = 2500$ GeV. Contributions from $W' \to ℓν$ with the τ-lepton decaying leptonically have been neglected and would increase the $W'$ event selection efficiencies by 3-4% for the highest masses. The background level is estimated for each mass by summing the EW and τℓ event counts from simulation, and adding the small QCD contribution in the electron channel.

<table>
<thead>
<tr>
<th>$W \to ℓν$</th>
<th>$W \to ℓν$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to ℓℓ$</td>
<td>$Z \to ℓℓ$</td>
</tr>
<tr>
<td>diboson</td>
<td>diboson</td>
</tr>
<tr>
<td>$tℓ$</td>
<td>$tℓ$</td>
</tr>
<tr>
<td>QCD</td>
<td>QCD</td>
</tr>
<tr>
<td>Total</td>
<td>Total</td>
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</table>
Figure 1: Spectra of $p_T$ (top), missing $E_T$ (center) and $m_T$ (bottom) for the electron (left) and muon (right) channels after event selection. The points represent data and the filled histograms show the stacked backgrounds. Open histograms are $W' \rightarrow \ell \nu$ signals added to the background with masses in GeV indicated in parentheses in the legend. The QCD backgrounds estimated from data are also shown. The signal and other background samples are normalized using the integrated luminosity of the data and the NNLO (approximate-NNLO for $t\bar{t}$) cross sections listed in Table 1.
Table 3: Inputs for the $W' \to e\nu$ and $W' \to \mu\nu$ $\sigma B$ limit calculations. The first three columns are the $W'$ mass, $m_{W'}$, threshold and decay channel. The next two are the signal selection efficiency, $\varepsilon_{\text{sig}}$, and the prediction for the number of signal events, $N_{\text{sig}}$, obtained with this efficiency. The last two columns are the expected number of background events, $N_{\text{bg}}$, and the number of events observed in data, $N_{\text{obs}}$. The uncertainties on $N_{\text{sig}}$ and $N_{\text{bg}}$ include contributions from the uncertainties on the cross sections but not from that on the integrated luminosity.

<table>
<thead>
<tr>
<th>$m_{W'}$ [GeV]</th>
<th>$m_{T_{\text{min}}}$ [GeV]</th>
<th>$\varepsilon_{\text{sig}}$</th>
<th>$N_{\text{sig}}$ [GeV]</th>
<th>$N_{\text{bg}}$</th>
<th>$N_{\text{obs}}$</th>
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<tbody>
<tr>
<td>500</td>
<td>398</td>
<td>$e\nu$</td>
<td>0.388 ± 0.019</td>
<td>6930 ± 620</td>
<td>101.9 ± 10.8</td>
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<td>$\mu\nu$</td>
<td>0.252 ± 0.015</td>
<td>4500 ± 430</td>
<td>63.7 ± 6.5</td>
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<tr>
<td>600</td>
<td>447</td>
<td>$e\nu$</td>
<td>0.456 ± 0.022</td>
<td>3910 ± 330</td>
<td>62.1 ± 7.1</td>
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<td></td>
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<td>$\mu\nu$</td>
<td>0.286 ± 0.016</td>
<td>2450 ± 220</td>
<td>41.8 ± 4.7</td>
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<tr>
<td>750</td>
<td>562</td>
<td>$e\nu$</td>
<td>0.429 ± 0.020</td>
<td>1420 ± 110</td>
<td>20.7 ± 3.7</td>
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<tr>
<td></td>
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<td>$\mu\nu$</td>
<td>0.293 ± 0.017</td>
<td>970 ± 79</td>
<td>14.3 ± 1.4</td>
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<tr>
<td>1000</td>
<td>708</td>
<td>$e\nu$</td>
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<td>$\mu\nu$</td>
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<td>3.09 ± 0.49</td>
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<td>0.367 ± 0.021</td>
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<td>891</td>
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<tr>
<td>1750</td>
<td>1000</td>
<td>$e\nu$</td>
<td>0.515 ± 0.024</td>
<td>17.3 ± 2.4</td>
<td>0.89 ± 0.20</td>
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<tr>
<td></td>
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<td>$\mu\nu$</td>
<td>0.338 ± 0.020</td>
<td>11.4 ± 1.7</td>
<td>0.82 ± 0.14</td>
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<tr>
<td>2000</td>
<td>1122</td>
<td>$e\nu$</td>
<td>0.472 ± 0.023</td>
<td>6.16 ± 0.99</td>
<td>0.48 ± 0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu\nu$</td>
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<td>0.48 ± 0.10</td>
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<td>1.97 ± 0.36</td>
<td>0.44 ± 0.09</td>
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<td>1122</td>
<td>$e\nu$</td>
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<td>0.48 ± 0.10</td>
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<td></td>
<td></td>
<td>$\mu\nu$</td>
<td>0.221 ± 0.017</td>
<td>0.53 ± 0.11</td>
<td>0.44 ± 0.09</td>
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</table>
The uncertainties on $\varepsilon_{\mathrm{sig}}$ and $N_{\mathrm{bg}}$ account for experimental and theoretical systematic effects as well as the statistics of the simulation samples. The experimental systematic uncertainties include efficiencies for the electron or muon trigger, reconstruction and selection. Lepton momentum and missing $E_T$ response, characterized by scale and resolution, are also included. Most of these performance metrics are measured at relatively low $p_T$ and their values are extrapolated to the high-$p_T$ regime relevant to this analysis. The uncertainties in these extrapolations are included but are too small to significantly affect the results. The uncertainty on the QCD background estimate also contributes to the background level uncertainties for the electron channel. In some cases, e.g. the missing $E_T$ scale and the muon QCD background, the experimental systematic uncertainties are significantly reduced from the previous study [4] because the additional available data allow more precise determination. In other cases they are similar or even larger, but have little effect on the final results.

Table 4 summarizes the uncertainties on the event selection efficiencies and background levels for the $W' \rightarrow \ell \nu$ signal with $m_{W'} = 1500 \text{ GeV}$ using $m_T > 891 \text{ GeV}$.

7. Results

None of the observations for any mass in either channel or their combination has a significance above three-sigma, so there is no evidence for the observation of $W' \rightarrow \ell \nu$. Table 3 and Fig. 2 present the 95% CL (confidence level) observed limits on $\sigma_B$ for both $W' \rightarrow \ell \nu$ decay channels and their combination. The figure also shows the expected limits and the theoretical $\sigma_B$ for an SSM $W'$. The intersection between the central theoretical prediction and the observed limits provides the 95% CL lower limit on the mass. Table 6 presents the expected and observed limits for the electron and muon decay channels and for the combination of the two channels.

The above results are obtained using a prior probability flat in $\sigma_B$. If this prior is replaced by one flat in coupling strength, the $\sigma_B$ limits improve by 20-28% for $m_{W'} \geq 1000 \text{ GeV}$ and by smaller amounts at the lower masses. The reference prior [28, 29], which minimizes the information supplied by the prior, gives intermediate results. Limits evaluated with $CL_s$ [30] for the electron and muon channels and including all uncertainties are nearly identical to the corresponding values in Table 2.

Prior to this letter, the best limits for $500 < m_{W'} < 800 \text{ GeV}$ were established by CDF [2] in $W' \rightarrow e \nu$ with $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ using an integrated luminosity of 5.3 fb$^{-1}$. At higher masses, the best limits were set by CMS [3] and ATLAS [4], each combining electron and muon channels and using $p\bar{p}$ collisions at $\sqrt{s} = 7 \text{ TeV}$ with 36 pb$^{-1}$ of data acquired in 2010. The CDF and CMS limits were obtained with a Bayesian approach, and the earlier ATLAS results were established with $CL_s$. Figure 3 compares the limits obtained here with those earlier

![Figure 2: Expected and observed limits on $\sigma_B$ for $W' \rightarrow e \nu$ (top), $W' \rightarrow \mu \nu$ (center), and the combination (bottom) assuming the same branching fraction for both channels. The NNLO calculated cross section and its uncertainty are also shown.](image-url)
Table 4: Relative uncertainties on the event selection efficiency and background level for a $W'$ with a mass of 1500 GeV. The efficiency uncertainties include contributions from trigger, reconstruction and event selection. The cross section uncertainty for $\varepsilon_{\text{sig}}$ is that assigned to the acceptance correction described in the text. The last row gives the total uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\varepsilon_{\text{sig}}$ $\pm \varepsilon_{\text{sig}}$</th>
<th>$N_{\text{bg}}$ $\pm N_{\text{bg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>2.7% $\pm$ 3.9%</td>
<td>2.7% $\pm$ 3.8%</td>
</tr>
<tr>
<td>Energy/momentum resolution</td>
<td>0.3% $\pm$ 2.3%</td>
<td>2.9% $\pm$ 0.6%</td>
</tr>
<tr>
<td>Energy/momentum scale</td>
<td>0.5% $\pm$ 1.3%</td>
<td>5.2% $\pm$ 3.0%</td>
</tr>
<tr>
<td>QCD background</td>
<td>- $\pm$ -</td>
<td>10.0% $\pm$ 1.3%</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>2.5% $\pm$ 3.1%</td>
<td>9.4% $\pm$ 9.9%</td>
</tr>
<tr>
<td>Cross section (shape/level)</td>
<td>3.0% $\pm$ 3.0%</td>
<td>9.5% $\pm$ 9.5%</td>
</tr>
<tr>
<td>All</td>
<td>4.7% $\pm$ 6.3%</td>
<td>18% $\pm$ 15%</td>
</tr>
</tbody>
</table>

Figure 3: Normalized cross section limits ($\sigma_{\text{limit}}/\sigma_{\text{SSM}}$) for $W' \rightarrow \ell \nu$ as a function of mass for this measurement and from CDF, CMS and the previous ATLAS search. The cross section calculations assume the $W'$ has the same couplings as the standard model $W$ boson. The region above each curve is excluded at the 95% CL.

8. Conclusions

The ATLAS detector has been used to search for new high-mass states decaying to a lepton plus missing $E_T$ in $pp$ collisions at $\sqrt{s} = 7$ TeV using 1.04 fb$^{-1}$ of integrated luminosity. No excess beyond SM expectations is observed. Bayesian limits on $\sigma B$ are shown in Figs. 2 and 3. These are the best published limits for $m_{W'} > 600$ GeV. A $W'$ with SSM couplings is excluded for masses up to 2.15 TeV at the 95% CL.

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Table 5: Upper limits on $W' \to \ell \nu \sigma_B$. The first two columns are the mass and decay channel and the following are the 95% CL limits with headers indicating the nuisance parameters for which uncertainties are included: S for the event selection efficiency ($\varepsilon_{sig}$), B for the background level ($N_{bg}$), and L for the integrated luminosity ($L_{int}$). Columns labeled SBL include all uncertainties and are used to evaluate mass limits. Results are given for the electron and muon channels and the combination of the two.

<table>
<thead>
<tr>
<th>$m_{W'}$ [GeV]</th>
<th>95% CL limit on $\sigma_B$ [fb]</th>
<th>none</th>
<th>S</th>
<th>SB</th>
<th>SBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 $e\nu$</td>
<td>97 98 117 121</td>
<td></td>
<td></td>
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<tr>
<td>600 $e\nu$</td>
<td>49 49 59 61</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>750 $e\nu$</td>
<td>23.0 23.1 28.1 28.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 $e\nu$</td>
<td>10.1 10.2 10.5 10.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1250 $e\nu$</td>
<td>14.4 14.5 14.6 14.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500 $e\nu$</td>
<td>8.8  8.9  9.0  9.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1750 $e\nu$</td>
<td>7.8  7.9  7.9  7.9</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2000 $e\nu$</td>
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<td></td>
<td></td>
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<tr>
<td>2250 $e\nu$</td>
<td>10.2 10.2 10.3 10.3</td>
<td></td>
<td></td>
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<tr>
<td>2500 $e\nu$</td>
<td>12.7 12.8 12.8 12.9</td>
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<tr>
<td>500 $\mu\nu$</td>
<td>171 174 186 191</td>
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<tr>
<td>600 $\mu\nu$</td>
<td>99 100 108 110</td>
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</tr>
<tr>
<td>750 $\mu\nu$</td>
<td>49.2 49.8 50.9 51.7</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 $\mu\nu$</td>
<td>16.1 16.3 16.5 16.7</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1250 $\mu\nu$</td>
<td>14.4 14.5 14.6 14.7</td>
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<tr>
<td>1500 $\mu\nu$</td>
<td>13.0 13.2 13.2 13.3</td>
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<tr>
<td>1750 $\mu\nu$</td>
<td>7.3  7.3  7.4  7.5</td>
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<tr>
<td>2000 $\mu\nu$</td>
<td>8.8  8.9  9.0  9.0</td>
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<tr>
<td>2250 $\mu\nu$</td>
<td>14.8 14.9 14.9 15.0</td>
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</tr>
<tr>
<td>2500 $\mu\nu$</td>
<td>19.2 19.5 19.6 19.7</td>
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</tr>
</tbody>
</table>

Table 6: Lower limits on the SSM $W'$ mass. The first column is the decay channel ($e\nu$, $\mu\nu$ or both combined) and the following give the expected (Exp.) and observed (Obs.) mass limits.

<table>
<thead>
<tr>
<th>$m_{W'}$ [TeV]</th>
<th>Exp., Obs.</th>
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</thead>
<tbody>
<tr>
<td>$e\nu$</td>
<td>2.17, 2.08</td>
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<tr>
<td>$\mu\nu$</td>
<td>2.08, 1.98</td>
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<tr>
<td>both</td>
<td>2.23, 2.15</td>
</tr>
</tbody>
</table>

References

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

Department of Physics, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst MA, United States of America

Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science, Nagoya University, Nagoya, Japan

(a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

Department of Physics, Northern Illinois University, DeKalb IL, United States of America

Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia

Department of Physics, New York University, New York NY, United States of America

Ohio State University, Columbus OH, United States of America

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

Department of Physics, Oklahoma State University, Stillwater OK, United States of America

Palacký University, RCPTM, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene OR, United States of America

LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France

Graduate School of Science, Osaka University, Osaka, Japan

Department of Physics, University of Oslo, Oslo, Norway

Department of Physics, Oxford University, Oxford, United Kingdom

(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy

Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

Petersburg Nuclear Physics Institute, Gatchina, Russia

(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

(a) Laboratorio de Instrumentacion and Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain

Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
136 Department of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
137 Czech Technical University in Prague, Praha, Czech Republic
138 State Research Center Institute for High Energy Physics, Protvino, Russia
139 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
140 Physics Department, University of Regina, Regina SK, Canada
141 Ritsumeikan University, Kusatsu, Shiga, Japan
142 INFIN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
143 INFIN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
144 INFIN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
145 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
146 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
147 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
148 Department of Physics, University of Washington, Seattle WA, United States of America
149 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
150 Department of Physics, Shinshu University, Nagano, Japan
151 Fachbereich Physik, Universität Siegen, Siegen, Germany
152 Department of Physics, Simon Fraser University, Burnaby BC, Canada
153 SLAC National Accelerator Laboratory, Stanford CA, United States of America
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 Valencia and CSIC, Valencia, Spain
157 Dipartimento di Elettronica and Instituto de Microelettronica de Barcelona (IMB-CNM), University of Barcelona, Barcelona, Spain
158 Fachbereich Physik, Universität Siegen, Siegen, Germany
159 Indian Institute of Science Education and Research, Kolkata, India
160 Department of Physics, Lawrence Berkeley National Laboratory, Berkeley CA, United States of America
161 Institute of Physics, Academia Sinica, Taipei, Taiwan
162 Physics Department, Technion: Israel Inst. of Technology, Haifa, Israel
163 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
164 Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
165 Physics Department, Royal Institute of Technology, Stockholm, Sweden
166 Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
167 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
168 School of Physics, University of Sydney, Sydney, Australia
169 Institute of Physics, Academia Sinica, Taipei, Taiwan
170 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
171 Department of Physics, University of British Columbia, Vancouver BC, Canada
172 Department of Physics, University of Wisconsin, Madison WI, United States of America