Search for high-mass states with one lepton plus missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector


DOI
10.1016/j.physletb.2011.05.043

Publication date
2011

Document Version
Final published version

Published in
Physics Letters B

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Search for high-mass states with one lepton plus missing transverse momentum in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

A R T I C L E  I N F O

Article history:
Received 7 March 2011
Received in revised form 6 May 2011
Accepted 7 May 2011
Available online 30 May 2011
Editor: H. Weerts

Keywords:
Exotics
Electroweak interaction
Particle and resonance production

A B S T R A C T

The ATLAS detector is used to search for high-mass states, such as heavy charged gauge bosons ($W', W^*$), 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 36 pb$^{-1}$. No excess beyond standard model expectations is observed. A $W'$ with sequential standard model couplings is excluded at 95% confidence level for masses below 1.49 TeV, and a $W^*$ (charged chiral boson) for masses below 1.35 TeV.

© 2011 CERN. Published by Elsevier B.V. All rights reserved.

Although the standard model (SM) of strong and electroweak interactions is remarkably consistent with particle physics observations to date, the high-energy collisions at the CERN Large Hadron Collider provide new opportunities to search for physics beyond it. One extension common to many models is the existence of additional heavy gauge bosons [1], the charged ones commonly denoted $W'$. Such particles are most easily searched for in their decay to a charged lepton (either electron or muon) and a neutrino. In this Letter, 7 TeV $pp$ collision data collected with the ATLAS detector during 2010 and corresponding to a total integrated luminosity of 36 pb$^{-1}$ are used to supplement current limits [2–6] on $σB$ (cross section times branching fraction) as a function of $W'$ mass. A lower limit on the mass of a $W'$ boson in the sequential standard model (SSM) [7] 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 $W'$ mass.

Limits are also established for $W^*$, the charged partner of the chiral bosons described in [8]. Theoretical motivation for such bosons is provided in [9]. The anomalous (magnetic-moment type) coupling of the $W^*$ leads to kinematic distributions significantly different from those of the $W'$. To fix the coupling strength, a model with total and partial decay widths equal to those of the SSM $W'$ with the same mass is adopted [10].

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

$$m_T = \sqrt{2p_T^{miss}(1 - \cos \phi_{ln})}$$  

which displays a Jacobian peak that, for $W' \rightarrow \ell\nu$, falls sharply above the resonance mass. Here $p_T$ is the lepton transverse momentum, $E^{miss}_T$ is the magnitude of the missing transverse momentum (missing $E_T$), and $\phi_{ln}$ 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 $\phi$ 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 $W'$ and $W^*$ signals comes from the high-$m_T$ tail of SM $W \rightarrow \ell\nu$ decay. Other backgrounds are $Z$ bosons decaying into two leptons where one lepton is not reconstructed, $W$ or $Z$ decaying to $\tau$-leptons where the $\tau$ 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 $W'/W^*$ masses considered here where it constitutes about 20% of the background after final selection. Other background sources, where a light or heavy hadron decays semileptonically or a jet is misidentified as an electron, are estimated to be at most 3% of the total background (with the uncertainty on this estimate less than 10% of the total background level). These are called QCD background in the following.

The ATLAS detector [11] 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. Three stations of drift tubes and cathode strip chambers provide precision measurements and resistive-plate and thin-gap chambers provide muon triggering capability and measurement of the \(\phi\) coordinate.

Most of the data were recorded with highly efficient triggers requiring the presence of an electron or muon candidate with \(p_T > 20\) GeV. Lower thresholds were used for the early data.

Each energy cluster reconstructed in the electromagnetic compartment of the calorimeter with \(E_T > 20\) GeV and \(|\eta| < 2.47\) is considered as an electron candidate if it loosely 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. The intrinsic resolution of the energy measurement is about 2\% at 50 GeV, improving to approximately 1\% at 200 GeV. Electron candidates with clusters containing cells overlapping with the few problematic regions of the calorimeter readout are removed. This reduces the acceptance by 8\%.

Electrons are further identified based on 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 also required to reduce background from photon conversions in the inner detector material. These requirements give about 89\% identification efficiency for electrons with \(E_T > 25\) GeV and a 1/5000 probability to falsely identify jets as electrons before isolation requirements are imposed [12].

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 high-\(p_T\) resolution of the inner detector and muon spectrometer systems is sensitive to detector alignment. The muons used for this analysis are restricted to those which pass through the barrel part of the muon spectrometer, \(|\eta| < 1.05\), where the muon spectrometer alignment is best understood, in particular using high-energy cosmic rays [13]. The momentum of the muon is obtained from the muon spectrometer and the average momentum resolution is currently about 20\% at \(p_T = 1\) TeV. Muons are required to have hits in all three muon stations to ensure this precise measurement of the momentum. About 80\% of the muons in the barrel are reconstructed, with most of the loss coming from regions with limited detector coverage.

For the electron channel, the missing \(E_T\) is obtained from a vector sum over calorimeter cells associated with topological clusters [14]:

\[
E_{T}^{\text{miss}} = E_{T}^{\text{miss}}_{\text{calo}} = -\sum_{\text{topo}} E_{T}^{\text{clus}}.
\]

In the muon channel, most of the muon energy is not deposited in the calorimeter and the missing \(E_T\) is obtained from

\[
E_{T}^{\text{miss}} = E_{T}^{\text{miss}}_{\text{calo}} - p_T + E^{\text{\mu loss}}_T,
\]

where 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 2010 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 36 pb\(^{-1}\) for each channel. The uncertainty on this estimate is 11\% [15].

The \(W\) signal and the \(W/Z\) boson backgrounds are generated with Pythia 6.421 [16] using MRST LO* [17] parton distribution functions (PDFs). The \(t\bar{t}\) background is generated with Mc@nlo 3.41 [18]. \(W \to \ell v\) events are generated with ComPHEP [19] using CTEQ6L1 [20] PDFs followed by Pythia for parton showering and underlying event generation. For all samples, final-state photon radiation is handled by Photos [21] and the propagation of particles and response of the detector are evaluated using ATLAS full detector simulation [22] based on Geant4 [23].

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 \(\tau\nu\), \(u\bar{d}\), \(s\bar{c}\) and \(t\bar{b}\), are included in the calculation of the \(W\) and \(W'\) widths but are not explicitly included as signal or background.

The \(W'\to \ell v, W \to \ell v\) and \(Z \to \ell\ell\) cross sections are calculated at next-to-next-to-leading order QCD (NNLO) using FEWZ [24,25] with MSTW2008 PDFs [26]. For the \(W\) and \(Z\), higher-order electroweak corrections (beyond the photon radiation included in the simulation) are calculated using HORACE [27,28]. In the high-mass region of interest, the electroweak corrections reduce the cross sections, with the reduction increasing with mass. For \(m_{W'} > 750\) GeV, the electroweak corrections reduce the \(W \to \ell v\) cross section by 6\%. Electroweak corrections beyond final-state radiation are not included for \(W\) because the calculation for the SM \(W\) cannot be applied directly. The \(t\bar{t}\) cross section is calculated at near-NNLO using the results from Ref. [29] and assuming a top-quark mass of 172.5 GeV. The signal and most important background cross sections are listed in Table 1. Cross-section uncertainties for \(W'\to \ell v\) and the \(W/Z\) [12] and \(t\bar{t}\) [30] backgrounds are estimated from PDF error sets, the difference between MSTW and CTEQ PDF sets, and standard variations of renormalization and factorization scales. The uncertainties for the LO \(W'\to \ell v\) cross sections include only the contributions from the PDFs.

### Table 1

<table>
<thead>
<tr>
<th>Process</th>
<th>Order</th>
<th>Mass [GeV]</th>
<th>(\sigma) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W' \to \ell v)</td>
<td>NNLO</td>
<td>500</td>
<td>17.25</td>
</tr>
<tr>
<td>(W \to \ell v)</td>
<td>NNLO</td>
<td>500</td>
<td>12.6</td>
</tr>
<tr>
<td>(Z/\gamma^* \to \ell\ell) (m_{Z/\gamma^*} &gt; 60) GeV</td>
<td>NNLO</td>
<td>989</td>
<td></td>
</tr>
<tr>
<td>(t\bar{t} \to \ell X)</td>
<td>Near-NNLO</td>
<td>89.4</td>
<td></td>
</tr>
</tbody>
</table>
Except for QCD and cosmic-ray contamination, expected signal and background levels are evaluated with simulated samples and normalized using the aforementioned cross sections and the integrated luminosity of the data. The same reconstruction and event selection are applied to both data and simulated samples.

Events are required to have a primary vertex reconstructed from at least three tracks with $p_T > 150$ MeV and longitudinal distance less than 150 mm from the center of the collision region. 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. [31]). Events are required to have exactly one candidate electron or one candidate muon, defined as follows. A candidate electron is one reconstructed with $E_T > 25$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.40$. A muon is considered a candidate if it has $p_T > 25$ GeV, $|\eta| < 1.05$ and has matching tracks in the inner detector and muon spectrometer. In addition, the inner detector track associated with the electron or muon is required to be compatible with originating from the primary vertex, specifically with transverse distance of closest approach $|r_0| < 1$ mm and longitudinal distance at this point $|z_0| < 5$ mm.
The above requirements constitute the event preselection criteria. 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 $\Delta R < 0.4 \times (\Delta R = \sqrt{(\Delta y)^2 + (\Delta \varphi)^2})$ around the electron track and the requirement is $\sum E_T < 10 \text{ GeV}$, where the sum excludes the core energy deposited by the electron and is corrected to account for leakage of the electron energy outside this core. In the muon channel, the isolation energy is measured using inner detector tracks with $p_T > 1 \text{ GeV}$ in a cone $\Delta R < 0.3$ around the muon track. The isolation requirement is $\sum p_T < 0.05 p_T$, 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, a missing $E_T$ threshold is applied to further suppress the QCD background. In both channels, a fixed threshold is applied: $E_T^{miss} > 25 \text{ GeV}$. In the electron channel, where QCD jets may be misidentified as electrons, a scaled threshold is also applied: $E_T^{miss} > 0.6 E_T$. Taken together, all the above constitute the final selection requirements.

Fig. 1 shows the $p_T$, missing $E_T$, and $m_T$ spectra in both channels after final selection for the data, for the expected background, and for three examples of $W'$ signals at different masses. The agreement between the data and expected background is good. Table 2 shows an example how different sources contribute to the background for $m_T > 750 \text{ GeV}$, which is the region used to search for a $W'$ or $W^*$ with a mass of 1500 GeV. There are significant differences between the background levels in the electron and muon channels. The background from $W \rightarrow \ell \nu$ and $t\bar{t}$ is higher in the muon channel because of the worse momentum resolution for high-$p_T$ muons. The difference is even larger for the $Z \rightarrow \ell \ell$ background because there is additionally a much larger chance that one lepton is lost due to the restricted acceptance in $\eta$. The QCD background in the electron channel is less than that in the muon channel because of the tighter electron selection criteria: an isolation threshold that is not scaled with $p_T$ and the addition of a scaled missing $E_T$ threshold.

In the electron channel, four techniques are used to estimate the QCD background level from data through the use of subsidiary samples which are disjoint from the analysis region. In the "Inverted identification" technique, the distributions of the QCD background as a function of $p_T$, missing $E_T$, or $m_T$ are estimated from events which pass relaxed identification criteria but fail the normal selection. The normalization is obtained by fitting the missing $E_T$ distribution plus the estimates for EW and $t\bar{t}$ to the observed data. The other techniques are described elsewhere: "Isolation templates" [12], "Three control regions" [32], "Matrix" [33,30]. Fig. 2 shows the estimates obtained from all four techniques after final selection as a function of $m_T$ along with the power-law fit to all four sets of results and its $1 \sigma$ uncertainty band. The extrapolation of this fit and uncertainty band provides the estimate of the QCD background level and uncertainty in the high-$m_T$ region used for the limit calculations.

The shape of the QCD background for the muon channel is evaluated by starting with the muon preselection and replacing the isolation threshold with a range of values in the non-isolated region: $0.2 \times \sum p_T^\text{trk}/p_T < 0.4$. The normalization of the QCD background is determined by fitting the resulting missing $E_T$ spectrum plus the EW and $t\bar{t}$ predictions from simulation to the data after final selection, excluding the missing $E_T$ threshold. The isolation range used to determine the shape is varied to determine the uncertainty in the prediction for the QCD background level. Fig. 3 shows the predicted background level after final selection as a function of $m_T$ along with the unbinsed power-law fit and its $1 \sigma$ uncertainty band. The range of $m_T$ used for the fit is the one which gives largest values for the upper end of this band. The lower end of the uncertainty band corresponds to a negligible background level for all fits. The extrapolation of the fit and uncertainty band provides the QCD background level and uncertainty in the high-$m_T$ region used for the limit calculations.

Cosmic rays can mimic the signal in the muon channel if the muon is only reconstructed on one side of the detector. Most of this background is rejected by the requirement that the muon pass close to the primary vertex and the remainder is estimated by looking at the rate away from the vertex. The measured rate after final selection is less than 2% of the total background for any $m_T$ threshold relevant to this analysis.

### Table 2

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \ell \nu$</td>
<td>$0.145 \pm 0.001$</td>
</tr>
<tr>
<td>$Z \rightarrow \ell \ell$</td>
<td>$0.0001 \pm 0.0001$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$0.011 \pm 0.001$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.003 \pm 0.003$</td>
</tr>
<tr>
<td>QCD</td>
<td>$0.001 \pm 0.004$</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>$0.006 \pm 0.003$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.159 \pm 0.005$</td>
</tr>
</tbody>
</table>

The expected number of events from the various background sources in both decay channels for $m_T > 750 \text{ GeV}$, the region used to search for $W'/W^*$ with a mass of 1500 GeV. The $W \rightarrow \ell \nu$ and $Z \rightarrow \ell \ell$ entries include the expected contributions from the $t$-lepton. The uncertainties are statistical.
The data show no evidence for any excess above SM expectations and are used to set limits on \( \sigma B \) for \( W' \) and \( W^* \) production with the masses listed in Table 1. The limits are evaluated using a single-bin likelihood analysis, i.e. by counting events with \( m_T > 0.5m_W/W^* \). The expected number of events in each channel is

\[ N_{\text{exp}} = \varepsilon_{\text{sig}} L \varepsilon_{\text{int}} \sigma B + N_{\text{bg}}, \]

where \( L \varepsilon_{\text{int}} \) is the integrated luminosity of the data sample and \( \varepsilon_{\text{sig}} \) is the event selection efficiency, i.e. the fraction of events that pass final 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:

\[ \mathcal{L}(\sigma B) = \frac{(L \varepsilon_{\text{int}} \varepsilon_{\text{sig}} \sigma B + N_{\text{bg}})^{N_{\text{obs}}}}{N_{\text{obs}}!} e^{-\left(L \varepsilon_{\text{int}} \varepsilon_{\text{sig}} \sigma B + N_{\text{bg}}\right)} \]

and this expression is used to set limits on \( \sigma B \). Uncertainties are handled by introducing nuisance parameters and multiplying by the probability density function (pdf) characterizing that uncertainty:

\[ \mathcal{L}(\sigma B, \theta_1, \ldots, \theta_k) = \mathcal{L}(\sigma B) \prod g_i(\theta_i), \]

where \( g_i(\theta_i) \) is the Gaussian pdf for nuisance parameter \( \theta_i \). The nuisance parameters are taken to be the explicit dependencies: \( L \varepsilon_{\text{int}}, \varepsilon_{\text{sig}} \) and \( N_{\text{bg}} \). Correlations between these are neglected. This is justified by the small effect that the nuisance parameters themselves have on the limits, as demonstrated below.

The fraction of fully simulated signal events that pass final selection and are above \( m_T \) threshold provides an initial estimate of the expected numbers of events for each mass. Small corrections are made to account for differences between the kinematical distributions at NNLO (obtained from FEWZ) and those in the LO simulation. The largest correction is around 4%. Contributions from \( W' \rightarrow t\nu \) with the \( t \)-lepton decaying leptonically have been neglected and would increase the \( W' \) selection efficiencies by 3–4%.

The EW and \( tt \) background predictions are also obtained from full simulation, normalized to the integrated luminosity of the data. For the EW background, small corrections are again made to account for differences between kinematic distributions in LO simulation and higher order calculations, now using NLO MCFM [34] because the present version of FEWZ does not provide reliable values far from the resonance peak. The background level for each mass is obtained by adding the small QCD and cosmic-ray contributions to these values.

The uncertainties on \( \varepsilon_{\text{sig}} \) and \( N_{\text{bg}} \) account for experimental and theoretical systematic effects as well as the statistics of the simulation samples. The experimental systematic uncertainties include efficiencies for lepton trigger, reconstruction, impact parameter and isolation as well as event vertex reconstruction. 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 due to these extrapolations are included but are too small to significantly affect the \( W'/W^* \) limits. The uncertainties on the QCD and cosmic-ray background estimates also contribute to \( N_{\text{bg}} \). Theoretical systematic uncertainties arise from the calculation of cross sections and their kinematical distributions, lepton isolation, and the distribution of the ratio of neutrino to lepton \( p_T \) which affects the scaled missing \( E_T \) selection efficiency.

Table 3 summarizes the uncertainties on the event-selection efficiencies and background levels for a \( W' \) signal with \( m_{W'} = 1500 \) GeV (i.e. for \( m_T > 750 \) GeV).

Table 3 Relative uncertainties on the event-selection efficiency and background level for a \( W' \) with a mass of 1500 GeV. The most important uncertainties are indicated in bold. The last row gives the total uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>( \varepsilon_{\text{sig}} )</th>
<th>( N_{\text{bg}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_T ) scale</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.0%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Rec. and id. efficiency</td>
<td>3.2%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Isolation leakage</td>
<td>2.7%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Energy/momentum resolution</td>
<td>0.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Energy/momentum scale</td>
<td>0.8%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Correlated misalignment</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>QCD background</td>
<td>2.2%</td>
<td>7.7%</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>1.7%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Cross section (shape/level)</td>
<td>0.7%</td>
<td>8.5%</td>
</tr>
<tr>
<td>Isolation</td>
<td>1.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Other</td>
<td>0.2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>All</td>
<td>5.3%</td>
<td>12.6%</td>
</tr>
</tbody>
</table>

For \( \varepsilon_{\text{sig}} \), most of the uncertainty in the electron channel comes from electron identification except for the higher masses where the isolation leakage is also important. The total is less than 6% for all \( W'/W^* \) masses and has a negligible effect on the limit evaluation. The signal uncertainties are even smaller in the muon channel. For \( N_{\text{bg}} \), the dominant uncertainties in the electron channel come from the electron energy scale and the cross-section calculation. For the muon channel, the simulation statistics followed by the uncertainties on the QCD background and cross-section calculation dominate. The first is large because momentum smearing pushes events with low \( p_T \) and hence higher cross section, into the high-\( m_T \) bins used in the limit evaluation. The cross-section uncertainties are large (around 8% in Table 3) because it is the high-mass tail that is relevant to this analysis.

Limits for 95% CL (confidence level) exclusion on \( \sigma B \) for each \( W' \) and \( W^* \) mass and decay channel are set using the likelihood function in Eq. (6) as input to the estimator \( CL = CL_{\text{ev}} + CL_{\text{obs}} \) [35]. The inputs for the limit calculation are \( L \varepsilon_{\text{int}}, \varepsilon_{\text{sig}}, N_{\text{bg}}, N_{\text{obs}} \) and the uncertainties on the first three. Except for \( L \varepsilon_{\text{int}} \) and its uncertainty, these inputs are all listed in Table 4. The table also lists the predicted numbers of signal events, \( N_{\text{sig}} \), their uncertainty including both that of \( \varepsilon_{\text{sig}} \) and the cross-section calculation. The uncertainties on \( \varepsilon_{\text{sig}}, N_{\text{bg}} \) and \( N_{\text{sig}} \) account for all relevant experimental and theoretical effects except for integrated luminosity which is included separately to allow for the correlation between signal and background. The numbers of observed events are in good agreement with the expected numbers of background events for all mass bins in the electron channel and for the lowest bin (\( m_T > 250 \) GeV) in the muon channel. A discrepancy is observed in the muon channel for \( m_T > 375 \) GeV where 5.48 muon events are predicted and none are observed, a result for which the Poisson probability is only 0.4%. However, the muon \( p_T \) spectrum in Fig. 1 shows no evidence of any discrepancy between data and predicted background at high \( p_T \), confirming that, as expected, the muon efficiency remains stable at high \( p_T \).

Table 5 and Fig. 4 show the \( W' \) and \( W^* \) observed limits on \( \sigma B \) for both decay channels and their combination. The figure also shows the expected limits and the theoretical \( \sigma B \). The intersection between the central theoretical prediction and the observed limits provides the 95% CL lower limit on the mass. Table 6 presents the \( W' \) and \( W^* \) expected and observed mass limits for the electron and muon decay channels and for the combination of both channels. These limits increase by 5–10 GeV if the uncertainties on \( \varepsilon_{\text{sig}}, N_{\text{bg}} \) and \( L \varepsilon_{\text{int}} \) are neglected. For both channels, the effect of the \( \varepsilon_{\text{sig}} \) and \( N_{\text{bg}} \) uncertainties on the limits is small for the lowest-\( m_T \) bin and negligible for the others.
Table 4
Inputs for the $W'/W^* \to \ell \nu \sigma B$ limit calculations for an integrated luminosity of 36 pb$^{-1}$. The first two columns are the $W'/W^*$ mass and decay mode. The next four are the corrected signal selection efficiency, $\epsilon_{\text{sig}}$, 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 for $N_{\text{sig}}$ and $N_{\text{bg}}$ include contributions from the uncertainties in the cross sections but not from the integrated luminosity.

<table>
<thead>
<tr>
<th>$m$ [GeV]</th>
<th>Decay</th>
<th>$\epsilon_{\text{sig}}$</th>
<th>$N_{\text{sig}}$</th>
<th>$N_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$W'$</td>
<td>$W^*$</td>
<td>$W'$</td>
</tr>
<tr>
<td>500</td>
<td>$e\nu$</td>
<td>0.556 $\pm$ 0.024</td>
<td>0.455 $\pm$ 0.019</td>
<td>349 $\pm$ 30</td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.339 $\pm$ 0.008</td>
<td>0.228 $\pm$ 0.004</td>
<td>212 $\pm$ 17</td>
</tr>
<tr>
<td>750</td>
<td>$e\nu$</td>
<td>0.565 $\pm$ 0.025</td>
<td>0.466 $\pm$ 0.020</td>
<td>65.8 $\pm$ 4.8</td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.362 $\pm$ 0.009</td>
<td>0.230 $\pm$ 0.005</td>
<td>42.1 $\pm$ 2.7</td>
</tr>
<tr>
<td>1000</td>
<td>$e\nu$</td>
<td>0.562 $\pm$ 0.025</td>
<td>0.473 $\pm$ 0.021</td>
<td>17.1 $\pm$ 1.4</td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.381 $\pm$ 0.010</td>
<td>0.242 $\pm$ 0.005</td>
<td>11.6 $\pm$ 0.9</td>
</tr>
<tr>
<td>1250</td>
<td>$e\nu$</td>
<td>0.552 $\pm$ 0.026</td>
<td>0.469 $\pm$ 0.021</td>
<td>5.23 $\pm$ 0.51</td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.386 $\pm$ 0.011</td>
<td>0.237 $\pm$ 0.005</td>
<td>3.66 $\pm$ 0.33</td>
</tr>
<tr>
<td>1500</td>
<td>$e\nu$</td>
<td>0.530 $\pm$ 0.028</td>
<td>0.457 $\pm$ 0.023</td>
<td>1.71 $\pm$ 0.21</td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.383 $\pm$ 0.012</td>
<td>0.235 $\pm$ 0.006</td>
<td>1.24 $\pm$ 0.14</td>
</tr>
<tr>
<td>1750</td>
<td>$e\nu$</td>
<td>0.503 $\pm$ 0.027</td>
<td>0.454 $\pm$ 0.027</td>
<td>0.59 $\pm$ 0.09</td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.360 $\pm$ 0.012</td>
<td>0.239 $\pm$ 0.006</td>
<td>0.43 $\pm$ 0.06</td>
</tr>
</tbody>
</table>

Limits on $W' \to \ell \nu$ have been reported in many other experiments [1–6]. Prior to this Letter and the recent $W' \to \mu\nu$ results from CMS [6], the best limits in the high-mass region were reported by CDF [4] and CMS [5], both for $W' \to e\nu$. The CDF measurement was made with $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using an integrated luminosity of 5.3 fb$^{-1}$. Both CMS results were obtained at the same collision energy ($\sqrt{s} = 7$ TeV) and during the same run period as those reported here. The CMS limits were set using a Bayesian approach. Ref. [6] also reports a combination of the CMS results in the two decay channels with an SSM $W'$ mass limit of 1580 GeV. Fig. 5 compares the result presented here with the $W' \to e\nu$ result from CDF and the combination from CMS. The comparison is made using the ratio of the limit to the calculated value of $\sigma_B$, a quantity that is proportional to the square of the coupling strength. The NNLO cross sections in Table 1 are used for both the ATLAS and CMS points.

In conclusion, the ATLAS detector has been used to search for new high-mass states decaying to a lepton plus missing $E_T$ in $p\bar{p}$ collisions at $\sqrt{s} = 7$ TeV using 36 pb$^{-1}$ of integrated luminosity. No excess beyond SM expectations is observed. Limits on $\sigma B$ are shown in Figs. 4 and 5. A $W'$ with SSM couplings is excluded for masses below 1490 GeV at 95% CL. The exclusion for $W^*$ with couplings set in accordance with Ref. [10] is 1350 GeV. These are the first direct limits on $W^*$ production.

Acknowledgements

We wish to thank CERN for the efficient commissioning and operation of the LHC during this initial high-energy data-taking period as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MINECO and CONICET, Spain; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF,
Fig. 4. Limits at 95% CL for $W'$ (left) and $W^*$ (right) production in the decay channels $W'/W^* \to e\nu$ (top), $W'/W^* \to \mu\nu$ (center), and the combination of these (bottom). The solid lines show the observed limits with all uncertainties. The expected limit is indicated with dashed lines surrounded by 1σ and 2σ shaded bands. Dashed lines show the theory predictions (NNLO for $W'$, LO for $W^*$) between solid lines indicating their uncertainties. The $W'$ $\sigma B$ uncertainties are obtained by varying renormalization and factorization scales and by varying PDFs. Only the latter are included for $W^*$.

MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNISW, Poland; GRCIES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.
Fig. 5. Normalized cross-section limits ($\sigma_{\text{limit}}/\sigma_{\text{theory}}$) for $W'$ as a function of mass for this measurement and those from CDF and CMS. The cross-section calculations above each curve is excluded at 95% CL.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References


ATLAS Collaboration

Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18 (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
19 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20 Physikalisches Institut, Universität Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston, MA, United States
22 Department of Physics, Brandeis University, Waltham, MA, United States
23 (a) Universidade Federal do Rio De Janeiro COPPE/EE/RI, Rio de Janeiro; (b) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
25 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
26 Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa, ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
31 (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington, NY, United States
35 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
36 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavacata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas, TX, United States
40 Physics Department, University of Texas at Dallas, Richardson, TX, United States
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham, NC, United States
45 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wien Neustadt, Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Matematik und Physik, Albert-Ludwigs-Universität, Freiburg i.B., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3, Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton, VA, United States
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington, IN, United States
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City, IA, United States
64 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jozef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 Department of Physics, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiksa Institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst, MA, United States
85 Department of Physics, McGill University, Montreal, QC, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
88 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
89 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus