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


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Abstract

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 36pb$^{-1}$. 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.

The ATLAS Collaboration

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 $W'$, the charged ones commonly denoted $W^\prime$. 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 on $\sigma_B$ (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) 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 $W'$. 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' boson and thus a width which increases linearly with $W'$ mass is adopted.

The analysis presented here identifies candidates in the electron and muon channels, sets separate limits for the same mass is adopted [10].

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. These are 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 \( \varphi \) coordinate.

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

Each energy cluster reconstructed in the electromagnetic compartment of the calorimeter with \( E_T > 20 \text{ GeV} \) 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 \( E_T > 25 \text{ GeV} \) 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 \( p_T = 1 \text{ TeV} \). 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]:

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

(2)

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

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

(3)

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 \( \sqrt{s} = 7 \text{ TeV} \) 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 \( W^\prime \) signal and the \( W/Z \) boson backgrounds are generated with \textsc{Pythia} 6.421 [16] using MRST LO* [17] parton distribution functions (PDFs). The \( tt \) background is generated with MC@NLO 3.41 [18]. \( W^\prime \rightarrow \ell\nu \) events are generated with \textsc{CompHEP} [19] using CTEQ6L1 [20] PDFs followed by \textsc{Pythia} for parton showering and underlying event generation. For all samples, final-state photon radiation is handled by \textsc{Photos} [21] and the propagation of particles and response of the detector are evaluated using \textsc{ATLAS} full detector simulation [22] based on \textsc{Geant4} [23].

The \textsc{Pythia} signal model used as a benchmark for \( W^\prime \) has \( V-A \) SM couplings but does not include interference between \( W \) and \( W^\prime \). Decays to channels other than \( \ell\nu \) and \( \mu\nu \), including \( \tau\nu, u\bar{d}, s\bar{c} \) and \( t\bar{b} \), are included in the calculation of the \( W^\prime \) and \( W^\ast \) widths but are not explicitly included as signal or background.

The \( W^\prime \rightarrow \ell\nu, W \rightarrow \ell\nu \) and \( Z \rightarrow \ell\ell \) cross sections are calculated at next-to-next-to-leading order QCD (NNLO) using \textsc{FEWZ} [24, 25] with \textsc{MSTW}2008 PDFs [20]. For the \( W \) and \( Z \), higher-order electroweak corrections (beyond the photon radiation included in the simulation) are calculated using \textsc{HORACE} [27, 28]. In the high-mass region of interest, the electroweak corrections reduce the cross sections, with the reduction increasing with mass. For \( m_T > 750 \text{ GeV} \), the electroweak corrections reduce the \( W \rightarrow \ell\nu \) cross section by 6\%. Electroweak corrections beyond final-state radiation are not included for \( W^\prime \) because the calculation for the SM \( W \) cannot be applied directly. The \( tt \) cross section is calculated at near-NNLO using the results from reference [29] and assuming a top-quark mass of 172.5 GeV. The signal and most important background cross sections are listed in Table 4. Cross-section uncertainties for \( W^\prime \rightarrow \ell\nu \) and the \( W/Z \) [12] and \( tt \) [30] backgrounds are estimated from PDF error sets, the difference between \textsc{MSTW} and \textsc{CTEQ} PDF sets, and standard variations of renormalization and factorization scales. The uncertainties for the LO \( W^\ast \rightarrow \ell\nu \) cross sections include only the contributions from the PDFs.

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.
<table>
<thead>
<tr>
<th>Process</th>
<th>Order</th>
<th>Mass [GeV]</th>
<th>$\sigma B$ [pb]</th>
</tr>
</thead>
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<td>$W' \rightarrow \ell\nu$</td>
<td>NNLO</td>
<td>500</td>
<td>17.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>750</td>
<td>3.20</td>
</tr>
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<td>1250</td>
<td>0.261</td>
</tr>
<tr>
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<td></td>
<td>1500</td>
<td>0.0887</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1750</td>
<td>0.0325</td>
</tr>
<tr>
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<td>LO</td>
<td>500</td>
<td>10.8</td>
</tr>
<tr>
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<td></td>
<td>750</td>
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<td></td>
<td></td>
<td>1750</td>
<td>0.0212</td>
</tr>
<tr>
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<td>NNLO</td>
<td>10460</td>
<td></td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \ell\ell$</td>
<td>NNLO</td>
<td>989</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \ell X$</td>
<td>Near-NNLO</td>
<td>89.4</td>
<td></td>
</tr>
</tbody>
</table>

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 $\Delta R < 0.4$ ($\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$) around the electron track and the requirement is $\sum E_T < 10$ 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 $p_T^{trk} > 1$ GeV in a cone $\Delta R < 0.3$ around the muon track.

The isolation requirement is $\sum p_T^{trk} < 0.05 p_T$, 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: $E_T^{miss} > 25$ 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.

Figure [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 $W'$ 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.
Figure 1: Spectra of \( p_T \) (top), missing \( E_T \) (center) and \( m_T \) (bottom) for the electron (left) and muon (right) channels after final event selection. The points represent ATLAS data and the filled histograms show the stacked backgrounds. Both direct production of leptons and indirect from \( \tau \)-leptons are included. Open histograms are \( W' \) signals added to the background with masses in GeV indicated in parentheses in the legend. The QCD background is estimated from data. The signal and other background samples are normalized using the integrated luminosity of the data and the NNLO (near-NNLO for \( t\bar{t} \)) cross sections listed in Table 1.
“Isolation templates” [12], “Three control regions” [32], “Matrix” [33, 31]. Figure 2 shows the estimates obtained from all four techniques after final selection as a function of \( m_T \) with the power-law fit to all four sets of results and its 1\( \sigma \) uncertainty band also shown.

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 < \( \sum p_{T}^{trk}/p_{T} < 0.4 \). 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. Figure 3 shows the predicted background level after final selection and are above \( m_T > 0.5 \) \( m_W/W' \). The expected number of events in each channel is

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

where \( L_{\text{int}} \) 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:

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

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:

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

where \( g_i(\theta_i) \) is the Gaussian pdf for nuisance parameter \( \theta_i \). The nuisance parameters are taken to be the explicit dependencies: \( L_{\text{int}}, \varepsilon_{\text{sig}} \) 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 \( W' \rightarrow \tau \nu \) with the \( \tau \)-lepton decaying leptonically have been neglected and would increase the \( W' \) selection efficiencies by 3-4%.
The EW and $t\bar{t}$ 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 kinematical distributions in LO simulation and higher order calculations, now using NLO MCDFM [32] 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 $m_{W'} > 750$ GeV). 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-$p_T$ 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. (5) as input to the estimator $CL_s = CL_{s+b}/CL_b$ [33]. The inputs for the limit calculation are $L_{\text{int}}, \varepsilon_{\text{sig}}, N_{\text{bg}}, N_{\text{obs}}$ and the uncertainties on the first three. Except for $L_{\text{int}}$ and its uncertainty, these inputs are all listed in Table 3. The table also lists the predicted numbers of signal events, $N_{\text{sig}}$, with 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 in the muon channel. A discrepancy is observed in the muon channel for $m_{W'} > 750$ 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. 4 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 $p_T$.

Limits on $W' \rightarrow \ell \nu$ have been reported in many other experiments [1, 2, 3, 4, 5, 6]. Prior to this letter and the recent $W' \rightarrow \ell \nu$ results from CMS [6], the best limits in the high-mass region were reported by CDF [3] and CMS [4], both for $W' \rightarrow e\nu$. The CDF measurement was made with $pp$ 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. Figure 5 compares the result presented here with the $W' \rightarrow e\nu$ 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 4 are used for both the ATLAS and CMS points.

In conclusion, the ATLAS detector has been used to perform a search for new high-mass states decaying to a lepton plus missing $E_T$ in $pp$ 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 reference [10] is 1350 GeV. The limits for $W^*$ are the most stringent to date.
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_{bg}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\nu$</td>
<td>$\mu\nu$</td>
</tr>
<tr>
<td>Missing $E_T$ 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>Reco. and id. efficiency</td>
<td>3.6%</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>
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</tr>
<tr>
<td>QCD background</td>
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<tr>
<td>Monte Carlo statistics</td>
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<td>1.6%</td>
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<tr>
<td>Cross section (shape/level)</td>
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<tr>
<td>Isolation</td>
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<td>1.5%</td>
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<tr>
<td>Other</td>
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<td>0.4%</td>
</tr>
<tr>
<td>All</td>
<td>5.3%</td>
<td>3.0%</td>
</tr>
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Table 4: Inputs for the $W'/W^* \rightarrow \ell \nu \sigma B$ 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, $\varepsilon_{\text{sig}}$, 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 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>$\varepsilon_{\text{sig}}$</th>
<th>$W'$</th>
<th>$W^*$</th>
<th>$N_{\text{sig}}$</th>
<th>$W'$</th>
<th>$W^*$</th>
<th>$N_{\text{bg}}$</th>
<th>$N_{\text{obs}}$</th>
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<tr>
<td>500</td>
<td>$e\nu$</td>
<td>0.556 ± 0.024</td>
<td>0.530 ± 0.022</td>
<td>349 ± 30</td>
<td>208 ± 18</td>
<td>21.5 ± 2.0</td>
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<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.339 ± 0.008</td>
<td>0.265 ± 0.005</td>
<td>212 ± 17</td>
<td>104 ± 8</td>
<td>20.3 ± 1.1</td>
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<tr>
<td>750</td>
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<td>0.520 ± 0.022</td>
<td>65.8 ± 4.8</td>
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<tr>
<td></td>
<td>$\mu\nu$</td>
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<td>0.257 ± 0.005</td>
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<tr>
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<td>$e\nu$</td>
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<td>0.516 ± 0.022</td>
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<td>0.264 ± 0.006</td>
<td>11.6 ± 0.9</td>
<td>5.4 ± 0.5</td>
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<tr>
<td>1250</td>
<td>$e\nu$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.386 ± 0.011</td>
<td>0.255 ± 0.006</td>
<td>3.66 ± 0.33</td>
<td>1.63 ± 0.20</td>
<td>1.01 ± 0.17</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>$e\nu$</td>
<td>0.530 ± 0.028</td>
<td>0.488 ± 0.025</td>
<td>1.71 ± 0.21</td>
<td>1.06 ± 0.17</td>
<td>0.159 ± 0.020</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.383 ± 0.012</td>
<td>0.252 ± 0.006</td>
<td>1.24 ± 0.14</td>
<td>0.54 ± 0.08</td>
<td>0.62 ± 0.13</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1750</td>
<td>$e\nu$</td>
<td>0.503 ± 0.027</td>
<td>0.482 ± 0.028</td>
<td>0.59 ± 0.09</td>
<td>0.37 ± 0.07</td>
<td>0.069 ± 0.009</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu\nu$</td>
<td>0.360 ± 0.012</td>
<td>0.254 ± 0.007</td>
<td>0.43 ± 0.06</td>
<td>0.20 ± 0.04</td>
<td>0.47 ± 0.09</td>
<td>0</td>
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<td></td>
</tr>
</tbody>
</table>
Figure 4: Limits at 95% CL for $W'$ (left) and $W^*$ (right) production in the decay channels $W'/W^* \rightarrow e\nu$ (top), $W'/W^* \rightarrow \mu\nu$ (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 $W^*$. 
Table 5: Upper limits on $W'$ and $W^*$ $\sigma_B$. 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 ($\varepsilon_{\text{sig}}$), B for the background level ($N_{\text{bg}}$), and L for the integrated luminosity ($L_{\text{int}}$). 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>mass [GeV]</th>
<th>$\sigma_B$ limit on $W'$ [fb]</th>
<th>$\sigma_B$ limit on $W^*$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>none</td>
<td>S</td>
</tr>
<tr>
<td>500 $\mu\nu$</td>
<td>625</td>
<td>625</td>
</tr>
<tr>
<td>750 $\mu\nu$</td>
<td>227</td>
<td>228</td>
</tr>
<tr>
<td>1000 $\mu\nu$</td>
<td>108</td>
<td>109</td>
</tr>
<tr>
<td>1250 $\mu\nu$</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>1500 $\mu\nu$</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>1750 $\mu\nu$</td>
<td>95</td>
<td>96</td>
</tr>
</tbody>
</table>

Table 6: Lower limits on $W'$ and $W^*$ masses. 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>decay</th>
<th>Mass limit [GeV]</th>
<th>$W'$</th>
<th>$W^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\nu$</td>
<td>1370</td>
<td>1370</td>
<td>1260</td>
</tr>
<tr>
<td>$\mu\nu$</td>
<td>1210</td>
<td>1290</td>
<td>1020</td>
</tr>
<tr>
<td>both</td>
<td>1450</td>
<td>1490</td>
<td>1320</td>
</tr>
</tbody>
</table>

Figure 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 assume the $W'$ has the same couplings as the standard model $W$ boson. The region above each curve is excluded at 95% CL.

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