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DOI
10.1016/j.physletb.2011.09.093

Publication date
2011

Document Version
Final published version

Published in
Physics Letters B

Link to publication

Citation for published version (APA):

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Search for a heavy gauge boson decaying to a charged lepton and a neutrino in 1 fb\(^{-1}\) of pp collisions at \(\sqrt{s} = 7\) TeV using the ATLAS detector

ATLAS Collaboration

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 \([1]\), 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 during 2011 and corresponding to a total integrated luminosity of 1.04 fb\(^{-1}\). No excess above 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.

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 above 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.

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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 $\psi$ 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 (less than 2%) $\eta$-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 $|\eta| < 1$ and a $2 \times 10^{-4}$ probability to falsely identify jets as electrons before isolation requirements are imposed.

Muons 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 [8]:

$$E_{T}^{\text{miss}} = E_{T}^{\text{miss \; \text{calo}}} = - \sum_{\text{topo}} E_{T}^{\text{cell}}. \quad (2)$$

The topological clusters reduce contributions from electronic noise. 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

$$E_{T}^{\text{miss \; \mu}} = E_{T}^{\text{miss \; \text{calo}}} - E_{T}^{\text{miss \; \text{loss}}}. \quad (3)$$

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 Pythia signal model for $W'$ has $V-A$ SM couplings but does not include interference between $W$ and $W'$. Decays to channels other than $\ell\nu$ and $\mu\nu$, including $t\tau$, $u\nu$, $s\nu$, and $t\bar{b}$ 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 $W \rightarrow \ell\nu$ 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 $G_{\mu}$ 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 $m_{W'} = 1$ TeV and by 18% at $m_{W'} = 2$ TeV.

The $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ cross sections are calculated at NNLO using FEWZ [19,20] with the same PDFs, scheme and electroweak corrections used in the ZWPROD event reweighting. The $W' \rightarrow \ell\nu$ 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 [21–23] assuming a top-quark mass of 172.5 GeV. The signal and most important background values for $W'$ are listed in Table 1.

Cross-section uncertainties for $W' \rightarrow \ell\nu$ and the $W/Z$ [7] and $t\bar{t}$ [24] backgrounds are estimated from the MSTW2008 PDF error sets, the difference between MSTW2008 and CTEQ6.6 [25] PDF sets, and variation of renormalization and factorization scales by a factor of two. The estimates from the three sources are combined in quadrature. Most of the net uncertainty comes from the error sets and the MSTW–CTEQ difference, in roughly equal proportion. The uncertainty on the cross section for the $W \rightarrow \ell\nu$ background varies from 5% at $m_{W'} = 500$ GeV to 19% at $m_{W'} = 2500$ GeV.

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. [26]. 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 $\sum E_T < 9$ 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 $p_T^{\text{trk}} > 1$ GeV in a cone $|\Delta R| < 0.3$ around the muon track. The isolation requirement is $\sum p_T^{\text{trk}} < 0.05 p_T$, 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, 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 hadronic 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 [27] with the isolation energy and missing $E_T$ serving as discriminants. Consistent results are obtained using the “inverted isolation” technique described in Ref. [4]. In the higher mass bins ($m_T > 700$ 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 $m_T$ 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 [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.

<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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<tr>
<td></td>
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<td>1250</td>
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</tr>
<tr>
<td></td>
<td>1500</td>
<td>0.0887</td>
</tr>
<tr>
<td></td>
<td>1750</td>
<td>0.0225</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>0.0126</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>
</tbody>
</table>
| $W \to \ell \

The same reconstruction and event selection are applied to both data and simulated samples. Fig. 1 shows the $p_T$, missing $E_T$, and $m_T$ spectra for each channel after event 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 as an example how different sources contribute to the background for $m_T > 891$ GeV, the region used to search for a $W'$ with a mass of 1500 GeV. The $W \to \ell \nu$ background dominates. The $Z \to \ell \ell$ background is much larger in the muon channel because most of the energy of the undetected muon is not captured in the calorimeter.

### 5. Statistical analysis

A Bayesian analysis is performed to determine if there is significant evidence for existence of a $W' \to \ell \nu$ 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

$$N_{\text{exp}} = \epsilon_{\text{sig}} L \int \sigma^B + N_{\text{bg}},$$

where $L$ is the integrated luminosity of the data sample and $\epsilon_{\text{sig}}$ 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

$$L(N_{\text{obs}} | \sigma B) = \frac{L^{\text{int}} \epsilon_{\text{sig}}^B + N_{\text{bg}}}{N_{\text{obs}}!} e^{-L^{\text{int}} \epsilon_{\text{sig}}^B + N_{\text{bg}}}.$$  

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

$$L_B(N_{\text{obs}} | \sigma B) = \int L(N_{\text{obs}} | \sigma B) \prod g_i(\theta_i) d\theta_i.$$  

The nuisance parameters are taken to be explicit dependencies: $L^{\text{int}}, \epsilon_{\text{sig}}$ and $N_{\text{bg}}$, with the latter evaluated at the central value of $L^{\text{int}}$. Correlations between the nuisance parameters are neglected.

The measurements in the two decay channels are combined assuming the same branching fraction for each. Eq. (6) remains valid with the Poisson likelihood replaced by the product of the Poisson likelihoods for the two channels. The electron and muon integrated luminosities are measurements 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 $\sigma B$ limits for
Bayes theorem gives the posterior probability that the \( W' \to \ell \nu \) has signal strength \( \sigma_B \):

\[
    P_{\text{post}}(\sigma_B | N_{\text{obs}}) = \frac{N L_B(N_{\text{obs}} | \sigma_B) P_{\text{prior}}(\sigma_B)}{N_{\text{obs}}}
\]

where \( P_{\text{prior}}(\sigma_B) \) is the assumed prior probability, here chosen to be one (i.e. flat in \( \sigma_B \)) for \( \sigma_B > 0 \). 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 \( \sigma_B \).

The inputs for the evaluation of \( L_B \) (and hence \( P_{\text{post}} \)) are \( L_{\text{int}} \), \( \epsilon_{\text{sig}} \), \( N_{\text{sig}} \), \( N_{\text{obs}} \) 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 \( \epsilon_{\text{sig}} \) and \( N_{\text{sig}} \) account for simulation statistics and 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 \( \epsilon_{\text{sig}} \) and the cross-section calculation.

**6. Parameter estimation and systematics**

The inputs for the evaluation of \( L_B \) (and hence \( P_{\text{post}} \)) are \( L_{\text{int}} \), \( \epsilon_{\text{sig}} \), \( N_{\text{sig}} \), \( N_{\text{obs}} \) 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 \( \epsilon_{\text{sig}} \) and \( N_{\text{sig}} \) account for simulation statistics and 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 \( \epsilon_{\text{sig}} \) and the cross-section calculation.
The maximum value for the signal selection efficiency is at \( m_{W'} = 1500 \text{ GeV} \). For lower masses, the efficiency falls because the relative \( m_T \) threshold, \( m_{T\text{min}}/m_{W'} \), 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 \( m_{W'} \ll m_{W'} \).

The fraction of fully simulated signal events that pass the event selection and are above the \( m_{T} \) threshold provides the initial estimate of \( \epsilon_{\text{sig}} \) 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 \( m_{W'} = 500 \text{ GeV} \) to a 10% decrease for \( m_{W'} = 2500 \text{ GeV} \). Contributions from \( W' \rightarrow \tau \nu \) with the \( \tau \) -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 \( \tau \tau \) event counts from simulation, and adding the small QCD contribution in the electron channel.

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 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.

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.
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 \( m_{W'} \gtrsim 1000 \text{ GeV} \) 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 5.

Prior to this Letter, the best limits for \( 500 < m_{W'} < 800 \text{ GeV} \) were established by CDF \([2]\) in \( W' \to e\nu \) with \( pp \) 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 pp 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 CLs. Fig. 3 compares the limits obtained here with those earlier measurements. 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

![Figure 2](image-url)

Fig. 2. Expected and observed limits on \( \sigma B \) for \( W' \to e\nu \) (top), \( W' \to \mu \nu \) (center), and the combination (bottom) assuming the same branching fraction for both channels. The NNLO calculated cross section and its uncertainty are also shown.

### Table 5

<table>
<thead>
<tr>
<th>( m_{W'} ) [GeV]</th>
<th>95% CL limit on ( \sigma B ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 500 ) ( e\nu )</td>
<td>97 ( \pm ) 98 ( \pm ) 117 ( \pm ) 121</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>171 ( \pm ) 174 ( \pm ) 186 ( \pm ) 191</td>
</tr>
<tr>
<td>( 600 ) ( e\nu )</td>
<td>49 ( \pm ) 49 ( \pm ) 59 ( \pm ) 61</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>99 ( \pm ) 100 ( \pm ) 108 ( \pm ) 110</td>
</tr>
<tr>
<td>( 750 ) ( e\nu )</td>
<td>23.0 ( \pm ) 23.1 ( \pm ) 28.1 ( \pm ) 28.5</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>46.2 ( \pm ) 49.8 ( \pm ) 50.9 ( \pm ) 51.7</td>
</tr>
<tr>
<td>( 1000 ) ( e\nu )</td>
<td>10.1 ( \pm ) 10.2 ( \pm ) 10.5 ( \pm ) 10.6</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>16.1 ( \pm ) 16.3 ( \pm ) 16.5 ( \pm ) 16.7</td>
</tr>
<tr>
<td>( 1250 ) ( e\nu )</td>
<td>0.9 ( \pm ) 0.9 ( \pm ) 1.0 ( \pm ) 1.0</td>
</tr>
<tr>
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<td>14.4 ( \pm ) 14.5 ( \pm ) 14.6 ( \pm ) 14.7</td>
</tr>
<tr>
<td>( 1750 ) ( e\nu )</td>
<td>7.8 ( \pm ) 7.9 ( \pm ) 7.9 ( \pm ) 7.9</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>12.0 ( \pm ) 12.1 ( \pm ) 12.1 ( \pm ) 12.2</td>
</tr>
<tr>
<td>( 2000 ) ( e\nu )</td>
<td>6.9 ( \pm ) 7.0 ( \pm ) 7.0 ( \pm ) 7.0</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
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</tr>
<tr>
<td>( 2250 ) ( e\nu )</td>
<td>10.2 ( \pm ) 10.3 ( \pm ) 10.3 ( \pm ) 10.3</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>14.9 ( \pm ) 14.9 ( \pm ) 14.9 ( \pm ) 14.9</td>
</tr>
<tr>
<td>( 2500 ) ( e\nu )</td>
<td>7.5 ( \pm ) 7.6 ( \pm ) 7.6 ( \pm ) 7.6</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>19.2 ( \pm ) 19.5 ( \pm ) 19.6 ( \pm ) 19.7</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>9.5 ( \pm ) 9.6 ( \pm ) 9.6 ( \pm ) 9.6</td>
</tr>
</tbody>
</table>

### Table 6

<table>
<thead>
<tr>
<th>( m_{W'} ) [TeV]</th>
<th>Exp.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e\nu )</td>
<td>2.17</td>
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<td>( \mu \nu ) both</td>
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<td>1.98</td>
</tr>
<tr>
<td>( \mu \nu ) both</td>
<td>2.23</td>
<td>2.15</td>
</tr>
</tbody>
</table>
for both the ATLAS and CMS points. The limits presented here provide significant improvement for masses above 600 GeV.

8. Conclusions

The ATLAS detector has been used to search for new high-mass states decaying to a lepton plus missing $E_T$. The search is performed in $pp$ collisions at $\sqrt{s} = 7$ TeV using $1.04$ fb$^{-1}$ of integrated luminosity. No excess above 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 SM couplings is excluded for masses up to $2.15$ TeV at the 95% CL.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not have been operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; MINECO, Spain; BMBWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Armenia; ARC, Australia; BMWF, Austria; ANAS, A

References


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