Search for a heavy gauge boson \( W' \) in the final state with an electron and large missing transverse energy in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV \(^\star\)

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A search for a heavy gauge boson \( W' \) has been conducted by the CMS experiment at the LHC in the decay channel with an electron and large transverse energy imbalance \( E_T^{\text{miss}} \), using proton–proton collision data corresponding to an integrated luminosity of 36 \( \text{pb}^{-1} \). No excess above standard model expectations is seen in the transverse mass distribution of the electron-\( E_T^{\text{miss}} \) system. Assuming standard-model-like couplings and decay branching fractions, a \( W' \) boson with a mass less than 1.36 TeV/\( c^2 \) is excluded at 95% confidence level.

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energy deposit with that expected for an electron. The electrons must have a transverse energy greater than 30 GeV, and should be isolated in a cone of radius \( \Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3 \) around the electron candidate direction, both in the tracker and in the calorimeter. In the tracker, the sum of the \( p_T \) of the tracks, excluding tracks within an inner cone of 0.04, is required to be less than 7 (15) GeV for electron candidates reconstructed within the barrel (endcap) acceptance. For the isolation using calorimeters, the total transverse energy in the barrel, excluding deposits associated to the electron, should be less than 0.03 \( \cdot E_{T}^{\text{ele}} + 2.0 \) GeV. In the endcap, the isolation exploits the segmentation of the hadron calorimeter to minimize contamination from the multi-jet background. For electrons in the endcap with \( E_{T}^{\text{ele}} > 50 \) GeV, the sum of \( E_T \) of deposits in the electromagnetic and the first segment of the hadron calorimeter, not associated to the electron itself, must be less than 0.03 \( \cdot (E_{T}^{\text{ele}} - 50) + 2.5 \) GeV. For endcap electrons of less than 50 GeV the sum of \( E_T \) should be below 2.5 GeV. The \( E_T \) of deposits in the second segment of the hadron calorimeter must be less than 0.5 GeV [9]. These selections are designed to ensure high efficiency for electrons and a high rejection of misreconstructed electrons from multi-jet backgrounds. Since the amount of background from multi-jet events differs in the central and the forward region, the selections described are optimized for high energy electrons separately in the two regions [9].

To account for the energy imbalance due to the escaping neutrino, we use a particle flow technique, which reconstructs a complete list of particles in an event using all the available information [10]. Muons, electrons, photons, and charged and neutral hadrons are reconstructed individually. We denote the negative vector sum of the energy of all reconstructed particles in the event projected on the transverse plane as \( \mathbf{E}_{\text{miss}} \). It represents an estimate of the vector sum of the transverse momentum of all escaping neutral particles, such as neutrinos.

Since we are searching for a two-body decay which reconstructs to a high mass, the energy of the neutrino and electron are expected to be mostly balanced in the transverse plane, both in direction and in magnitude. We therefore require \( 0.4 < E_{T}^{\text{ele}}/E_{T}^{\text{miss}} < 1.5 \). For the same reason, we require that the angle between the electron and the \( \mathbf{E}_{\text{miss}} \) be close to \( \pi \) radians: \( \Delta \phi_{\text{ele}E_{\text{miss}}} > 2.5 \) rad.

The primary discriminating variable is the transverse mass \( M_T \). The transverse mass is the equivalent of the invariant mass of a four-vector computed with only the transverse components of those four-vectors: \( M_T = \sqrt{2 \cdot E_{T}^{\text{ele}} \cdot E_{T}^{\text{miss}} \cdot (1 - \cos \Delta \phi_{\text{ele}E_{\text{miss}}})} / c^2 \). As with a \( W \), we expect the \( M_T \) distribution of \( W \) events to exhibit a characteristic Jacobian edge at the value of the mass of the decaying particle.

After applying these event selection criteria, the main background consists of \( W \rightarrow e\nu \) decays in the tails of the SM \( W \) mass distribution. Given the high transverse mass of a potential signal, multi-jet production constitutes a background when one jet is misreconstructed and the \( E_{T}^{\text{miss}} \) is a result of this misreconstruction. Further contributions are due to \( W \rightarrow \tau\nu \) decays where the tau-lepton subsequently decays to an electron and neutrinos. Since these electrons result from several preceding decays, their energies are rather low and do not spread much into the signal region. Electrons from semi-leptonic decays of \( t \) events may also constitute a background primarily at low energies. Small contributions are caused by Drell–Yan \( Z/\gamma \) production followed by decays into \( e^+e^- \) pairs where one electron is not detected, diboson production and other QCD backgrounds such as \( \gamma + \text{jet} \). All backgrounds are summarized in Table 1.

Estimates of the \( M_T \) distribution for all backgrounds except for the two backgrounds, \( W \rightarrow e\nu \) and multi-jet events, are obtained using Monte Carlo simulations, with a combination of PYTHIA v6.422 [11] and MADGRAPH [12] event generators. The geometric and kinematic acceptances are calculated using a GEANT-based simulation of the CMS detector [13]. The CTQG61 parton distribution functions are used to model the momentum distribution of the initial-state partons [14]. For the signal sample, the PYTHIA event generator with its implementation of the reference model [4] is used at varying mass points up to \( M_W = 2.0 \) TeV/c\(^2\). A mass-dependent \( K \)-factor of about 1.3 approximating the next-to-next-to-leading-order (NNLO) cross sections is applied [15,16], varying between 1.26 (for \( M_W = 2 \) TeV/c\(^2\)) and 1.32 (for \( M_W = 0.6 \) TeV/c\(^2\)). After the final event selections, the product of geometric acceptance and efficiency for the \( W \) signal is greater than 64%, independent of mass, for the range \( M_W = 0.9-2.0 \) TeV/c\(^2\). The electron identification efficiency is measured with the tag-and-probe method in data and simulation using a clean sample of \( Z \rightarrow e^+e^- \). In this method one lepton candidate, called the “tag”, satisfies certain selection criteria while the other lepton candidate, called the “probe”, is required to pass specific criteria which define the particular efficiency under study. This method measured the electron identification efficiency to be about 2% lower in data than in Monte Carlo simulations and therefore a correction factor was applied to the simulation.

The \( W \) and multi-jet background estimates are derived from a combination of experimental data and Monte Carlo simulations. For the \( W \rightarrow e\nu \) background, we obtain an initial estimate of the \( M_T \) shape from simulations using the PYTHIA event generator. Differences in the \( E_{T}^{\text{miss}} \) resolution between the data and simulations are corrected using a technique based on the measurement of \( E_{T}^{\text{miss}} \) in \( Z \rightarrow e^+e^- \) events [17]. The absolute normalizations of the multi-jet and \( W \) backgrounds are obtained using the \( E_{T}^{\text{ele}}/E_{T}^{\text{miss}} \) distribution. A Crystal Ball [18] function is used to describe the distribution for \( W \) bosons and an empirical shape is used for the multi-jet background, while for all other backgrounds the distributions and the normalisations are fixed to the standard model predictions. After subtraction of the latter backgrounds, a simultaneous fit to the \( E_{T}^{\text{ele}}/E_{T}^{\text{miss}} \) distribution in the data provides the multi-jet and \( W \) normalizations. Fig. 1 shows the result of this fit.

Table 1 shows the resulting number of predicted background and observed events. The background estimate models the number of observed events well, including the low transverse mass region (\( M_T > 45 \) GeV/c\(^2\)), which contains most of the \( W \)-boson sample and provides a validation of the background model. For \( M_T > 400 \) GeV/c\(^2\) the total expected background amounts to

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**Fig. 1.** Distributions of the variable \( E_{T}^{\text{ele}}/E_{T}^{\text{miss}} \). The curves show the result of a simultaneous fit of the normalizations of multi-jet and \( W \) background shapes to the data, after subtraction of the contribution of the other backgrounds.
recoil correction. If we examine a region 39% for $t \tau$ and $W \mu$ for the main background $W \tau \nu$ and $t \tau$ [20] using the CMS measurement for the latter. With respect to electrons, reconstruction and identification efficiency uncertainties of 1.9 and 1.8%, respectively, are included for signal and backgrounds as determined in an analysis of $Z \rightarrow e^+ e^-$ events. For the electron energy scale an uncertainty of 1% in the central section and 3% for electrons in the endcaps of the electromagnetic calorimeter [21] is included. For the $E_T^{miss}$ resolution we assume a new W boson-like gauge particle with standard-model-like couplings and branching fractions with masses ranging from 5% for diboson and $Z \rightarrow e^+ e^-$ to 39% for $t \tau$ [20] using the CMS measurement for the latter. With respect to electrons, reconstruction and identification efficiency uncertainties of 1.9 and 1.8%, respectively, are included for signal and backgrounds as determined in an analysis of $Z \rightarrow e^+ e^-$ events. For the electron energy scale an uncertainty of 1% in the central section and 3% for electrons in the endcaps of the electromagnetic calorimeter [21] is included. For the $E_T^{miss}$ resolution we assume an uncertainty of 10% [22], applied as an extra smearing to the reconstructed $E_T^{miss}$ in the simulation. The impact on the number of events from all backgrounds is below 1%. A similar approach is used to evaluate the impact of the $E_T^{miss}$ scale. A shift of 5% is applied event by event to the $E_T^{miss}$ scale [23] and the impact on the event count for $M_T > 200$ GeV/c$^2$ is found to be smaller than 10% for all backgrounds considered. For the $W \rightarrow e\nu$ background, the $E_T^{miss}$ and its associated uncertainty are derived using the hadronic recoil correction. If we examine a region $M_T > 200$ GeV/c$^2$, the resulting uncertainty on the predicted number of event counts is 8% for the main background $W \rightarrow e\nu$ (dominated by the uncertainty on the shape of the $M_T$ distribution due to the energy scale uncertainty) and 50% for the sub-dominant multi-jet background (studied by inverting the isolation requirement and analyzing the multi-jet template in bins of $M_T$). The uncertainty on the number of signal events, shown in Table 2, is dominated by the luminosity uncertainty (11%) unlike the number of background events which is determined by the electron and $E_T^{miss}$ scale and resolution uncertainties (in total 28.7%). The limits reported in the same table are relatively insensitive to systematic uncertainties.

With all background estimates in hand, we examine the data for evidence of non-SM events. Fig. 2 shows the CMS data overlaid with background expectations. Since no excess is observed in the data beyond the SM background prediction, we set a lower bound on the mass of the W' boson in the reference model. For each mass point, we choose a minimum $M_T$ requirement that provides the best a priori limit and use the $M_T$ region above this threshold as the search window.

The resultant minimum $M_T$ requirement ranges from 400 to 675 GeV/c$^2$ across the W' mass range and is shown in Table 2 along with the corresponding number of potential signal and background events. The errors include all systematic uncertainties. The number of events found in data is also shown. The highest transverse mass event we observe has $M_T = 493$ GeV/c$^2$ and is shown in Fig. 3.

We use a Bayesian technique to determine an upper limit on the cross section as a function of the W' boson mass with a C.L. of 95%, following the method described in [24]. We assume a flat prior probability distribution for the cross section. To incorporate the systematic uncertainties described above, we treat them as nuisance parameters and use a log-normal distribution to integrate over these parameters. Fig. 4 shows both the expected and the observed limit. The uncertainty on the theoretical cross section was determined by re-weighting each event using all the eigenvectors of the CTEQ6 PDF set. We exclude the existence of W' bosons with standard model-like couplings and branching fractions with masses up to 1.36 TeV/c$^2$ at 95% C.L. using the central value of the theoretical cross section.

In summary, we have performed a search for a heavy gauge boson W' in the decay channel with an electron and large transverse energy imbalance. We observe no excess over the background. A new W boson-like gauge particle with standard-model-like couplings and branching fractions up to a mass of 1.36 TeV/c$^2$ is excluded by the data, the most stringent limit to date.

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**Table 2**

Lower $M_T$ requirement as a function of $W'$ mass and expected and observed data counts. The entries $n_s$, $n_b$, and $n_d$ correspond to the expected signal and background counts and the observed data counts, respectively. The cross sections $\sigma_t$, $\sigma_e$, and $\sigma_o$ correspond to the theoretical $W'$ production cross section and the expected and observed limits, respectively. The errors include all systematic uncertainties.

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<thead>
<tr>
<th>$M_{W'}$ (TeV/$c^2$)</th>
<th>$\text{min} M_T$ (TeV/$c^2$)</th>
<th>$n_s$</th>
<th>$n_b$</th>
<th>$n_d$</th>
<th>$\sigma_t$ (pb)</th>
<th>$\sigma_e$ (pb)</th>
<th>$\sigma_o$ (pb)</th>
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</thead>
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<tr>
<td>0.6</td>
<td>0.400</td>
<td>129.38 $\pm$ 20.16</td>
<td>3.29 $\pm$ 0.61</td>
<td>2</td>
<td>8.290</td>
<td>0.379</td>
<td>0.289</td>
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<tr>
<td>0.7</td>
<td>0.500</td>
<td>60.77 $\pm$ 9.61</td>
<td>1.21 $\pm$ 0.35</td>
<td>0</td>
<td>4.264</td>
<td>0.314</td>
<td>0.215</td>
</tr>
<tr>
<td>0.8</td>
<td>0.500</td>
<td>39.54 $\pm$ 6.08</td>
<td>1.21 $\pm$ 0.35</td>
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<td>2.426</td>
<td>0.274</td>
<td>0.188</td>
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<tr>
<td>0.9</td>
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<td>25.24 $\pm$ 3.85</td>
<td>1.21 $\pm$ 0.35</td>
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<td>0.246</td>
<td>0.168</td>
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<td>1.21 $\pm$ 0.35</td>
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<td>0.838</td>
<td>0.232</td>
<td>0.159</td>
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<td>6.00 $\pm$ 0.24</td>
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<td>0.334</td>
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<td>0.170</td>
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<td>1.3</td>
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<td>3.92 $\pm$ 0.60</td>
<td>0.51 $\pm$ 0.21</td>
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<td>0.215</td>
<td>0.207</td>
<td>0.168</td>
</tr>
<tr>
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<td>0.51 $\pm$ 0.21</td>
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<td>0.203</td>
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<tr>
<td>1.5</td>
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<td>0.51 $\pm$ 0.21</td>
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<td>0.099</td>
<td>0.196</td>
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</tr>
<tr>
<td>2.0</td>
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<td>0.27 $\pm$ 0.04</td>
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<td>0</td>
<td>0.014</td>
<td>0.206</td>
<td>0.167</td>
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**Fig. 3.** Displays of the highest $M_T$ event. The projection on the left shows the envelope of the inner tracking detector along with the electromagnetic and hadron calorimeters, and part of the muon system. The 3D view on the right shows an enlarged view of the inner region. Charged particle tracks as well as the deposited energy per calorimeter cell are displayed. The electron energy and $E_{\text{miss}}$ are shown in red, with the amount of energy represented graphically by the length of the bar. For scale, the largest tower in the electromagnetic calorimeter has an energy of 258 GeV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

**Fig. 4.** Limit using a Bayesian technique with a counting experiment in the search window, for the reference model. The intersection of the cross section limit curve and the central value of the theoretical cross section yields a lower limit of $M_{W'} > 1.36$ TeV/$c^2$ at 95% CL for the assumed $\sigma \times B(W' \rightarrow e\nu)$.

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