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Search for a W′ boson decaying to a muon and a neutrino in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration[*]

Abstract

A new heavy gauge boson, W′, decaying to a muon and a neutrino, is searched for in pp collisions at a centre-of-mass of 7 TeV. The data, collected with the CMS detector at the LHC, correspond to an integrated luminosity of 36 pb^{-1}. No significant excess of events above the standard model expectation is found in the transverse mass distribution of the muon-neutrino system. Masses below 1.40 TeV are excluded at the 95% confidence level for a sequential standard-model-like W′. The W′ mass lower limit increases to 1.58 TeV when the present analysis is combined with the CMS result for the electron channel.

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New heavy gauge bosons, generally indicated as Z' and W', are predicted in various extensions of the standard model (SM). Such extensions include Left-Right Symmetric Models [1–3], Compositeness models [4] and Little Higgs models [5]. The search for a W' is usually performed in the context of the benchmark model of Ref. [6], where the W' boson is considered a heavy analogue of the SM W boson with the same left-handed fermionic couplings. Thus the W' decay modes and branching fractions are similar to those of the W boson, with the notable exception of the $t\bar{b}$ channel, which opens up for W' masses above 180 GeV. No interaction with the SM gauge bosons or with other heavy gauge bosons such as Z' is assumed. In this context, CDF [7] and D0 [8] searched for a W' boson in the decay to an electron and a neutrino, and excluded W' masses below 1.1 TeV at the 95% confidence level (C.L.). Recently, a search in this decay channel by CMS extended the lower limit on the W' mass to 1.36 TeV [9].

In this letter, the W' decay to a muon and a neutrino with an assumed branching fraction of 8.5% (for all W' masses) is investigated and combined with a similar search in the electron channel [9]. The data sample, collected in 2010 by the CMS detector with pp collisions delivered by the LHC at centre-of-mass energy of 7 TeV, corresponds to 36 pb^{-1}.

A more detailed description of CMS can be found elsewhere [10]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. Both barrel and endcap regions are instrumented with four muon stations combining high precision tracking detectors (drift tubes in the barrel and cathode strip chambers in the endcaps) with resistive plate chambers for triggering as well as contributing to the tracking. The muon transverse momentum, p_{T}, is measured through bending of its track when passing the magnetized return yoke. Each station consists of a multi-layer chamber, twelve and six layers for the drift and the cathode strip chambers, respectively. All muon stations contribute to the first level trigger and identify the bunch crossing from which the muon originated. A cylindrical coordinate system about the beam axis is used, in which the polar angle θ is measured with respect to the counterclockwise beam direction, and η is the pseudo-rapidity defined by $\eta = -\ln\tan\theta/2$.

Each muon track is matched to a tracker track, measured in the silicon tracker. A global track fit is performed [11], and the resulting global muon p_{T} resolution amounts to 1 to 10% for p_{T} values up to 1 TeV. The inner tracker measures charged particle trajectories within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of about 15 μm and a transverse momentum p_{T} resolution of about 1.5 % for p_{T} =100 GeV particles.

The primary sources of background to the $W' \rightarrow \mu\nu$ search include standard model $W \rightarrow \mu\nu$ decays, QCD multijet events, $t\bar{t}$, Drell-Yan events and cosmic ray muons. Diboson processes (WW, WZ, ZZ) with decays to electrons, muons or taus are also considered. Monte Carlo (MC) simulation is used to obtain event samples that are employed to evaluate signal and background efficiencies. The generated events are processed through the full CMS GEANT4 [12, 13] based detector simulation, trigger emulation, and event reconstruction chain. The W' signal sample is produced with the PYTHIA 6.409 generator [14] and the CTEQ6L parton distribution functions (PDF) [15]. Events are generated for W' masses ranging between 0.6 TeV and 1.5 TeV in steps of 100 GeV and for a W' mass of 2 TeV. Next-to-next-to-leading order (NNLO) corrections to the W' production cross sections, called k-factors, are available [16, 17] and amount to 1.32 for $m_{W'}$=0.6 TeV to 1.26 for $m_{W'}$=2 TeV.

The samples for the electroweak background processes $W \rightarrow \mu\nu$ and $Z \rightarrow \mu^+\mu^-$ are produced with POWHEG [18–20] interfaced with PYTHIA for showering and hadronization. Samples of

$W \rightarrow \mu\nu$, produced with PYTHIA with and without the simulation of pile-up effects, are used for cross-checks. The PYTHIA generator is also used for the production of $W \rightarrow \tau\nu$, $Z \rightarrow \tau^+\tau^-$, the diboson (ZZ, WZ, WW) samples, and QCD multijet events. For $t\bar{t}$ events, the MADGRAPH [21] generator is used in combination with PYTHIA for showering and hadronization. Most background processes are normalized to the integrated luminosity with NNLO cross section calculations. However, for $t\bar{t}$ and QCD multijet, the NLO and LO cross sections are used, respectively.

Candidate events with at least one high-p_T muon in the pseudorapidity range $|\eta| < 2.1$ are selected with a set of single-muon triggers. Only global muons reconstructed offline with $p_T > 25\,\text{GeV}$ in the range $|\eta| < 2.1$ are used in the analysis; the global muon track is required to have at least eleven hits in the silicon tracker and at least one hit in the pixel detector. The global track is also required to satisfy $\chi^2/N_{\text{dof}} < 10$ and to have at least two matching track segments in different muon stations. Since the segments have multiple hits and are typically found in different muon detectors separated by thick layers of iron, this requirement significantly reduces the amount of hadronic punch-through. The transverse impact parameter $|d_0|$ of a muon track with respect to the beam spot is required to be less than 0.02 cm, in order to reduce the cosmic muon background. Furthermore, the muon is required to be isolated with a combined relative isolation of less than 0.15. The latter variable is defined as the ratio between the addition (within a $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.3$ cone around the muon direction) of the deposited transverse energy in the calorimeters and the scalar sum of the transverse momenta of all tracks that originate from the interaction vertex, and the muon p_T. An additional requirement that there be no more than one muon in the event with $p_T > 25\,\text{GeV}$ is used to reduce the Z and Drell-Yan and cosmic ray muon backgrounds.

Muon reconstruction, identification, and selection efficiencies, along with their uncertainties, are determined from $Z \rightarrow \mu^+\mu^-$ decays using tag-and-probe techniques. One lepton candidate, called the "tag", satisfies the trigger criteria and all identification and isolation requirements. The other lepton candidate, called the "probe", is used to determine the efficiency of specific criteria under study.

The combined muon identification efficiency is measured to be 95%, including efficiencies for the muon reconstruction, the muon selection requirements, the isolation, and the inner track measured by the silicon strip tracker. The value for the combined efficiency is very similar in data and simulation, with the data/MC ratio being 99%. The trigger efficiency was studied with two complementary methods, the first one using tag-and-probe in dimuon events and the second one using a sample of jet-triggered data, which result in the trigger efficiencies of 92% and 91%, respectively, differing in data and simulation by 4%. Muons from a W' would have higher momenta than those used in the tag-and-probe studies. So far, only muons up to $p_T = 240\,\text{GeV}$ from pp collisions have been recorded and efficiency studies for O(500) GeV muons are done with simulated W' samples. The combined efficiency does not depend on p_T despite the fact that the showering probability in the iron yoke increases with the muon energy. This assumption has been checked with cosmic muons up to 1 TeV [11] and is a consequence of the redundancy of the muon system.

The neutrino from a potential W' signal is not detected, but gives rise to missing transverse energy (E_T^{miss}) in the detector, which is calculated using the particle flow technique [22]. The technique aims at reconstructing a complete, unique list of particles in each event using all the components of the CMS detector: muons, electrons, photons, and charged and neutral hadrons are all reconstructed individually. The E_T^{miss} for the event is given by the negative sum of the p_T of all the reconstructed particles in the event. The W' transverse mass, M_T , is thereafter

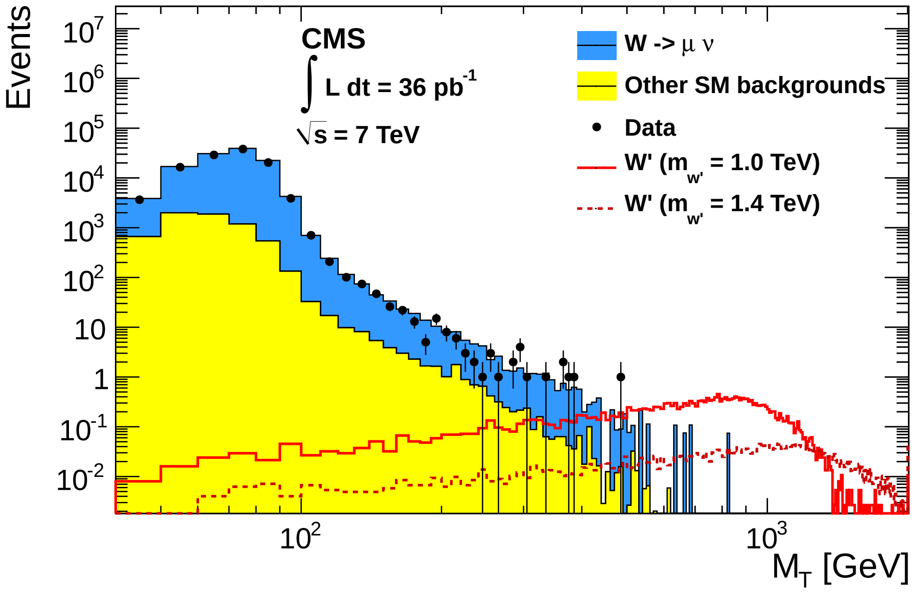

Figure 1: The M_T distribution after all the selection steps, in the data and in the simulation. A W′ signal with two different hypothetical masses is shown.

calculated as:

$$M_T = \sqrt{2 \cdot p_T \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\mu,\nu})}$$

where $\Delta\phi_{\mu,\nu}$ is the opening azimuthal angle between the muon and the direction of E_T^{miss} measured in radians.

The two-body decay kinematics is exploited to further select events with signal-like topology where the muon and E_T^{miss} are expected to be nearly back-to-back in the transverse plane and also balanced in transverse energy. A selection on the ratio of the muon p_T and E_T^{miss} is then applied, $0.4 < p_T/E_T^{\text{miss}} < 1.5$. Further, the angular difference is required to be $\Delta\phi_{\mu,\nu} > 2.5$. After this selection, the W′ signal efficiency for the explored W′ mass range is found to be between 79% and 82.5% within the muon acceptance of $|\eta| < 2.1$.

Estimated SM backgrounds, based on MC simulations, are shown in Fig. 1 separately for W bosons and for smaller contributions due to QCD, $t\bar{t}$, Drell-Yan, and diboson production. The dominant background up to high transverse masses is the $W \to \mu\nu$ contribution, which is difficult to suppress as it also decays to a muon and a neutrino. The data are also shown in Fig. 1, in agreement with the SM expectation.

The background in the signal region is estimated using the lower $180 < M_T < 350$ GeV side band region of the high M_T part of the spectrum. A relativistic Breit-Wigner function is used as an ad-hoc empirical shape to fit the M_T distribution in the side band, both in the simulation and the data. The parameters of the fitting function are then used to calculate the number of expected background events in the different bins of M_T outside the side band. The choice of the side band lower and upper limits is made in order to minimize the contribution from a hypothetical W′ signal and find a region that gives reliable extrapolations of the background in the signal region, based on simulation studies. According to the simulation, 71±8 events are expected in the side band region for the combination of all SM backgrounds, for an integrated luminosity of 36 pb^{-1}. The signal contamination would be 1.63±0.07 or 0.17±0.01 W′ events for a mass of 1.0 and 1.4 TeV, respectively. In the data, this region contains 52 events, consistent with the prediction within the systematic uncertainties in luminosity, background composition and theoretical uncertainties. The difference between the background modeling in the data and the predicted SM background from simulation in various search windows is considered as systematic uncertainty in the determination of the expected background events in the signal region. The robustness of this method has been tested by varying the binning of the M_T distribution and the interval range defining the sideband region, and it was confirmed that it does not introduce any significant systematic uncertainties.

Unlike in the electron channel [9], high-p_T cosmic ray muons constitute an additional source of background for this analysis. Their spectrum shows a different M_T dependence from that of the dominant W boson contribution. Cosmic ray muons are identified with a transverse impact parameter with respect to the beam spot larger than 0.02 cm. The number of cosmic ray muons expected after this requirement is determined to be between 0.15±0.04 for M_T >350 GeV and 0.08±0.03 for M_T >600 GeV.

Table 1: Minimum M_T requirement for the search windows, along with the expected numbers of signal (N_{sig}) and background (N_{bkg}) events and data. Also shown are the theoretical, expected and observed excluded cross section × BR limit for each W′ signal sample, using a Bayesian method as discussed in the text.

$m_{W'}$ (GeV)	M_T (GeV)	N_{sig} (Events)	N_{bkg} (Events)	N_{data} (Events)	$\sigma \cdot$ BR (pb)	Expected limit (pb)	Observed limit (pb)
600	390	152 ± 16	2.54 ± 0.68	1	8.290	0.308	0.212
700	450	78 ± 8	1.54 ± 0.41	1	4.264	0.267	0.227
800	470	49 ± 5	1.33 ± 0.35	1	2.426	0.236	0.212
900	500	29 ± 3	1.09 ± 0.29	0	1.389	0.216	0.150
1000	530	18 ± 1.9	0.91 ± 0.23	0	0.849	0.204	0.147
1100	590	11 ± 1.2	0.65 ± 0.16	0	0.516	0.193	0.151
1200	610	7.1 ± 0.7	0.59 ± 0.15	0	0.334	0.188	0.150
1300	630	4.7 ± 0.5	0.54 ± 0.13	0	0.214	0.180	0.146
1400	630	3.0 ± 0.3	0.54 ± 0.13	0	0.141	0.175	0.139
1500	680	2.1 ± 0.2	0.42 ± 0.10	0	0.094	0.175	0.146
2000	690	0.29± 0.03	0.40 ± 0.10	0	0.014	0.185	0.153

The numbers of background events expected and observed are reported in Table 1. The uncertainties on the number of background events in Table 1 correspond to the statistical uncertainty of the side band fit itself, as the background is completely determined from data.

The number of signal events expected is evaluated from simulation and given in the third column of Table 1 for different W′ masses along with the total uncertainty.

The following sources of systematic uncertainties have been considered.

- **Muon p_T resolution and muon momentum scale:** Systematic uncertainties due to the muon p_T resolution and momentum scale are evaluated from detailed studies of the $Z \to \mu^+\mu^-$ mass distribution [23] and high-p_T cosmic ray muons [11]. In order to estimate the effect on the number of events expected, the data muon p_T spectrum is scaled and smeared using the values obtained from those studies, the missing transverse energy is recomputed, and finally a distorted M_T distribution is obtained. The fit in the side band is performed again with the new M_T distribution. From comparison with the background estimation obtained from the original undistorted sample, an uncertainty in the final number of expected background events for $M_T > 500\,\text{GeV}$ of approximately 3% is derived. For the signal yield, where higher values of p_{T} should be considered, a conservative value of about 10% is assigned as systematic uncertainty due to this effect.

- **$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution:** An uncertainty of 10% [24] is assumed on the hadronic component of the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution, and used to smear the x and y components of the reconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$. The impact on the number of W′ signal events (averaged over all masses) in the M_{T} search window with respect to the unsmeared distribution is found to be below 1%.
- **Muon trigger and identification efficiency:** An uncertainty close to 4% on the combined muon identification and trigger efficiency is considered for the signal yield.
- **Uncertainty on luminosity:** The uncertainty on the absolute value of the integrated luminosity is taken as 11% [25].

The high M_{T} region is then used to search for $\mathrm{W}' \to \mu\nu$ which would manifest itself as an excess of events in the TeV region of the M_{T} distribution. No significant excess is observed (Fig. 1). The highest transverse mass event observed has M_{T} = 487 GeV and is displayed in Fig. 2.

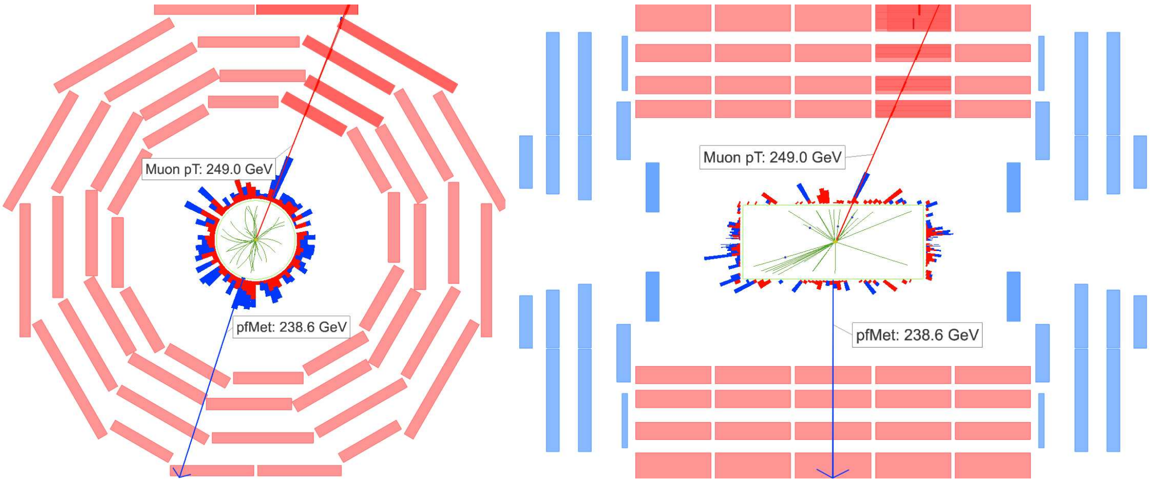

Figure 2: Display of the highest-M_{T} event in transverse view (left) and longitudinal view (right). The four barrel muon stations are shown in red, the forward muon stations in blue. Charged particle tracks as well as the deposited energy per calorimeter cell are displayed. The muon with p_{T} =249 GeV is symbolized by a red line moving upward, and the $E_{\mathrm{T}}^{\mathrm{miss}}$ =238.6 GeV ("pfMet") by a blue line moving downward.

An upper limit is set on the production cross section times the branching ratio into $\mu\nu$, $\sigma \cdot \mathrm{BR}(W' \to \mu\nu)$. The limit is derived using the RooStats [26] interface to BAT [27] to calculate the limits with the help of Markov Chain Monte Carlo methods. A flat prior probability distribution is assumed for the signal cross section. The number of data events above an optimized M_{T} threshold are counted and compared to the expected number of background events. Systematic uncertainties on the signal efficiency and background events are treated as nuisance parameters with a log-normal prior distribution and integrated over. The M_{T} threshold is optimized for the best expected limit and defines the lower bound of the search window for each value of the W′ mass. The expected and observed 95% C.L. limits for $\sigma\cdot$ BR are shown in Table 1. The value of the theoretical cross section, shown in Table 1, is used to translate the excluded cross section into a W′ mass limit. The existence of a W′ with SM-like couplings and masses below 1.40 TeV is excluded at 95% C.L. with an expected limit of 1.35 TeV. Inclusion of $\mathrm{W}' \to \tau\nu$ decays does not appreciably add to the acceptance of the $\mathrm{W}' \to \mu\nu$ signal process.

Finally, the results of this search are combined with those of the $\mathrm{W}' \to e\nu$ analysis [9]. The muon channel exhibits slightly higher sensitivity (due to the larger efficiency of about 79-82%, compared to 64-67% in the electron channel). In either channels, no events are seen at high transverse masses. Identical NNLO signal cross sections with the same *k*-factors and the same PDF uncertainties are used for both channels under the assumption of lepton universality. The search windows are optimized individually for each channel based on the best expected limit. The search windows for both channels can be found in Table 2. For each channel the likelihood function is determined and the two likelihood functions are combined.

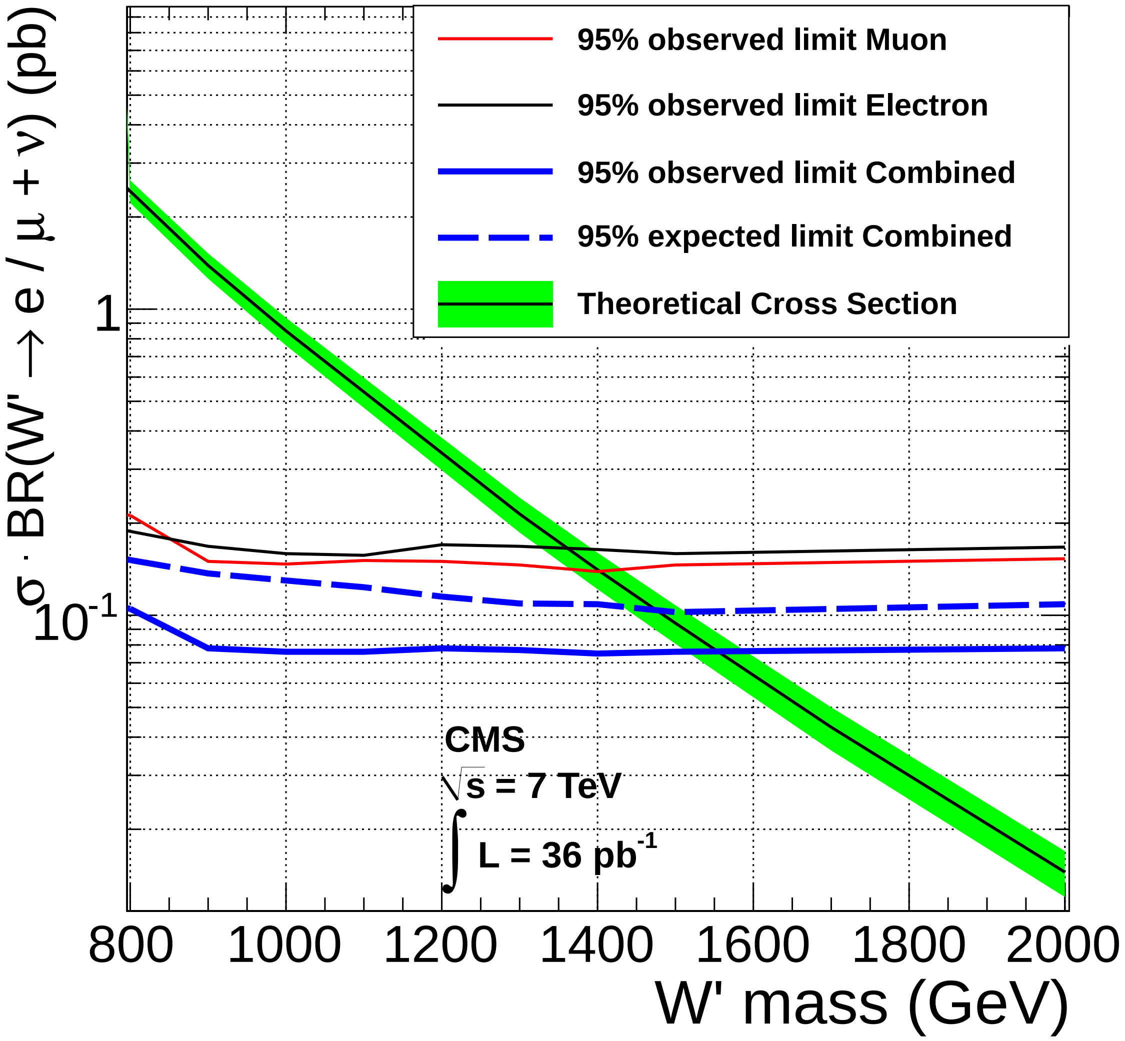

Figure 3: Individual limits as observed for the electron (black line) and the muon channel (red line). Their combination is shown as a solid blue line for the observed limit (expected as dashed blue line), using a Bayesian technique with only the luminosity uncertainty correlated.

The limits for the two individual channels as well as the limit obtained by combining them are shown in Fig. 3. The systematic uncertainties for resolution, trigger and lepton identification efficiencies are assumed to be fully uncorrelated between both channels. The uncertainty on the luminosity is taken as fully correlated, as well as the *k*-factors and PDF uncertainties on the theoretical cross section. When all background uncertainties are assumed to be fully correlated between the two channels, the combined limit remains unchanged. From this combination, a W' with SM-like couplings and with mass below 1.58 TeV is excluded at the 95% confidence level.

Table 2: The first two columns show the channel-independent theoretical NNLO cross section for various W′ mass points. Columns three and five show the individually optimized minimum M_T thresholds for the electron and muon channels, respectively, along with the excluded cross section × BR per channel in columns four and six. Finally, the right-most column is the combined limit by using a Bayesian method.

$m_{W'}$ GeV	$\sigma \cdot$ BR (pb) per channel	M_T (e) (GeV)	Obs. limit electron (pb)	M_T (μ) (GeV)	Obs. limit muon (pb)	Obs. limit combined (pb)
600	8.290	400	0.289	390	0.212	0.134
700	4.264	500	0.215	450	0.227	0.116
800	2.426	500	0.188	470	0.212	0.105
900	1.389	500	0.168	500	0.150	0.078
1000	0.849	500	0.159	530	0.147	0.076
1100	0.516	500	0.157	590	0.151	0.076
1200	0.334	650	0.170	610	0.150	0.078
1300	0.214	675	0.168	630	0.146	0.077
1400	0.141	675	0.164	630	0.139	0.075
1500	0.094	675	0.159	680	0.146	0.076
2000	0.014	675	0.167	690	0.153	0.078

In summary, a search for a new heavy gauge boson W′ that decays to a muon and a neutrino has been performed with 36 pb^{-1} of data collected by the CMS experiment. No evidence has been found for W′ boson production assuming SM-like couplings and 95% C.L. upper limits have been set on $\sigma \cdot \text{BR}(W' \rightarrow \mu\nu)$. Additionally, a 95% C.L. lower bound on the mass of a W′ boson is set at 1.40 TeV. This lower bound is increased to 1.58 TeV when this analysis is combined with a similar search for $W' \rightarrow e\nu$. This result represents a significant improvement over previously published limits.

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