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Search for leptonic decays of W' bosons in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$

The CMS Collaboration[*]

Abstract

A search for a new heavy gauge boson W' decaying to an electron or muon, plus a low mass neutrino, is presented. This study uses data corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$, collected using the CMS detector in pp collisions at a centre-of-mass energy of 7 TeV at the LHC. Events containing a single electron or muon and missing transverse momentum are analyzed. No significant excess of events above the standard model expectation is found in the transverse mass distribution of the lepton-neutrino system, and upper limits for cross sections above different transverse mass thresholds are presented. Mass exclusion limits at 95% CL for a range of W' models are determined, including a limit of 2.5 TeV for right-handed W' bosons with standard-model-like couplings and limits of 2.43–2.63 TeV for left-handed W' bosons, taking into account their interference with the standard model W boson. Exclusion limits have also been set on Kaluza–Klein W_{KK} states in the framework of split universal extra dimensions.

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[*] See Appendix A for the list of collaboration members

1 Introduction

This Letter describes a search for a new heavy gauge boson $W^{'}$, using proton-proton collision data collected during 2011 using the Compact Muon Solenoid (CMS) detector [1] at the Large Hadron Collider (LHC) at a centre-of-mass energy of 7 TeV. The dataset corresponds to an integrated luminosity of $5.0 \pm 0.1\,\mathrm{fb}^{-1}$ [2]. The search attempts to identify an excess of events with a charged lepton (an electron or muon) and a neutrino in the final state, and an interpretation of the results is provided in the context of several theoretical models.

2 Physics models

New heavy gauge bosons such as the $W^{'}$ and Z' are predicted by various extensions of the standard model (SM). In the sequential standard model (SSM) [3], the $W^{'}$ boson is considered to be a left-handed heavy analogue of the W. It is assumed to be a narrow *s*-channel resonance with decay modes and branching fractions similar to those of the W, with the addition of the $t\bar{b}$ channel that becomes relevant for $W^{'}$ masses above 180 GeV. Interference between the $W^{'}$ and W is assumed to be negligible. If the $W^{'}$ is heavy enough to decay to top and bottom quarks, the predicted branching fraction is about 8.5% for each of the two leptonic channels studied in the present analysis. Under these assumptions, the width of a 1 TeV $W^{'}$ is about 33 GeV. Decays of the $W^{'}$ into WZ dibosons are usually suppressed in this model.

The assumptions of the SSM were used in previous searches in leptonic channels at the Tevatron [4, 5] and the LHC [6–9]. The signature of a charged high-momentum lepton and a neutrino would also be observed in the decays of a right-handed W'_{R}, predicted by left-right symmetric models [10–13]. This particle is typically predicted to decay to a heavy right-handed neutrino [14–16].

However, the mass of the right-handed neutrino is not constrained, and it could be light as long as it does not couple to SM weak bosons. This would result in the same W'_{R} decay signature as for the W.

If the $W^{'}$ is right-handed it will not interfere with the W. However, if it is left-handed (W'_{L}), interference with the W is expected expected [17–19]. Constructive (destructive) interference occurs in the mass range between W and $W^{'}$ if the coupling of the $W^{'}$ boson to quarks and leptons has opposite sign to (same sign as) the coupling of the W boson to left-handed fermions (g_{L}). While constructive interference increases the $W^{'}$ production cross section, and therefore allows experimental sensitivity at higher masses, destructive interference would yield a lower cross section, rendering previously published LHC mass exclusion limits [7, 9] slightly optimistic. Interference has previously been considered in searches for the decay to top and bottom quarks [19, 20], but never for leptonic decays.

Figure 1 shows the transverse mass distribution for a $W^{'}$ of 2.5 TeV mass for the cases of constructive, destructive and non-interference, along with the background due to the SM W. In the absence of interference the cross sections and transverse mass spectrum of left- and right-handed $W^{'}$ are identical. The $W^{'}$ manifests itself as a Jacobian peak with its width almost independent of the presence and type of interference. However, the intermediate region around $M_{\mathrm{T}} \sim 1$ TeV shows a clear variation of the shape. Destructive interference of a W'_{L} boson with mass ≥ 2 TeV modulates the W transverse mass tail, resulting in a faster fall-off. The modulation strength and the resulting effect on the cross section both increase with the $W^{'}$ mass and width. Given sufficient detector resolution, the constructive and destructive interference scenarios may be distinguishable.

The leptonic final states under study may also be interpreted in the framework of universal extra dimensions (UED) with bulk mass fermions, or split-UED [21, 22]. This is a model based on an extended space-time with an additional compact fifth dimension of radius R. All SM fermions and gauge bosons have Kaluza–Klein (KK) states, for instance $\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}$, where n denotes the n-th KK excitation mode, and

$$m_{\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}}^2 \equiv m_n^2 = m_W^2 + \left(\frac{n}{R}\right)^2, \tag{1}$$

$$g_n = g^{\mathrm{SM}} \mathcal{F}_n(\pi \mu R), \tag{2}$$

$$\mathcal{F}_n(x) = \begin{cases} 0 & \text{if } n = 2m+1 \\ \frac{x^2[-1+(-1)^m \mathrm{e}^{2x}](\coth x - 1)}{\sqrt{2(1+\delta_{m0})(x^2+m^2\pi^2/4)}} & \text{if } n = 2m. \end{cases} \tag{3}$$

Here μ is the bulk mass parameter in five dimensions of the fermion field, with $[1/R, \mu]$ defining the UED parameter space. The coupling of the $\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}$ to SM fermions is denoted g_n and defined as a modification of the SM coupling g^{SM} of the W. The function $\mathcal{F}_{2m}(x)$ tends to approach $(-1)^m\sqrt{2}$ as $x \to \infty$. In minimal UED models, the parameter μ is assumed to be zero [23]. Following [21, 22], we assume a non-zero value for μ, thus increasing the cross sections sufficiently to allow observation by LHC experiments.

KK-odd modes of $\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}$ do not couple to SM fermions, owing to KK-parity conservation. Moreover, there is no expected sensitivity for $n \geq 4$ modes at the LHC centre-of-mass energy and luminosity used in this analysis. $\mathrm{W}_{\mathrm{KK}}^{2}$ is therefore the only mode considered. Under this assumption, the decay to leptons is kinematically identical to the sequential SM-like W' decay, and the observed limits obtained from the $\mathrm{W}' \to \mathrm{e}\nu$ and $\mathrm{W}' \to \mu\nu$ searches can directly be reinterpreted in terms of the $\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}$ mass considering the different widths. The width of a $\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}$ is $\mathcal{F}_n^2$ times the SSM-like W' width:

$$\Gamma_{\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}} = \mathcal{F}_n^2 \frac{4}{3} \frac{m_{\mathrm{W}_{\mathrm{KK}}^{\mathrm{n}}}}{m_{\mathrm{W}}} \Gamma_{\mathrm{W}}. \tag{4}$$

3 The CMS detector

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. The electromagnetic calorimeter consists of nearly 76 000 lead tungstate crystals. The energy resolution for electrons with the very high transverse momentum used in this analysis, which are predominantly in the central pseudorapidity region, is about 1%. In the forward region the resolution is about 2%. Muons are measured in gas-ionization detectors embedded in the steel return yoke. Central and forward regions are instrumented with four muon stations combining high precision tracking detectors (drift tubes in the central region and forward cathode strip chambers) with resistive plate chambers, which contribute to the trigger as well as the track measurement. The muon transverse momentum, p_{T}^{μ}, is determined from the curvature of its track, measured as it traverses the magnetized return yoke. Each muon track is matched to a track measured in the silicon tracker, resulting in a muon p_{T} resolution of 1 to 10% for p_{T} of

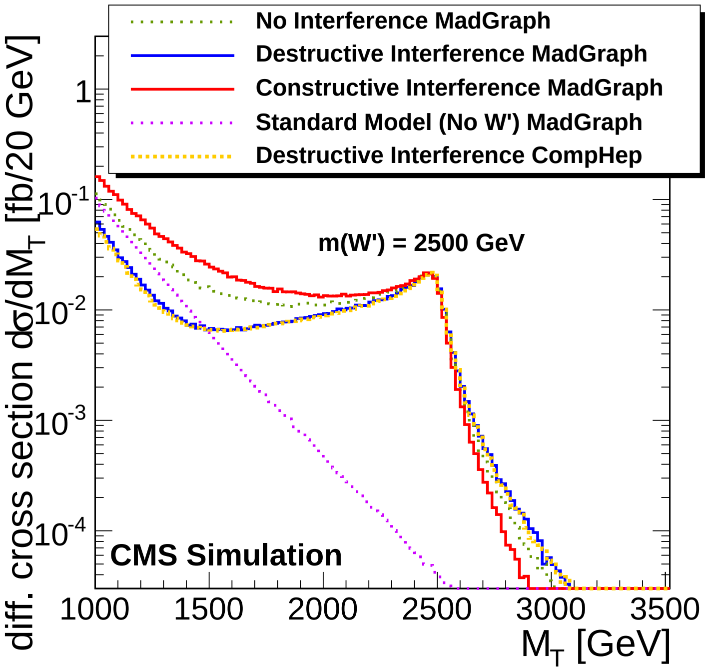

Figure 1: MADGRAPH and COMPHEP predictions of the transverse mass distribution for the SM W background and various W' models for $m(W')$=2.5 TeV. In the absence of interference, W'_R and W'_L cross sections are identical. A W'_L could experience constructive or destructive interference with the SM W, yielding the shown modulation of the M_T spectrum.

up to 1 TeV. CMS uses a two-level trigger system comprising custom hardware processors and a High-Level Trigger processor farm. Together, these systems select around 300 Hz of the most interesting recorded bunch-crossings for permanent storage. A detailed description of CMS can be found in Ref. [1].

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 the azimuthal angle ϕ is measured in the xy plane, where the x axis points towards the center of the LHC ring. The quantity η is the pseudo-rapidity, defined as $\eta = -\ln[\tan\theta/2]$.

4 Event selection

Candidate events with at least one high-transverse-momentum (p_T) lepton were selected using single-muon and single-electron triggers. The trigger thresholds were raised as the LHC luminosity increased during the data-taking period, the highest values being $p_T > 80$ GeV for electrons and $p_T > 40$ GeV for muons. Offline, electrons and muons were required to have p_T at least 5 GeV higher than the online threshold, which does not impair the search in the high mass region.

Muons were reconstructed by combining tracks from the inner tracker and the outer muon system. Well-reconstructed muons were selected by requiring at least one pixel hit, hits in eight tracker layers and segments in two muon stations. Since the segments have multiple hits and are typically found in different muon detectors separated by thick layers of iron, the latter 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 ray muon background. Furthermore, the muon is required to be isolated within a $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ cone around its direction. Muon isolation requires that the scalar sum of the transverse momenta of all tracks originating at the interaction vertex, excluding the muon, is less than 15% of its p_{T}. An additional requirement is that there be no second muon in the event with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ to reduce the Z, Drell-Yan and cosmic ray muon backgrounds.

Electrons were reconstructed as isolated objects in the electromagnetic calorimeter, with additional requirements on the shower shape and the ratio of hadronic to electromagnetic deposited energies. The electrons were required to have at least one inner hit, a transverse energy greater than 85 GeV, and required to be isolated in a cone of radius $\Delta R < 0.3$ 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, was required to be less than 5 GeV. For the isolation using calorimeters, the total transverse energy in the barrel, excluding deposits associated to the electron, was required to be less than $0.03 \cdot p_{\mathrm{T}}^{\mathrm{ele}} + 2.0\,\mathrm{GeV}$. The isolation requirements were modified as luminosity increased, owing to the increase in the typical number of additional pp interactions ('pile-up') per LHC bunch crossing. These selections are designed to ensure high efficiency for electrons and a high rejection of misreconstructed electrons from multi-jet backgrounds.

The main observable in this search is the transverse mass M_{T} of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system, calculated as

$$M_{\mathrm{T}} \equiv \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})} \tag{5}$$

where $\Delta\phi_{\ell,\nu}$ is the azimuthal opening angle between the charged lepton's transverse momentum (p_{T}^{ℓ}) and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) direction. The neutrino is not detected directly, but gives rise to experimentally observed $E_{\mathrm{T}}^{\mathrm{miss}}$. This quantity was determined using a particle-flow technique [24], an algorithm designed to reconstruct a complete list of distinct particles using all the subcomponents of the CMS detector. Muons, electrons, photons, and charged and neutral hadrons were all reconstructed individually. The $E_{\mathrm{T}}^{\mathrm{miss}}$ for each event was then calculated as the vector opposing the total transverse momentum of all reconstructed particles in each event.

In W' decays, the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ are expected to be almost back-to-back in the transverse plane, and balanced in transverse energy. Candidate events were therefore selected through a requirement on the ratio of the lepton p_{T} and the $E_{\mathrm{T}}^{\mathrm{miss}}$, $0.4 < p_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}} < 1.5$. A requirement was also imposed on the angular difference in the transverse plane of the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ direction, $\Delta\phi_{\ell,\nu} > 0.8 \times \pi$. No selection is made on jets. After these selections, the average W' signal efficiency for masses up to 2.5 TeV in simulated events was found to be around 80% in both channels, including the roughly 90% geometrical acceptance corresponding to a requirement of $|\eta_{\mu}| < 2.1$ for muons, and with $|\eta_{\mathrm{e}}| < 1.442$ or $1.56 < |\eta_{\mathrm{e}}| < 2.5$ for electrons. The transverse mass distributions after these selections are shown in Figure 2.

5 Signal and background simulation

Several large samples of simulated events were used to evaluate signal and background efficiencies. The generated events were processed through a full simulation of the CMS detector based on GEANT4 [25, 26], a trigger emulation, and the event reconstruction chain.

The event samples for the W'_{R} signal were produced separately from the SM W sample, using the PYTHIA 6.4.9 generator [27]. This is consistent with the case of non-interference assumed

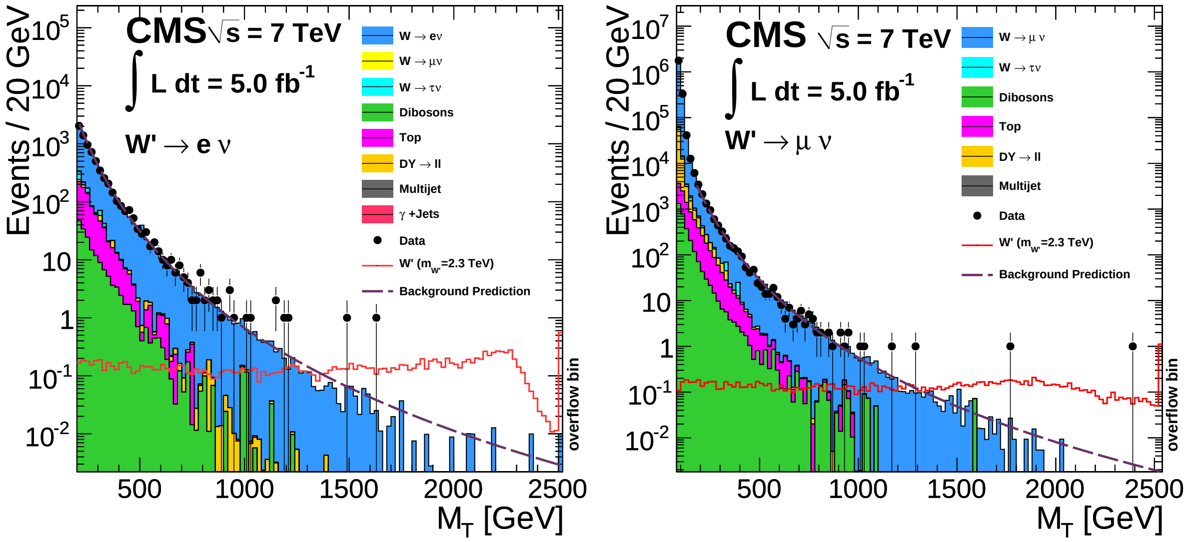

Figure 2: Observed transverse mass distributions for the electron (left) and muon (right) channels. Simulated signal distributions for a (left- or right-handed) W' without interference of 2.3 TeV mass are also shown, including detector resolution effects. The simulated background labelled as 'diboson' includes WW, ZZ and WZ contributions. The top background prediction includes single top and top pair production. The total background prediction from a fit to the simulated transverse mass spectrum in each channel is shown by the dashed line.

for the previous ATLAS and CMS studies. In order to include interference of W'_{L} and W in this analysis, a model of a single new heavy vector boson W' with a SM-like left-handed coupling strength $|g'_{\mathrm{L}}| \approx 0.65$ was implemented in the MADGRAPH event generator [28]. This model includes spin correlations as well as finite-width effects. For such a left-handed scenario with interference, the generation of samples is technically more challenging. Since the scattering amplitude responsible for the $\ell\nu$ final state is the sum of W'_{L} and SM W boson terms, both contributions have to be generated simultaneously. A threshold in M_{T} was applied to suppress the dominant W contribution around the W-mass, where interference effects are negligible for the W'_{L} masses considered in this search. The simulation uses MADGRAPH 4.5.1, matched to PYTHIA for showering and hadronisation. For the hadronisation model, the PYTHIA Tune Z2 was used for both the W'_{R} and W'_{L} simulations. Both generators simulate at leading order (LO) and use the CTEQ6L1 parton distribution functions (PDF) [29]. Mass-dependent K-factors, varying from 1.14 to 1.36, for the next-to-next-to-leading order (NNLO) correction were calculated with FEWZ [30, 31]. The resulting NNLO $\mathrm{W}' \rightarrow \ell\nu$ production cross section times branching fraction ranged from 17.7 pb (for $m_{\mathrm{W}'} = 0.5$ TeV) to 0.71 fb (for $m_{\mathrm{W}'} = 3$ TeV) for a W' without interference (see Table 1 for cross sections). Efficiencies and detector acceptance are then taken into account for estimating the expected number of signal events. The acceptance is nearly maximal since the decay products of such heavy particles tend to populate low pseudorapidities. Efficiencies are high because the selections have been optimised. Detailed numbers for both quantities are given in Section 4. The Tevatron $\mathrm{W}'_{\mathrm{L}} \rightarrow \mathrm{t\bar{b}}$ search used the COMPHEP generator [32, 33] which has the case of destructive interference implemented. The agreement between the model implementations in COMPHEP and MADGRAPH is demonstrated for the case of destructive interference in Figure 1.

The primary source of background is the off-peak, high transverse mass tail of the standard model $\mathrm{W} \rightarrow \ell\nu$ decays. Other important backgrounds arise from QCD multijet, $\mathrm{t\bar{t}}$, and Drell–

Yan events. Dibosons (WW, WZ, ZZ) decaying to electrons, muons, or taus were also considered. The event samples for the electroweak background processes $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ ($\ell = \mathrm{e}, \mu, \tau$) were produced using PYTHIA. NNLO cross sections were accounted for via a single K-factor of 1.32 for the W, and mass-dependent K-factors, ranging from 1.28 to 1.23, for the Z. The PYTHIA generator was also used for QCD multijet events. The $\mathrm{t\bar{t}}$ events were generated with MADGRAPH in combination with PYTHIA, and the newly-calculated NNLL (next-to-leading-order including the leading logarithms of NNLO) cross section was applied [34]. All other event samples were normalised to the integrated luminosity of the recorded data, using calculated NNLO cross sections. The only exceptions were the diboson and QCD samples, for which the NLO and LO cross sections were used respectively. We note that multijet background is largely suppressed by the event selection requirements. The simulation of pile-up is included in all event samples by superimposing minimum bias interactions onto the main background processes.

In order to provide a background estimate independent of any interference effects in the W transverse mass tail, the shape of the background was determined from simulation. The full transverse mass spectrum was modelled by a function optimised to best describe the spectrum in either channel up to very high masses. This function, of the form

$$f(M_\mathrm{T}) = \frac{a}{(M_\mathrm{T} + b)^c} \tag{6}$$

was fitted to the simulation and then normalised to data in the region $200\,\mathrm{GeV} < M_\mathrm{T} < 500\,\mathrm{GeV}$, and used to estimate the expected number of SM background events for all transverse mass bins (shown as the dashed lines in Figure 2). A cross check under the assumption of no interference was done by fitting the M_T distribution in data confirming the simulation. To determine the uncertainty introduced by this method, in addition to statistical errors on the fit parameters, two alternative functions were fitted:

$$f(M_\mathrm{T}) = \frac{a}{(M_\mathrm{T}^2 + b \cdot M_\mathrm{T} + c)^d} \tag{7}$$

$$f(M_\mathrm{T}) = \frac{a(1 + M_\mathrm{T})^b}{(M_\mathrm{T}^{c + d \cdot \ln M_\mathrm{T}})} \tag{8}$$

The largest difference in the background prediction with respect to the original fit was taken as a systematic uncertainty. For M_T larger than 1.4 TeV, this corresponds to an additional uncertainty of 0.14 events with a background expectation of 0.98 events in the muon channel and 0.26 events with a background expectation of 1.28 events in the electron channel.

6 Systematic uncertainties

The expected number of potential signal and background events was evaluated from simulation. In addition to uncertainties due to the fit procedure for the background, systematic uncertainties due to imperfections in the description of the detector performance were included. Uncertainties due to the lepton energy or momentum resolution and scale, ranging between 0.4% and 10% [6, 7] were applied to the transverse mass spectrum. Uncertainties due to momentum scale were evaluated using detailed studies of the $Z \rightarrow \mu\mu$ shape and high p_T muons. The muon p_T resolution has been previously determined with cosmic ray muons to within 10% for high momentum tracks [35]. In order to estimate the uncertainty on the number of expected events, the muon p_{T} spectrum was distorted (scaled and smeared) according to the values extracted from comparisons with data. The missing transverse energy was adjusted accordingly, and finally a distorted transverse mass spectrum was obtained and observed to vary by $\sim$1%. The electron energy scale uncertainty was around 1% in the ECAL barrel and 3% in the endcaps. Its impact on the number of signal events above the threshold of $M_{\mathrm{T}} > 600\,\mathrm{GeV}$ was ascertained to be less than 1% for all W' masses. We assume an uncertainty of 10% on the hadronic component of the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution (that is, excluding the lepton), and the x and y components of the reconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$ in the simulation were smeared accordingly. The impact on the number of signal events was found to be around 2%.

Effects caused by pile-up were modeled by adding to the generated events multiple interactions with a multiplicity distribution matched to the luminosity profile of the collision data. The resulting impact on the signal was studied by varying the mean of the distribution of pile-up interactions by 8%, yielding a variation of the signal efficiency of $\sim$2%. Following the recommendations of the PDF4LHC group [36], the signal event samples for W'_{R} generated with PYTHIA were reweighted using the LHAPDF package [37]. PDF and α_{s} variations of the MSTW2008 [38], CTEQ6.6 [39] and NNPDF2.0 [40] PDF sets were taken into account and the impact on the signal cross sections was estimated.

7 Results and limits

A $\mathrm{W}' \rightarrow \mathrm{e}\nu$ or $\mathrm{W}' \rightarrow \mu\nu$ signal is expected to manifest itself as an excess over the SM expectation in the tail of the M_{T} distribution. No significant excess has been observed in the data.

For W' masses well below the centre-of-mass energy of $\sqrt{s} = 7\,\mathrm{TeV}$ the signal events are expected to lie in the Jacobian peak corresponding to the W' mass. For masses above 2.3 TeV, the reduced phase space results in many events below the Jacobian peak, and the acceptance for the $M_{\mathrm{T}}^{\mathrm{min}}$ cut drops from about 40% for intermediate masses to 14% at very high W' masses. The expected signal yields given in Table 1 for a range of W'_{R} masses are largely unaffected when introducing interference effects, owing to the high M_{T} cut corresponding to the optimum search window, which naturally lies around the Jacobian peak.

We set upper limits on the production cross section times the branching fraction $\sigma_{\mathrm{W}'_{\mathrm{R}}} \times \mathcal{B}(\mathrm{W}'_{\mathrm{R}} \rightarrow \ell\nu)$, with $\ell = \mathrm{e}$ or μ. The observed highest transverse mass events had $M_{\mathrm{T}} = 1.6 \pm 0.1\,\mathrm{TeV}$ in the electron channel, and $M_{\mathrm{T}} = 2.4 \pm 0.1\,\mathrm{TeV}$ in the muon channel. For $M_{\mathrm{T}} > 1.6\,\mathrm{TeV}$, the background expectation from the fit to simulation is less than one event in each channel. Cross-section limits were derived using a Bayesian method [41] with a uniform prior probability distribution for the signal cross section. The number of data events above an optimised transverse mass threshold $M_{\mathrm{T}}^{\mathrm{min}}$ was compared to the expected number of signal and background events. Systematic uncertainties on the signal and background yield were included via nuisance parameters with a log-normal prior distribution. The $M_{\mathrm{T}}^{\mathrm{min}}$ threshold was optimised for the best expected exclusion limit, a procedure used in previous analyses [7] which is also appropriate for establishing a W' discovery. The $M_{\mathrm{T}}^{\mathrm{min}}$ threshold defining the search window increases with W' mass up to masses around 2.5 TeV, following the Jacobian peak. For larger masses, cross sections become so small that fewer than two events are expected in the recorded data. These events are likely to have lower transverse mass because the production is shifted to the off-peak region, as mentioned above. Both these effects serve to lower the $M_{\mathrm{T}}^{\mathrm{min}}$ threshold of the search window for very heavy W' bosons. The expected number of signal and background events listed separately for the two channels are summarized in Table 1. A common theoretical NNLO cross section is assumed.

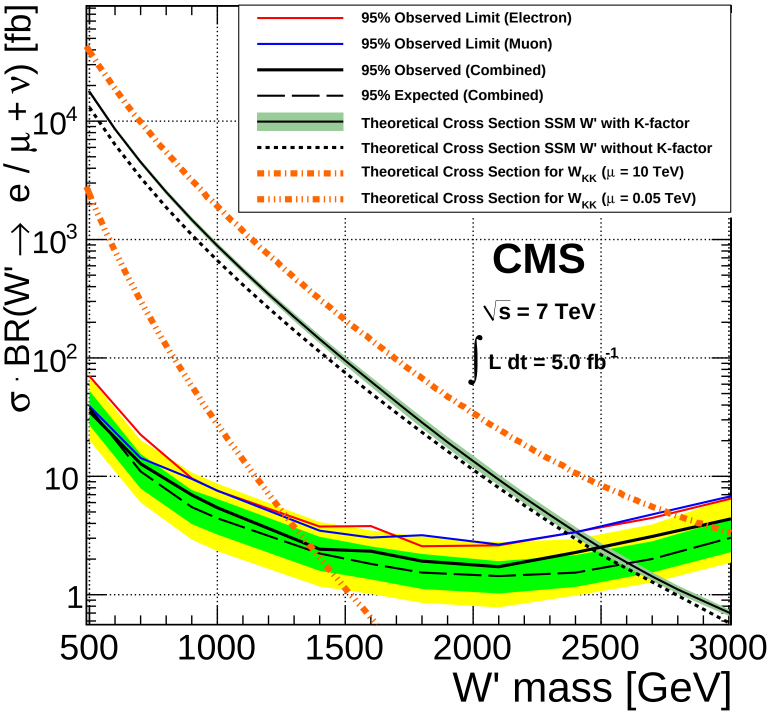

Figure 3: Upper limits on $\sigma(W'_R) \times B(W'_R \rightarrow \ell\nu)$, with $\ell = e, \mu$, and their combination at 95% confidence level. The one (two) sigma uncertainty bands are shown in green (yellow). The theoretical cross section, with PDF uncertainties, is displayed with and without a mass-dependent NNLO K-factor for the right-handed model without interference. The theoretical cross sections for Kaluza–Klein W^2_{KK} with μ=0.05 TeV and μ=10 TeV are also shown.

Table 1: $M_{\mathrm{T}}^{\mathrm{min}}$ requirement for different W'_{R} masses, expected number of signal and background events, number of observed events, theoretical cross section and upper limits on $\sigma(\mathrm{W}'_{\mathrm{R}}) \times B(\mathrm{W}'_{\mathrm{R}} \to \ell\nu)$, with $\ell = \mathrm{e}, \mu$.

W' mass (GeV)	$M_{\mathrm{T}}^{\mathrm{min}}$ (GeV)	N_{sig} (Events)	N_{bkg} (Events)	N_{obs} (Events)	σ_{theory} (fb)	Exp. Limit (fb)	Obs. Limit (fb)
Electron channel							
500	350	44000 ± 4200	830 ± 85	850	17723	64.15	70.18
700	550	9600 ± 1500	114 ± 15	128	4514	16.94	22.48
900	700	3160 ± 460	37.4 ± 5.7	41	1470	8.38	9.61
1000	800	1730 ± 280	20.0 ± 3.8	22	886	6.77	7.55
1400	1050	294 ± 36	5.4 ± 1.6	6	144	3.56	3.77
1600	1150	128 ± 13	3.4 ± 1.1	5	63.3	3.02	3.80
1800	1200	63.9 ± 5.5	2.79 ± 0.99	3	28.5	2.53	2.57
2100	1350	18.7 ± 1.5	1.55 ± 0.64	2	9.37	2.38	2.61
2400	1450	5.47 ± 0.39	1.08 ± 0.49	2	3.40	2.69	3.39
2700	1450	1.75 ± 0.13	1.08 ± 0.49	2	1.43	3.54	4.46
3000	1400	0.59 ± 0.05	1.29 ± 0.56	2	0.71	5.45	6.42
Muon channel							
500	350	41000 ± 3200	749 ± 47	732	17723	44.65	39.13
700	550	8700 ± 1000	102 ± 10	100	4514	15.42	14.28
900	700	2920 ± 370	32.6 ± 5.0	36	1470	8.24	9.51
1000	750	1840 ± 150	23.3 ± 4.2	26	886	6.62	7.57
1400	1000	313 ± 25	5.6 ± 1.9	6	144	3.37	3.47
1600	1100	136.3 ± 9.2	3.4 ± 1.4	4	63.3	2.83	3.04
1800	1250	56.5 ± 3.7	1.78 ± 0.86	3	28.5	2.48	3.18
2100	1300	18.5 ± 0.9	1.45 ± 0.75	2	9.37	2.35	2.65
2400	1400	5.54 ± 0.26	0.98 ± 0.56	2	3.40	2.59	3.37
2700	1450	1.68 ± 0.08	0.81 ± 0.49	2	1.43	3.45	4.77
3000	1400	0.58 ± 0.03	0.98 ± 0.56	2	0.71	5.17	6.73

The expected and observed upper limits for both channels and their combination, in the right-handed scenario without interference, are shown in Figure 3. Using the central value of the theoretical cross section times the branching fraction, we exclude at 95% confidence level (CL) the existence of a W'_{R} with SM-like couplings of masses less than 2.5 TeV (compared with an expected limit of 2.6 TeV). Note that the background uncertainty has a negligible impact on the lower limits on W' mass, owing to the lack of observed events in the tail of the M_{T} distribution.

A similar search procedure was performed including the effect of interference. The theoretical cross sections are approximately 10–30% lower (higher) for destructive (constructive) interference when integrating over the transverse mass spectrum above 500 GeV and hence influence the resulting mass limits [17]. Optimising for the best expected cross section limit resulted in very similar search windows at high M_{T}, yielding lower limits on the W'_{L} mass of 2.63 (2.43) TeV for constructive (destructive) interference, based on the same MADGRAPH cross sections and K-factors as the ones used in Figure 3. We note that the interference affects mainly the medium M_{T} and hardly the Jacobian peak region, with the latter being used to set the limits. The limits shown do not take into account higher order electroweak corrections at high mass, which can be sizable. The effect of these missing corrections would be a reduction of the size of interference effects, leading to limits that are closer to the ones quoted for the no-interference case.

In addition to the model dependent results on W' production, upper limits for the cross section of beyond-the-SM production of charged lepton-neutrino events are given in Table 2 and Figure 4. The results are presented as a function of the transverse mass threshold, $M_{\mathrm{T}}^{\mathrm{min}}$, and

Table 2: Excluded cross sections times branching fraction in the search window ($M_T > M_T^{min}$) in the electron and muon channels individually, along with their combination. The number of expected background events was taken from simulation. The expected and observed cross section limits are given for each search window.

	Electron channel				Muon channel				Combined channels	
M_T^{min}	Events		Limit (fb)		Events		Limit (fb)		Limit (fb)	
(GeV)	N_{bkg}	N_{obs}	Exp.	Obs.	N_{bkg}	N_{obs}	Exp.	Obs.	Exp.	Obs.
500	175 ± 22	192	10.14	13.85	158 ± 14	141	8.20	6.13	6.86	6.04
600	77 ± 10	83	5.99	7.13	67.9 ± 8.1	62	5.12	4.46	4.01	3.95
700	37.4 ± 5.7	41	3.80	4.57	32.6 ± 5.0	36	3.60	4.41	2.65	3.31
800	20.0 ± 3.8	22	3.03	3.24	17.0 ± 3.6	16	2.95	2.54	1.94	1.99
900	11.4 ± 2.6	12	2.10	2.30	9.5 ± 2.6	11	2.01	2.46	1.46	1.68
1000	6.8 ± 1.8	8	1.79	2.02	5.6 ± 1.9	6	1.57	1.80	1.11	1.32
1100	4.3 ± 1.3	6	1.40	1.88	3.4 ± 1.4	4	1.32	1.56	0.94	1.19
1200	2.79 ± 0.98	3	1.32	1.32	2.2 ± 1.0	3	1.18	1.45	0.78	0.92
1300	1.87 ± 0.74	2	1.15	1.15	1.45 ± 0.75	2	0.97	1.26	0.69	0.77
1400	1.29 ± 0.56	2	0.94	1.22	0.98 ± 0.56	2	1.00	1.32	0.59	0.85
1500	0.91 ± 0.43	1	0.97	0.97	0.68 ± 0.43	2	0.72	1.37	0.53	0.76

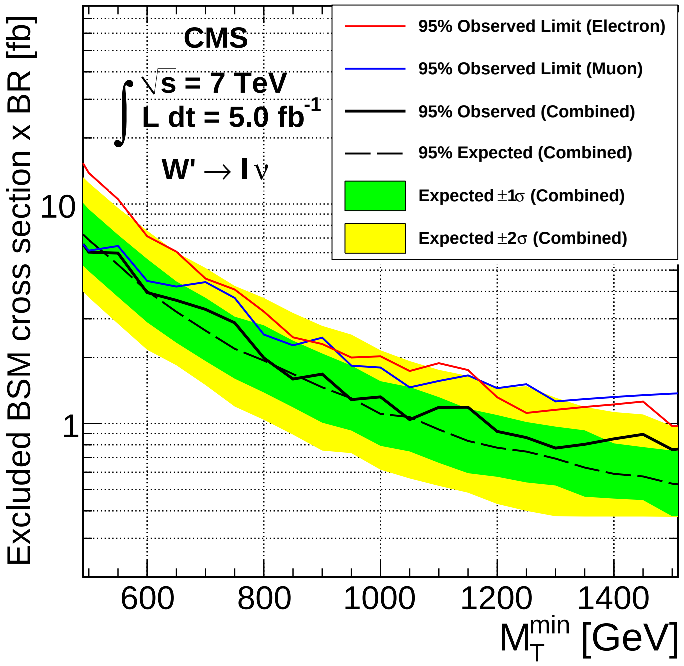

Figure 4: 95% confidence level upper limits on the cross section times branching fraction for physics beyond the SM (labelled BSM) for the charged lepton-neutrino production with transverse masses exceeding M_T^{min}. The results for the electron, the muon channel, as well as for both channels combined are presented. The one (two) sigma uncertainty bands are shown in green (yellow).

listed separately for the electron and the muon channels, and their combination. The only assumptions made here are that we are searching for a narrow s-channel produced resonance, using the detector acceptance and selection efficiency outlined in Section 4. Note that the $M_{\mathrm{T}}^{\mathrm{min}}$ threshold is on an experimentally-measured quantity affected by detector resolution.

These exclusion limits on the cross-section can be translated to excluded W' masses within the context of a given model, such as constructive or destructive W'_{L}, W'_{R} or something else.

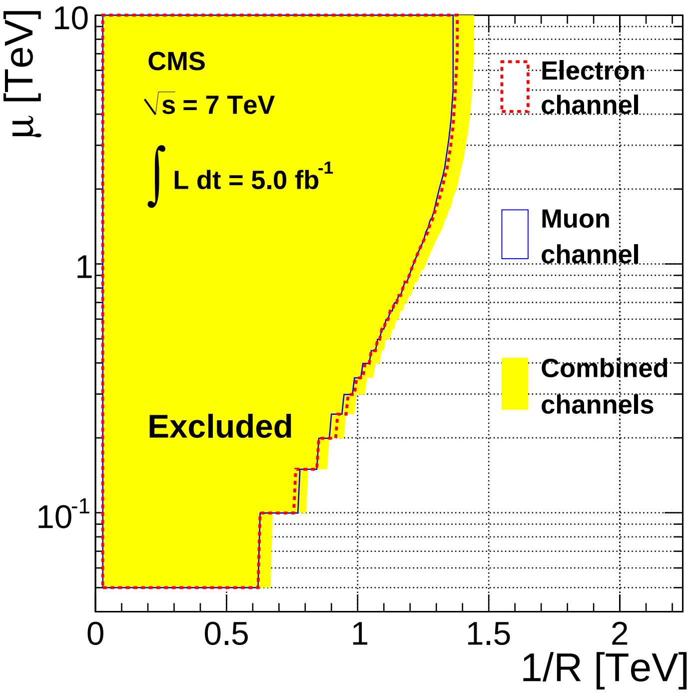

Figure 5: 95% confidence limits on the split-UED parameters μ and R derived from the W' mass limits taking into account the corresponding width of the $\mathrm{W}^2_{\mathrm{KK}}$. The colored areas correspond to the $\mathrm{W}^2_{\mathrm{KK}}$ exclusion regions with the same final state as the SM-like W'. Results are shown for the electron and muon channels, as well as for both channels combined. The $\mathrm{W}^2_{\mathrm{KK}}$ is the lowest state that can couple to SM fermions. Since it has even parity it can be produced singly.

The observed limits illustrated in Figure 3 can be reinterpreted in terms of the $\mathrm{W}^2_{\mathrm{KK}}$ mass, as shown in the same figure for values of the bulk mass parameters $\mu = 0.05\,\mathrm{TeV}$ and $\mu = 10\,\mathrm{TeV}$. For these parameters the second Kaluza–Klein excitation $\mathrm{W}^2_{\mathrm{KK}}$ has been excluded for masses below 1.4 TeV ($\mu = 0.05\,\mathrm{TeV}$) or 2.9 TeV ($\mu = 10\,\mathrm{TeV}$), respectively. The corresponding widths (Eq. (4)) are taken into account in the calculation of the cross section times the branching fraction of $\mathrm{W}^2_{\mathrm{KK}}$. These lower limits on the mass can be directly translated to bounds on the split-UED parameter space $[1/R, \mu]$ with μ being the mass parameter for bulk fermions and R the radius of the extra dimension. The results are displayed in Figure 5, using the relations between R, μ and the $\mathrm{W}^2_{\mathrm{KK}}$ mass, and the couplings to SM fermions described by expressions (1), (2) and (3). The split-UED model also allows for W-W' interference. When the constructive case is considered, it has a comparable sensitivity to the no-interference case.

8 Summary

A search for an excess of events with a final state consisting of a charged lepton (electron or muon) and significant missing transverse momentum has been performed, using 5.0 fb^{-1} of $\sqrt{s}$ = 7 TeV pp collision data. No significant excess over the SM expectation was observed in the distribution of transverse mass. A W'_{R} in the SSM with a mass of less than 2.5 TeV has been excluded at 95% CL. For the first time in such a study, W-$\mathrm{W}^{'}$ interference effects have been taken into account, and mass exclusion limits have been determined as 2.63 TeV and 2.43 TeV for constructive and destructive interference respectively. These are the most stringent limits yet published. An interpretation of the search results has also been made in a specific framework of universal extra dimensions with bulk mass fermions. The second Kaluza–Klein excitation $\mathrm{W}^{2}_{\mathrm{KK}}$ has been excluded for masses below 1.4 TeV, assuming a bulk mass parameter μ of 0.05 TeV or masses below 2.9 TeV for μ=10 TeV.

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