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Search for $\mathrm{W}' \to \mathrm{tb}$ decays in the lepton + jets final state in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

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Abstract: Results are presented from a search for the production of a heavy gauge boson W′ decaying into a top and a bottom quark, using a data set collected by the CMS experiment at $\sqrt{s} = 8\,\mathrm{TeV}$ and corresponding to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$. Various models of W′-boson production are studied by allowing for an arbitrary combination of left- and right-handed couplings. The analysis is based on the detection of events with a lepton (e, μ), jets, and missing transverse energy in the final state. No evidence for W′-boson production is found and 95% confidence level upper limits on the production cross section times branching fraction are obtained. For W′ bosons with purely right-handed couplings, and for those with left-handed couplings assuming no interference effects, the observed 95% confidence level limit is $M(\mathrm{W}') > 2.05\,\mathrm{TeV}$. For W′ bosons with purely left-handed couplings, including interference effects, the observed 95% confidence level limit is $M(\mathrm{W}') > 1.84\,\mathrm{TeV}$. The results presented in this paper are the most stringent limits published to date.

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Contents

1 Introduction

Massive charged gauge bosons, generically referred to as W′, are predicted by various extensions of the standard model (SM) [1–5]. Searches for W′ bosons at the Large Hadron Collider (LHC) have been conducted in the lepton-neutrino, diboson, and light-quark final states [6–15]. While the most stringent limits come from the searches in the leptonic final states ($W' \to \ell\nu$ where ℓ is a charged lepton), these constraints do not apply to W′ bosons with purely right-handed couplings if the mass of the hypothetical right-handed neutrino is larger than a few GeV [16]. Dedicated searches for W′ bosons with purely right-handed couplings have been performed by the CMS and ATLAS Collaborations assuming the mass of the right-handed neutrino is less than the mass of the W′ boson [17, 18]. Searches for right-handed W′ bosons that decay to a quark final state such as $W'^{+} \to t\overline{b}$ (or charge conjugate) make no assumptions regarding the mass of the right-handed neutrino and are thus complementary to searches in the leptonic channels. Furthermore, the decay chain $W' \to tb$, $t \to bW \to b\ell\nu$ is in principle fully reconstructable, thereby leading to observable resonant mass peaks even in the case of broad W′ resonances. In addition, because of the presence of leptons in the final state, it is easier to suppress the continuum multijet background for this decay chain than for a generic $W' \to qq'$ decay. Finally, in some models the W′ boson may couple more strongly to fermions of the third generation than to fermions of the first and second generations [19, 20]. Thus the $W' \to tb$ decay is an important channel in the search for W′ bosons.

Experimental searches for $W' \to tb$ decays have been performed at the Tevatron [21–23] and at the LHC [24, 25]. The CMS search at $\sqrt{s} = 7\,\text{TeV}$ [24] set the best present mass limit in this channel of 1.85 TeV for W′ bosons with purely right-handed couplings. If the W′ boson has left-handed couplings, interference between $W' \to tb$ and SM single-top-quark production via $W \to tb$ can contribute as much as 5–20% of the total W′ rate, depending on the W′ mass and couplings [26]. This interference effect was taken into account in the CMS search. The CMS analysis also set constraints on an arbitrary set of left- and right-handed couplings of the W′ boson.

This Letter describes the first $W' \to tb$ search in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ and uses data collected by the CMS experiment corresponding to an integrated luminosity of $19.5\,\text{fb}^{-1}$. For a W′ boson with a mass of 2 TeV, the production cross section at $\sqrt{s} = 8\,\text{TeV}$ is larger by approximately a factor of two compared to $\sqrt{s} = 7\,\text{TeV}$ [27]. The data set used in this analysis corresponds to an integrated luminosity that is approximately a factor of four larger than that in the $\sqrt{s} = 7\,\text{TeV}$ analysis. Following the approach of the earlier publication [24], we analyse events with an electron (e) or muon (μ), jets, and missing transverse energy ($E_{\text{T}}^{\text{miss}}$) for an arbitrary combination of left- and right-handed couplings.

2 CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Located within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Muons are identified and measured in gas-ionisation detectors embedded in the outer steel magnetic flux-return yoke of the solenoid. The detector is subdivided into a cylindrical barrel and endcap disks on each side of the interaction point. Forward calorimeters complement the coverage provided by the barrel and endcap detectors. A more detailed description of the CMS detector can be found elsewhere [28].

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the centre of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in radians in the x-y plane. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$.

The ECAL energy resolution for electrons with transverse energy $E_{\text{T}} \approx 45\,\text{GeV}$ from $Z \to ee$ decays is better than 2% in the central region of the ECAL barrel ($|\eta| < 0.8$), and is between 2% and 5% elsewhere. The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of $\sim 15\,\mu\text{m}$ and

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a transverse momentum (p_{T}) resolution of about 1.5% for 100 GeV particles. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with $20 < p_{\mathrm{T}} < 100$ GeV of 1.3-2.0% in the barrel and better than 6% in the endcaps. The p_{T} resolution in the barrel is better than 10% for muons with p_{T} up to 1 TeV [29].

A particle-flow (PF) algorithm [30, 31] combines the information from all CMS subdetectors to identify and reconstruct the individual particles emerging from all vertices: charged hadrons, neutral hadrons, photons, muons, and electrons. These particles are then used to reconstruct the $E_{\mathrm{T}}^{\mathrm{miss}}$ (defined as the modulus of the negative transverse momentum vector sum of all measured particles), jets, and to quantify lepton isolation. The PF jet energy resolution is typically 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40%, 12%, and 5% obtained when the calorimeters alone are used for jet clustering.

3 Signal and background modelling

The $\mathrm{W}' \to \mathrm{tb} \to \ell\nu\mathrm{bb}$ decay is characterized by the presence of a high-p_{T} isolated lepton, significant $E_{\mathrm{T}}^{\mathrm{miss}}$ associated with the neutrino, and at least two high-p_{T} b-jets (jets resulting from the fragmentation and hadronization of b quarks). Monte Carlo (MC) techniques are used to model the W′ signal and SM backgrounds capable of producing this final state.

3.1 Signal modelling

The signal modelling is identical to that in ref. [24] and uses the following lowest order effective Lagrangian to describe the interaction of the W′ boson with SM fermions:

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \big(a^{\mathrm{R}}_{f_i f_j}(1+\gamma^5) + a^{\mathrm{L}}_{f_i f_j}(1-\gamma^5) \big) \mathrm{W}'^{\mu} f_j + \mathrm{h.c.}, \tag{3.1}$$

where $a^{\mathrm{R}}_{f_i f_j}, a^{\mathrm{L}}_{f_i f_j}$ are the right- and left-handed couplings of the W′ boson to fermions f_i and f_j, $g_w = e/(\sin\theta_W)$ is the SM weak coupling constant and θ_{W} is the weak mixing angle; $V_{f_i f_j}$ is the Cabibbo-Kobayashi-Maskawa matrix element if the fermion f is a quark, and $V_{f_i f_j} = \delta_{ij}$ if it is a lepton, where δ_{ij} is the Kronecker delta and i, j are the generation numbers. For our search we consider models where $0 \leq a^{\mathrm{L,R}}_{f_i f_j} \leq 1$. For a SM-like W′ boson, $a^{\mathrm{L}}_{f_i f_j} = 1$ and $a^{\mathrm{R}}_{f_i f_j} = 0$.

We simulate W′ bosons with mass values ranging from 0.8 to 3.0 TeV . The SINGLETOP MC generator [27] is used, which simulates electroweak top-quark production processes based on the complete set of tree-level Feynman diagrams calculated by the CompHEP package [32]. Finite decay widths and spin correlations between resonance state production and subsequent decay are taken into account. The factorisation scale is set to the W′-boson mass for the generation of the samples and the computation of the leading-order (LO) cross section. The LO cross section is scaled to next-to-leading order (NLO) using a K factor of 1.2 based on refs. [33, 34]. In order to ensure that the NLO rates and shapes of relevant distributions are reproduced, the SINGLETOP generator includes NLO corrections, and normalisation and matching between various partonic subprocesses are

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performed. The top-quark mass is chosen to be 172.5 GeV and the CTEQ6M [35] parton distribution functions (PDF) are used. The uncertainty in the cross section is about 8.5% and includes contributions from the uncertainties in the renormalisation and factorisation scales (3.3%), PDFs (7.6%), α_s (1.3%), and the top-quark mass (<1%).

We produce the following sets of signal samples:

- W'_L with $a^\mathrm{L}_\mathrm{ud} = a^\mathrm{L}_\mathrm{cs} = a^\mathrm{L}_\mathrm{tb} = 1$ and $a^\mathrm{R}_\mathrm{ud} = a^\mathrm{R}_\mathrm{cs} = a^\mathrm{R}_\mathrm{tb} = 0$
- W'_R with $a^\mathrm{L}_\mathrm{ud} = a^\mathrm{L}_\mathrm{cs} = a^\mathrm{L}_\mathrm{tb} = 0$ and $a^\mathrm{R}_\mathrm{ud} = a^\mathrm{R}_\mathrm{cs} = a^\mathrm{R}_\mathrm{tb} = 1$
- W'_LR with $a^\mathrm{L}_\mathrm{ud} = a^\mathrm{L}_\mathrm{cs} = a^\mathrm{L}_\mathrm{tb} = 1$ and $a^\mathrm{R}_\mathrm{ud} = a^\mathrm{R}_\mathrm{cs} = a^\mathrm{R}_\mathrm{tb} = 1$

The W'_L bosons couple to the same fermion multiplets as the SM W boson. As a consequence, there will be interference between *s*-channel tb production via a W boson and via a W'_L boson. These two processes therefore cannot be generated separately. Thus the W'_L and W'_LR samples include SM *s*-channel tb production including its interference with the W'_L signal. Production of a tb final state via a W'_R boson does not interfere with tb production via a W boson and therefore the W'_R sample only includes W' production.

The W'_R boson can only decay leptonically if there is a right-handed neutrino ν_R of sufficiently small mass, $M(\nu_\mathrm{R})$, so that $M(\nu_\mathrm{R}) + M(\ell) < M(\mathrm{W}')$. If the mass of the right-handed neutrino is too large, W'_R bosons can only decay to $\mathrm{q}\overline{\mathrm{q}}'$ final states, leading to different branching fractions for the $\mathrm{W}'_\mathrm{R} \to \mathrm{tb}$ decay than for the $\mathrm{W}'_\mathrm{L} \to \mathrm{tb}$ decay. In the absence of interference between the SM W boson and the W' boson, and if there is a light right-handed neutrino, there is no practical difference for our search between W'_L and W'_R bosons.

3.2 Background modelling

The $\mathrm{t\bar{t}}$, W+jets, single-top-quark (*s*-channel, *t*-channel, and tW associated production), Z/γ^*+jets, and diboson (WW) background contributions are estimated from simulation, with corrections to the shape and normalisation derived from data.

The $\mathrm{t\bar{t}}$, W+jets, and Z/γ^*+jets background processes are generated with MadGraph 5.1 [36]. The $\mathrm{t\bar{t}}$ background is normalized to the next-to-NLO (NNLO) cross section [37]. The SM single-top-quark backgrounds are estimated using samples generated with powheg [38], normalized to an approximate NNLO cross section [39]. For the W'_R search, *s*-channel, *t*-channel, and tW single-top-quark events are considered as backgrounds. Because of interference between W' and *s*-channel single-top-quark production, in the analysis for W'_L and W'_LR bosons only the *t*-channel and the tW processes contribute to the background. The diboson (WW) background is generated with pythia 6.424 [40]. Instrumental background due to a jet misidentified as an isolated lepton was studied using a sample of QCD multijet events simulated with pythia and was found to be negligible after the final selection.

3.3 Simulation

For all simulated samples, pythia tune Z2* [41] is used for parton showering, hadronisation, and simulation of the underlying event. The pythia and MadGraph backgrounds use the CTEQ6L1 PDFs, and the POWHEG backgrounds use the CTEQ6M PDFs [35]. The resulting events are processed with the full GEANT4 [42] simulation of the CMS detector. The additional proton-proton interactions in each beam crossing (pileup) are modelled by superimposing extra minimum-bias interactions onto simulated events, with the distribution of the number of pileup interactions matching that in data.

4 Object and event preselection

The analysis relies on the reconstruction of electrons, muons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$. Candidate events are required to pass an isolated electron (muon) trigger with a p_{T} threshold of 27 (24) GeV and to have at least one reconstructed pp interaction vertex. In the offline selection, exactly one electron (muon) is required to be within the region of $|\eta| < 2.5$ (2.1). Additionally, the barrel/endcap transition region, $1.44 < |\eta| < 1.56$, is excluded for electrons. Electrons and muons are required to satisfy $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and a series of identification and isolation criteria. Electron candidates are selected using shower shape information, the quality of the track, the matching between the track and the electromagnetic cluster, the fraction of total cluster energy in the HCAL, and the amount of activity in the surrounding regions of the tracker and calorimeters. Events are removed whenever the electron is found to originate from a converted photon. The track associated with a muon candidate is required to have at least one pixel hit, hits in at least six layers of the inner tracker, at least one hit in the muon detector, and a good quality fit with $\chi^2/\mathrm{d.o.f.} < 10$. Both electrons and muons are separated from jets by requiring $\Delta R(\mathrm{jet}, \ell) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.3$. Additionally, the cosmic ray background is effectively eliminated by requiring the transverse impact parameter of the muon with respect to the beam spot to be less than 2 mm. Electrons (muons) are required to have PF based relative isolation, I_{rel}, less than 0.10 (0.12). The quantity I_{rel} is defined as the sum of the transverse momenta of all additional reconstructed particle candidates inside a cone around the electron (muon) in (η, ϕ) of $\Delta R < 0.3$ (0.4), divided by the p_{T} of the electron (muon). An event-by-event correction is applied to the computation of the lepton isolation in order to account for the effect of pileup. Events containing a second lepton with looser identification and isolation requirements are also rejected. Scale factors, derived from comparing the efficiencies measured in data and simulation using $\mathrm{Z} \to \ell\ell$ events, are obtained for lepton identification and isolation as a function of lepton p_{T} and η. These are applied as corrections to the simulated events.

Jets are clustered using the anti-k_{T} algorithm [43] with a distance parameter of $R = 0.5$ and are required to satisfy $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$. At least two jets are required in the event with the highest-p_{T} (leading) jet $p_{\mathrm{T}} > 120\,\mathrm{GeV}$ and the second leading jet $p_{\mathrm{T}} > 40\,\mathrm{GeV}$. The jet p_{T} in the simulated samples is smeared to account for the better jet energy resolution observed in the simulation compared to data [44]. Jet energy corrections are applied to correct for residual non-uniformity and non-linearity of the detector response. Jet energies are also corrected by subtracting the average contribution from pileup interactions [45, 46].

The final state of the $\mathrm{W}' \to \mathrm{tb}$ decay includes two b quarks; therefore at least one of the two leading jets is required to be tagged as a b-jet. We use the combined secondary

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vertex tagger with the medium operating point [47]. Data-to-simulation scale factors for the b-tagging efficiency and the light-quark or gluon (udsg) jet mistag rate are applied on a jet-by-jet basis to all b-jets, c-jets, and udsg jets in the simulated events. Scale factors are also applied to W+jets events in which a b, c, or udsg jet is produced in association with the W boson, in order to bring the data and simulation yields into agreement. The procedure used is identical to the one described in ref. [24]. Based on lepton + jets samples with various jet multiplicities, W+b and W+c corrections are derived [48]. To account for differences between the lepton + jets topology and the topology considered here, additional W+udsg and W+b/c corrections are derived from two background-dominated event samples, one without any b-tagged jets and one without any b-tagging requirement. These corrections are then applied to the simulated W+jets events. We find that the W+b, W+c, and W+udsg contributions need to be corrected by an overall factor of 1.21, 1.66, and 0.83, respectively. These corrections agree within their uncertainties with the corresponding corrections derived in ref. [24].

Finally, the $E_{\mathrm{T}}^{\mathrm{miss}}$ is required to exceed 20 GeV in both the electron and muon samples in order to reduce the QCD multijet background.

5 Data analysis

The distinguishing feature of a W′ signal is a narrow resonance structure in the tb invariant-mass spectrum. The tb invariant mass is reconstructed from the combination of the charged lepton, the neutrino, the jet which gives the best top-quark mass reconstruction, and the highest-p_{T} jet in the event that is not associated with the top quark. The x and y components of the neutrino momentum are obtained from the missing transverse energy. The z component is calculated by constraining the invariant mass of the lepton-neutrino pair to the W-boson mass (80.4 GeV). This constraint leads to a quadratic equation in p_z^ν. In the case of two real solutions, both of the solutions are used to reconstruct the W-boson candidates. In the case of complex solutions, the real part is assigned to p_z^ν and the imaginary part is forced to zero by relaxing the W-boson mass constraint and recomputing p_{T}^ν. The p_{T}^ν solution that gives the invariant mass of the lepton-neutrino pair closest to 80.4 GeV is chosen, resulting in a single W-boson candidate. Top-quark candidates are then reconstructed using the W-boson candidate(s) and all of the selected jets in the event, and the top-quark candidate with mass closest to 172.5 GeV is chosen. The W′-boson candidate is obtained by combining the best top-quark candidate with the highest-p_{T} jet, excluding the one used for the best top-quark candidate. For a 2.0 TeV W'_{R} boson, this procedure assigns the correct jets from the W′ decay 83% of the time.

Since the W+jets process is one of the major backgrounds for the W′ signal process (see table 1), a study is performed to check that the shape of the W+jets mass distribution is well-modelled by the simulation. This cross-check utilizes the fact that events that have no b-tagged jets, but satisfy all other selection criteria, are expected to originate predominantly from W+jets events. The purity of W+jets events for this control sample is greater than 85%. The shape of the W+jets background is obtained by subtracting the backgrounds from sources other than W+jets from the distributions in data. The resulting

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invariant-mass distribution is compared to the distribution from the W+jets MC sample with zero b-tagged jets. The difference between the distributions is included as a systematic uncertainty in the shape of the W+jets background. Using simulated events, the W+jets background was verified to be independent of the number of b-tagged jets by comparing the mass distribution with zero b-tagged jets with that obtained by requiring one or more b-tagged jets.

Measurements of the top-quark differential cross sections have shown that the top-quark p_{T} distribution is not properly modelled in simulated events [49]. We therefore reweight the $\mathrm{t\bar{t}}$ sample using an empirical function of the generated top quark and anti-quark p_{T} determined from studies of the $\mathrm{t\bar{t}}$ differential cross section. Residual differences with respect to the unweighted distribution are taken into account as a systematic uncertainty in the $\mathrm{t\bar{t}}$ background prediction. We check the applicability of these weights to our kinematic region by defining a control region in data that is dominated by $\mathrm{t\bar{t}}$ events. The control region is defined by the following requirements, which are designed to ensure small ($\lesssim$2%) potential signal contamination: $N_{\text{jets}} \geq 4$, the total number of b-tagged jets (including jets with p_{T} values less than those of the two leading jets) $N_{\text{b-tags}} \geq 2$, and $400 < M(\mathrm{tb}) < 750\,\mathrm{GeV}$. We perform a fit to the ratio of data to expected background events for the top-quark p_{T} distribution using a Landau function and reweight the events in the simulated $\mathrm{t\bar{t}}$ sample using the result of the fit. This method gives results that are consistent with the generator-level reweighting procedure.

Figure 1 shows the reconstructed tb invariant-mass distribution obtained from data and from simulated W′ signal samples with four different mass values ($M(\mathrm{W}') = 1.8$, 2.0, 2.5, and 3.0 TeV). Also shown are the dominant background contributions. The distributions are shown after the preselection described in section 4, as well as three final selection criteria which are imposed to improve the signal-to-background discrimination: the p_{T} of the selected top-quark candidate $p_{\mathrm{T}}^{\mathrm{t}} > 85\,\mathrm{GeV}$, the p_{T} of the vector sum of the two leading jets $p_{\mathrm{T}}^{\text{jet1,jet2}} > 140\,\mathrm{GeV}$, and the mass of the selected top-quark candidate with $130\,\mathrm{GeV} < M(\mathrm{t}) < 210\,\mathrm{GeV}$. The distributions are shown separately for the electron and muon samples, for events which have one or both of the two leading jets tagged as b-jets. The number of events remaining with one and two b-tagged jets after the preselection and final selection are listed in table 1. The yields measured in data and those predicted from simulation agree within the statistical and systematic uncertainties, which are described in the following section.

6 Systematic uncertainties

The systematic uncertainties that are relevant for this analysis fall into two categories: (i) uncertainties in the total event yield and (ii) uncertainties that impact both the shape and the total event yield of the distributions. The first category includes uncertainties in the total integrated luminosity of the data sample (2.6%) [50], lepton reconstruction and identification efficiencies (1%), trigger modelling (1–2%), and the theoretical $\mathrm{t\bar{t}}$ cross section (8%).

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	Number of selected events							
	Electron sample				Muon sample			
	Preselection		Final selection		Preselection		Final selection	
Process	1 b-tag	2 b-tags	1 b-tag	2 b-tags	1 b-tag	2 b-tags	1 b-tag	2 b-tags
Signal:								
$M(\mathrm{W}'_\mathrm{R}) = 1.8\,\mathrm{TeV}$	45.2	12.7	32.2	9.3	38.0	10.8	26.3	7.7
$M(\mathrm{W}'_\mathrm{R}) = 2.0\,\mathrm{TeV}$	20.9	5.6	14.6	4.0	17.5	4.7	11.8	3.2
$M(\mathrm{W}'_\mathrm{R}) = 2.5\,\mathrm{TeV}$	3.5	0.9	2.3	0.6	3.0	0.8	1.8	0.5
$M(\mathrm{W}'_\mathrm{R}) = 3.0\,\mathrm{TeV}$	0.8	0.3	0.5	0.2	0.7	0.2	0.4	0.2
$M(\mathrm{W}'_\mathrm{L}) = 1.8\,\mathrm{TeV}$	143.0	60.9	57.1	19.7	148.8	63.7	58.1	19.5
$M(\mathrm{W}'_\mathrm{L}) = 2.0\,\mathrm{TeV}$	125.2	57.9	44.7	17.8	128.3	61.0	45.7	18.1
$M(\mathrm{W}'_\mathrm{L}) = 2.5\,\mathrm{TeV}$	115.8	58.6	38.4	17.2	122.3	62.6	41.6	17.7
$M(\mathrm{W}'_\mathrm{L}) = 3.0\,\mathrm{TeV}$	121.3	58.1	41.0	16.7	126.6	64.4	42.2	17.9
Background:								
$\mathrm{t\bar{t}}$	34561	7888	12383	1639	35349	8191	12610	1650
s-channel (tb)	175	93	58	28	196	102	63	32
t-channel (tqb)	2113	357	710	108	2275	373	747	114
tW-channel	2557	362	847	107	2645	372	861	113
$\mathrm{W}(\rightarrow \ell\nu)$+jets	19970	563	3636	99	19697	679	3704	62
$\mathrm{Z}/\gamma^*(\rightarrow \ell\ell)$+jets	1484	83	260	10	1497	73	275	17
WW	205	9	47	3	219	7	47	2
Total bkg.	61065 $\pm$6188	9357 $\pm$1504	17942 $\pm$2514	1993 $\pm$399	61877 $\pm$6098	9797 $\pm$1524	18307 $\pm$2488	1991 $\pm$400
Data	63050	9646	18175	2063	62955	9865	18558	2081
Total bkg. / Data	0.969 $\pm$0.10	0.970 $\pm$0.16	0.987 $\pm$0.14	0.966 $\pm$0.19	0.983 $\pm$0.10	0.993 $\pm$0.15	0.986 $\pm$0.13	0.957 $\pm$0.19

Table 1. Number of selected data, signal, and background events. For the background samples, the number of expected events is computed corresponding to an integrated luminosity of 19.5 fb^{-1}. The final two columns for each sample include the following selections: $p_\mathrm{T}^\mathrm{t} > 85\,\mathrm{GeV}$, $p_\mathrm{T}^\mathrm{jet1,jet2} > 140\,\mathrm{GeV}$, $130 < M(\mathrm{t}) < 210\,\mathrm{GeV}$. The combined statistical and systematic uncertainty on the total background prediction is also shown. The standard model s-channel tb process contributes to the background only in the search for W'_R bosons owing to its interference with the $\mathrm{W}'_\mathrm{L} \rightarrow \mathrm{tb}$ process. The number of events for the W'_L signal takes into account the interference with the SM s-channel tb process.

The second category includes the uncertainty from the jet energy scale and resolution, and from the b-tagging and the mis-tagging efficiency scale factors. For the W+jets samples, uncertainties relating to the extraction of the light- (13%) and heavy-flavour (15%) scale factors from data are also included [47]. As discussed in the previous section, additional uncertainties are assigned relating to the W+jets background shape and to the top quark p_T spectrum. The variation of the renormalisation and factorisation scale Q^2 used in the strong coupling constant $\alpha_s(Q^2)$, and the jet-parton matching scale uncertainties in the MLM scheme [51] are evaluated for the $\mathrm{t\bar{t}}$ background sample. These uncertainties are evaluated by raising and lowering the corresponding parameters by one standard deviation (or in the case of the renormalisation and factorisation scale Q and the jet parton matching scale by a factor 2 and 0.5), and repeating the analysis.

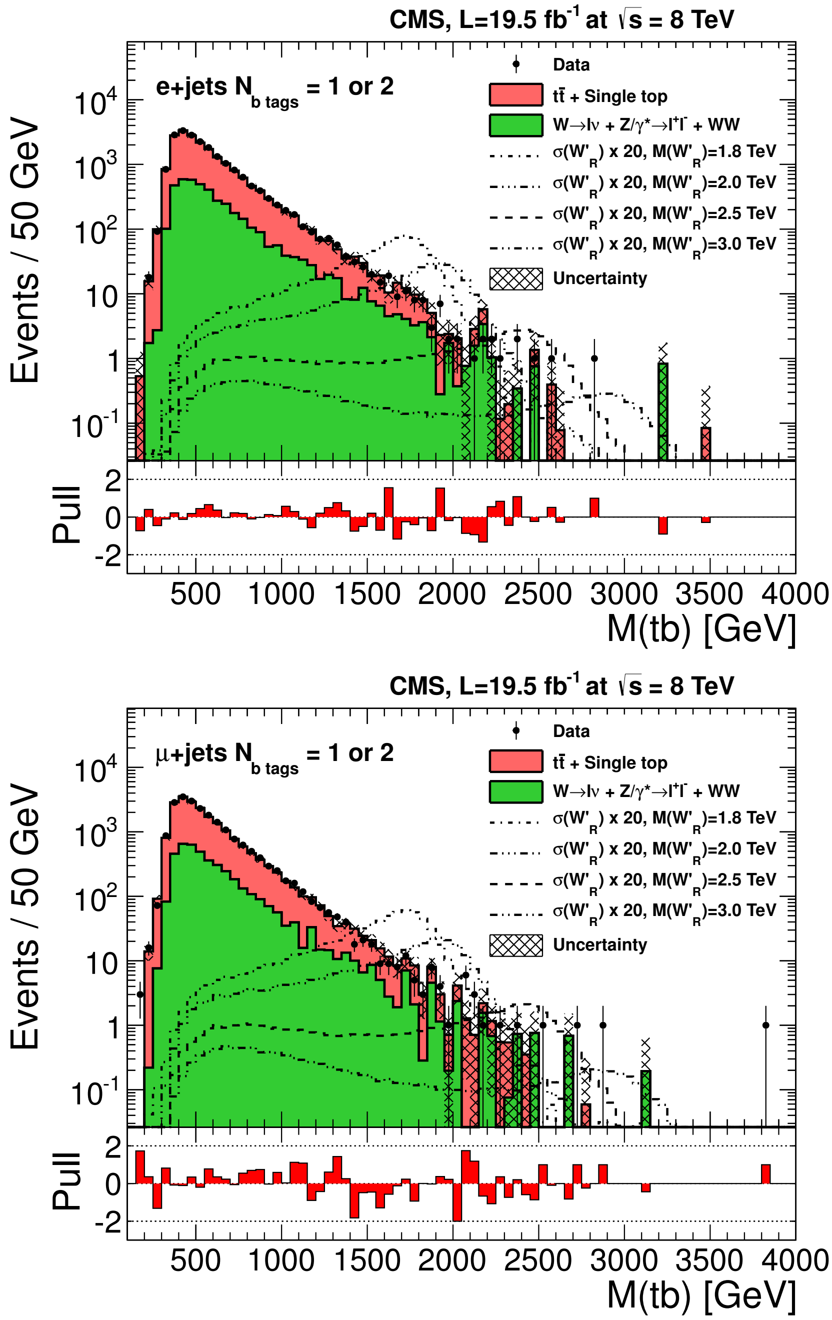

Figure 1. The reconstructed invariant-mass distribution of the W′-boson candidates after the final selection. Events with electrons (muons) are shown on the left (right) panel for data, background and four different W'_{R} signal mass hypotheses (1.8, 2.0, 2.5, and 3.0 TeV). All events are required to have one or both of the two leading jets tagged as b-jets. The hatched bands represent the total normalisation uncertainty in the predicted backgrounds. The pull is defined as the difference between the observed data yield and the predicted background, divided by the uncertainty. For these plots it is assumed that $M(\nu_{\mathrm{R}}) \ll M(\mathrm{W}'_{\mathrm{R}})$ and for the purpose of illustration the expected yields for the W'_{R} signal samples are scaled by a factor of 20.

7 Results

The W′-boson mass distribution observed in the data and the prediction for the total expected background agree within statistical and systematic uncertainties (see table 1 and figure 1). We set upper limits on the W′-boson production cross section for different W′-boson masses.

7.1 Cross section limits

The limits are computed using a Bayesian approach with a flat prior on the signal cross section with the THETA package [52]. In order to reduce the bin-by-bin statistical uncertainty in the predicted event yields obtained from the simulated samples, we bin the invariant-mass distribution using one bin from 100 to 300 GeV, 17 bins of 100 GeV width from 300 to 2000 GeV, and two additional bins from 2000 to 2200 GeV and from 2200 to 4000 GeV . Four categories are defined according to the lepton flavor (electron or muon) and b-tag multiplicity (one or two b-tagged jets) to improve the sensitivity of the analysis. The resulting distributions serve as the inputs to the limit setting procedure, and the limit is based on the posterior probability defined by using all categories simultaneously. A binned likelihood is used to calculate upper limits on the signal production cross section times total leptonic branching fraction: $\sigma(\mathrm{pp} \to \mathrm{W}') \times \mathcal{B}(\mathrm{W}' \to \mathrm{tb} \to \ell\nu\mathrm{bb})$, where $\ell = \mathrm{e}/\mu/\tau$. The search is sensitive to the $\mathrm{W}' \to \mathrm{tb} \to \tau\nu\mathrm{bb}$ decay mode if the tau subsequently decays to an electron or muon. Therefore $\tau \to \mathrm{e}/\mu$ events are included in the signal and background estimations of the electron and muon samples, respectively. The limit computation accounts for the effects of systematic uncertainties (discussed in section 6) in the normalisation and shape of the invariant-mass distributions, as well as for statistical fluctuations in the background templates. Expected limits on the production cross section for each W'_{R}-boson mass are also computed as a measure of the sensitivity of the analysis.

In figure 2, the solid black line denotes the observed limit and the red lines represent the predicted theoretical cross section times leptonic branching fractions. The lower mass limit is defined by the mass value corresponding to the intersection of the observed upper limit on the production cross section times leptonic branching fraction with the theoretical prediction. For W′ bosons with right-handed couplings to fermions the observed (expected) limit is 2.05 (2.02) TeV at 95% confidence level (CL). These limits also apply to a left-handed W′ boson when no interference with the SM is taken into account. Assuming heavy right-handed neutrinos ($M(\nu_{\mathrm{R}}) > M(\mathrm{W}')$), the observed (expected) limit is 2.13 (2.12) TeV at 95% CL.

7.2 Limits on coupling strengths

The effective Lagrangian given by eq. (1) can be analysed for arbitrary combinations of left-handed or right-handed coupling strengths [24]. The cross section for single-top-quark production in the presence of a W′ boson for any set of coupling values can be written in terms of the cross sections of our signal MC samples, σ_{L} for purely left-handed couplings $(a^{\mathrm{L}}, a^{\mathrm{R}}) = (1, 0)$, σ_{R} for purely right-handed couplings $(a^{\mathrm{L}}, a^{\mathrm{R}}) = (0, 1)$, σ_{LR} for mixed

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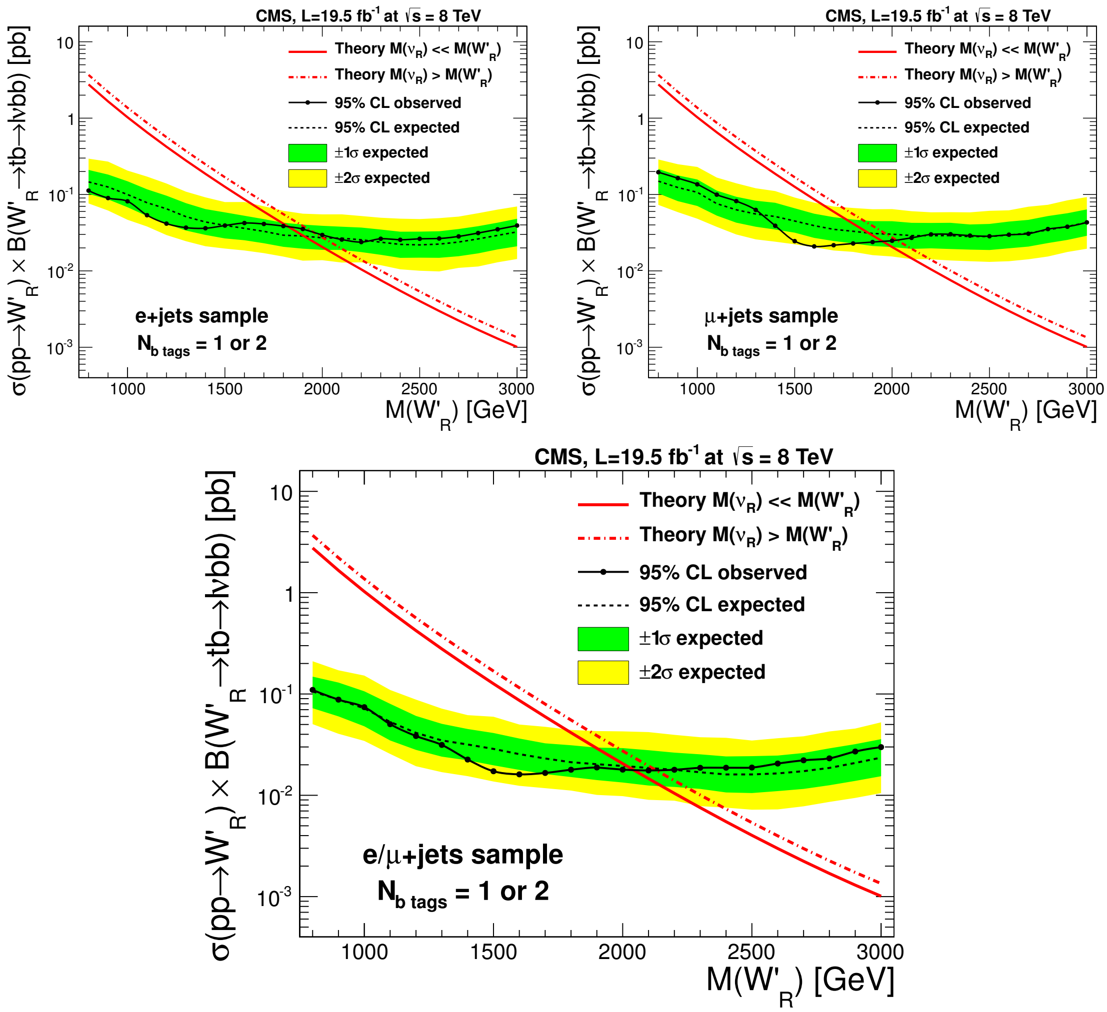

Figure 2. The expected (dashed black line) and observed (solid black line) 95% CL upper limits on the production cross section of right-handed W′ bosons obtained for the electron sample (top left), muon sample (top right), and their combination (bottom) along with the $\pm1\sigma$ and $\pm2\sigma$ uncertainty in the expected exclusion limit. The theoretical cross section times branching fraction for right-handed W′-boson production $\sigma(\mathrm{pp} \to \mathrm{W}'_\mathrm{R}) \times \mathrm{B}(\mathrm{W}'_\mathrm{R} \to \mathrm{tb} \to \ell\nu\mathrm{bb})$, where $\ell = \mathrm{e}/\mu/\tau$, is shown as a solid (dot-dashed) red line, when assuming light (heavy) right-handed neutrinos.

couplings $(a^\mathrm{L}, a^\mathrm{R}) = (1,1)$, and σ_SM for SM couplings $(a^\mathrm{L}, a^\mathrm{R}) = (0,0)$. It is given by:

$$\begin{aligned} \sigma = {} & \sigma_\mathrm{SM} + a^\mathrm{L}_\mathrm{ud} a^\mathrm{L}_\mathrm{tb} \left(\sigma_\mathrm{L} - \sigma_\mathrm{R} - \sigma_\mathrm{SM}\right) \\ & + \left(\left(a^\mathrm{L}_\mathrm{ud} a^\mathrm{L}_\mathrm{tb}\right)^2 + \left(a^\mathrm{R}_\mathrm{ud} a^\mathrm{R}_\mathrm{tb}\right)^2 \right) \sigma_\mathrm{R} \\ & + \frac{1}{2} \left(\left(a^\mathrm{L}_\mathrm{ud} a^\mathrm{R}_\mathrm{tb}\right)^2 + \left(a^\mathrm{R}_\mathrm{ud} a^\mathrm{L}_\mathrm{tb}\right)^2 \right) \left(\sigma_\mathrm{LR} - \sigma_\mathrm{L} - \sigma_\mathrm{R}\right). \end{aligned} \tag{7.1}$$

Note that for pure W'_R production this reduces to the sum of SM s-channel tb and W'_R production. For pure W'_L or W'_LR production this reduces to the cross section of the W'_L or the W'_LR sample which already includes SM s-channel tb production and its interference with W′ production.

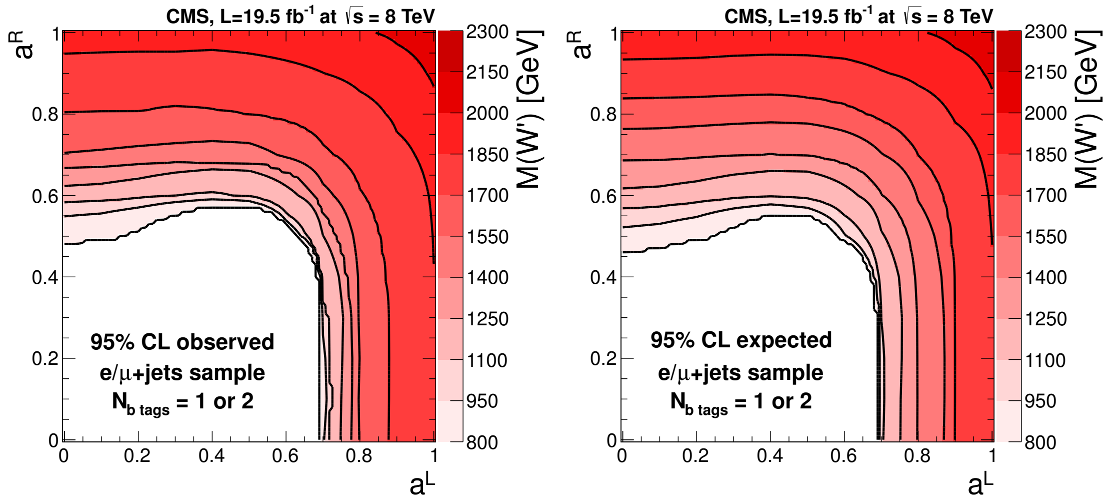

Figure 3. Contour plots of $M(\mathrm{W}')$ in the $(a^{\mathrm{L}}, a^{\mathrm{R}})$ plane for which the 95% CL cross section limit equals the predicted cross section for the combined e, μ+jets sample. The left (right) panel represents the observed (expected) limits. The colour axis represents the value of $M(\mathrm{W}')$ in GeV. The solid black lines are isocontours of W′-boson mass, plotted in 150 GeV intervals and starting from 800 GeV.

We assume that the couplings to first-generation quarks, a_{ud}, that are important for the production of the W′ boson, and the couplings to third-generation quarks, a_{tb}, that are important for the decay of the W′ boson, are equal. The event samples are combined according to eq. (7.1) to give the predicted invariant-mass distributions for each value of a^{L} and a^{R}.

We vary both a^{L} and a^{R} in the range (0,1) with a step size of 0.1, for each $M(\mathrm{W}')$. For each of these combinations of a^{L}, a^{R}, and $M(\mathrm{W}')$, we determine the expected and observed 95% CL upper limits on the cross section and compare them to the corresponding theoretical prediction. If the limit is below the theoretical prediction, this point in $(a^{\mathrm{L}}, a^{\mathrm{R}}, M(\mathrm{W}'))$ space is excluded. Figure 3 shows the excluded W′-boson mass for each point in the $(a^{\mathrm{L}}, a^{\mathrm{R}})$ plane. The observed (expected) mass limit for a W′ boson with only left-handed couplings, including interference with the SM, is 1.84 (1.84) TeV .

8 Summary

We have performed a search for a W′ boson in the tb decay channel using a data set corresponding to an integrated luminosity of 19.5 fb^{-1} of pp collisions collected by the CMS detector at $\sqrt{s} = 8$ TeV. No evidence for the presence of a W′ boson is found, and 95% confidence level upper limits on $\sigma(\mathrm{pp} \to \mathrm{W}') \times \mathcal{B}(\mathrm{W}' \to \mathrm{tb} \to \ell\nu\mathrm{bb})$ are set. We compare our measurement to the theoretical prediction for the cross section to determine the lower limit on the mass of the W′ boson. For W′ bosons with right-handed couplings to fermions (and for left-handed couplings to fermions, when assuming no interference effects) the observed (expected) limit is 2.05 (2.02) TeV at 95% confidence level. In the case with heavy right-

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handed neutrinos ($M(\nu_R) > M(W'_R)$), the observed (expected) limit is 2.13 (2.12) TeV at 95% confidence level. For a W′ boson with only left-handed couplings, including interference effects, the observed (expected) limit is 1.84 (1.84) TeV at 95% confidence level. We also set constraints on the W′ gauge coupling independent of their chiral structure. The results presented in this paper are the most stringent limits obtained to date.

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36 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
37 Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
38 Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
39 Also at University of Athens, Athens, Greece
40 Also at Paul Scherrer Institut, Villigen, Switzerland
41 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
42 Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
43 Also at Gaziosmanpasa University, Tokat, Turkey
44 Also at Adiyaman University, Adiyaman, Turkey
45 Also at Cag University, Mersin, Turkey
46 Also at Mersin University, Mersin, Turkey

47 Also at Izmir Institute of Technology, Izmir, Turkey
48 Also at Ozyegin University, Istanbul, Turkey
49 Also at Kafkas University, Kars, Turkey
50 Also at Istanbul University, Faculty of Science, Istanbul, Turkey
51 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
52 Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
53 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
54 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
55 Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
56 Also at Utah Valley University, Orem, U.S.A.
57 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
58 Also at Argonne National Laboratory, Argonne, U.S.A.
59 Also at Erzincan University, Erzincan, Turkey
60 Also at Yildiz Technical University, Istanbul, Turkey
61 Also at Texas A&M University at Qatar, Doha, Qatar
62 Also at Kyungpook National University, Daegu, Korea

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