Search for a $W'$ boson decaying to a bottom quark and a top quark in pp collisions at $\sqrt{s} = 7$ TeV

CMS Collaboration

1. Introduction

New charged massive gauge bosons, usually called $W'$, are predicted by various extensions of the standard model (SM), for example [1–4]. In contrast to the $W$ boson, which couples only to left-handed fermions, the couplings of the $W'$ boson may be purely left-handed, purely right-handed, or a mixture of the two, depending on the model. Direct searches for $W'$ bosons have been conducted in lepton final states and have resulted in lower limits for the $W'$ mass of 2.15 TeV [5] and 2.5 TeV [6], obtained at the Large Hadron Collider (LHC) by the ATLAS and CMS experiments respectively. CMS has also searched for the process $W' \rightarrow WZ$ using the fully leptonic final states and has excluded $W'$ bosons with masses below 1.14 TeV [7]. For $W'$ bosons that couple only to right-handed fermions, the decay to leptons will be suppressed if the mass of the right-handed neutrino is larger than the mass of the $W'$ boson. In that scenario, the limits from the leptonic searches do not apply. Thus it is important to search for $W'$ bosons also in quark final states. Searches for dijet resonances [8] have led to the limit $M(W') > 1.5$ TeV.

In this Letter, we present the results of a search for $W'$ via the $W' \rightarrow t\bar{b}$ ($tb$) decay channel. This channel is especially important because in many models the $W'$ boson is expected to be coupled more strongly to the third generation of quarks than to the first and second generations. In addition, it is easier to suppress the multijet background for the decay $W' \rightarrow tb$ than for $W'$ decays to first- and second-generation quarks. In contrast to the leptonic searches, the $tb$ final state is, up to a quadratic ambiguity, fully reconstructible, which means that one can search for $W'$ resonant mass peaks even in the case of wider $W'$ resonances.

Searches in the $W' \rightarrow tb$ channel at the Tevatron [9–11] and at the LHC by the ATLAS experiment [12] have led to the limit $M(W') > 1.13$ TeV. The SM $W$ boson and a $W'$ boson with non-zero left-handed coupling strength couple to the same fermion multiplets and hence would interfere with each other in single-top production [13]. The interference term may contribute as much as 5–20% of the total rate, depending on the $W'$ mass and its couplings [14]. The most recent D0 analysis [11], in which arbitrary admixtures of left- and right-handed couplings are considered, and interference effects are included, sets a lower limit on the $W'$ mass of 0.89 (0.86) TeV, assuming purely right-handed (left-handed) couplings. A limit on the $W'$ mass for any combination of left- and right-handed couplings is also included.

We present an analysis of events with the final state signature of an isolated electron, $e$, or muon, $\mu$, an undetected neutrino causing an imbalance in transverse momentum, and jets, at least one of which is identified as a b-jet from the decay chain $W' \rightarrow tb$, $t \rightarrow bW \rightarrow b\ell\nu$. The reconstructed $tb$ invariant mass is used to search for $W'$ bosons with arbitrary combinations of...
left- and right-handed couplings. A multivariate analysis optimized for W' bosons with purely right-handed couplings is also used. The primary sources of background are tt, W + jets, single-top (tW, s- and t-channel production), Z/γ* + jets, diboson production (WW, WZ), and QCD multijet events with one jet misidentified as an isolated lepton. The contribution of these backgrounds is estimated from simulated event samples after applying correction factors derived from data in control regions well separated from the signal region.

2. The CMS detector

The Compact Muon Solenoid (CMS) detector comprises a superconducting solenoid providing a uniform magnetic field of 3.8 T. The inner tracking system comprises a silicon pixel and strip detector and a conductive solenoid providing a uniform magnetic field of 3.8 T. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector. The inner tracking system comprises a silicon pixel and strip detector.

3. Signal and background modeling

3.1. Signal modeling

The most general model-independent lowest-order effective Lagrangian for the interaction of the W' boson with SM fermions [16] can be written as

$$\mathcal{L} = \frac{V_{ij}^{W'}}{2\sqrt{2}} G_W W^\mu \gamma_\mu \left( a^R_{ij} (1 + \gamma^5) + a^L_{ij} (1 - \gamma^5) \right) W^\nu W_f + \text{h.c.},$$

where $a^R_{ij}, a^L_{ij}$ 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 Weinberg coupling constant, and $\theta_W$ is the Weinberg angle. If the fermion is a quark, $V_{ij}^{W'}$ is the Cabibbo–Kobayashi–Maskawa matrix element, and if it is a lepton, $V_{ij}^{W'} = \delta_{ij}$ where $\delta_{ij}$ is the Kronecker delta and $i$ and $j$ are the generation numbers. The notation is defined such that for a W' boson with SM couplings $a^R_{ij} = 1$ and $a^L_{ij} = 0$.

This effective Lagrangian has been incorporated into the SingleTop Monte Carlo (MC) generator [17], which simulates electroweak top-quark production processes based on the complete set of tree-level Feynman diagrams calculated by the CompHEP [18] package. This generator is used to simulate the s-channel W' signal including interference with the standard model W boson. The complete chain of W', top quark, and SM W boson decays are simulated taking into account finite widths and all spin correlations between resonance state production and subsequent decay. The top-quark mass, $m_t$, is chosen to be 172.5 GeV. The CT18Q2.6M parton distribution functions (PDF) are used and the factorization scale is set to $M(W')$. Next-to-leading-order (NLO) corrections are included in the SingleTop generator and normalization and matching between various partonic subprocesses are performed, such that both NLO rates and shapes of distributions are reproduced [14,16,19-21].

### Table 1

<table>
<thead>
<tr>
<th>$M_{W'}$ (TeV)</th>
<th>$M_{W} &lt; M_{W'}$</th>
<th>$M_{W} &gt; M_{W'}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_R$</td>
<td>$\sigma_L$</td>
<td>$\sigma_R$</td>
</tr>
<tr>
<td>0.9</td>
<td>1.17</td>
<td>3.22</td>
</tr>
<tr>
<td>1.1</td>
<td>0.43</td>
<td>1.85</td>
</tr>
<tr>
<td>1.3</td>
<td>0.17</td>
<td>1.39</td>
</tr>
<tr>
<td>1.5</td>
<td>0.07</td>
<td>1.23</td>
</tr>
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<td>1.7</td>
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<td>1.12</td>
</tr>
<tr>
<td>1.9</td>
<td>0.015</td>
<td>1.11</td>
</tr>
</tbody>
</table>

The CompHEP simulation samples of W' bosons are generated at mass values ranging from 0.8 to 2.1 TeV. They are further processed with PYTHIA [22] for parton fragmentation and hadronization. The simulation of the CMS detector is performed using GEANT [23]. The leading-order (LO) cross section computed by CompHEP is then scaled to the NLO using a k-factor of 1.2 [16].

We generate the following simulated samples of s-channel tb production: $W'_L$ bosons that couple only to left-handed fermions ($a^L_{fi} = 1, a^R_{fi} = 0$), $W'_R$ bosons that couple only to right-handed fermions ($a^L_{fi} = 0, a^R_{fi} = 1$), and $W'_{LR}$ bosons that couple equally to both ($a^L_{fi} = 1, a^R_{fi} = 1$). All W' bosons decay to tb final states. We also generate a sample for SM s-channel tb production through an intermediate W boson. Since $W'_L$ bosons couple to the same fermion multiplets as the SM W boson, there is interference between SM s-channel tb production and tb production through an intermediate $W'_L$ boson. Therefore, it is not possible to generate separate samples of SM s-channel tb production and tb production through W' bosons that couple to left-handed fermions. The samples for $W'_L$ and $W'_{LR}$ include s-channel tb production and the interference. The $W'_R$ bosons couple to different final-state quantum numbers and therefore there is no interference with s-channel tb production. The $W'_R$ sample includes tb production only through $W'_R$ bosons. This sample can then simply be added to the s-channel tb production sample to create a sample that includes all processes for s-channel tb.

The leptonic decays of $W'_R$ involve a right-handed neutrino $\nu_R$ of unknown mass. If $M_{W_R} > M_{W'}$, $W'_R$ bosons can only decay to $q\bar{q}$ final states. If $M_{W_R} < M_{W'}$, they can also decay to $e\nu$ final states leading to different branching fractions for W' → tb. Table 1 lists the NLO production cross section times branching fraction, $\sigma(pp \to W'/B(W'/\to tb)$, here $\sigma_L$ is the cross section for s-channel tb production in the presence of a W' boson which couples to left-handed fermions, $(a^L, a^R) = (1, 0)$ including s-channel production and interference; $\sigma_{LR}$ is the cross section for W' bosons that couple to left- and to right-handed fermions $(a^L, a^R) = (1, 1)$, including SM s-channel tb production and interference; $\sigma_S$ is the cross section for tb production in the presence of W' bosons that couple only to right-handed fermions $(a^L, a^R) = (0, 1)$. The cross section for SM s-channel production, $(a^L, a^R) = (0, 0)$, $\sigma_{SM}$ is taken to be $4.63 \pm 0.07^{+0.19}_{-0.17}$ pb [24].

Fig. 1 shows the invariant mass distributions for $W'_R$, $W'_L$, and $W'_{LR}$ bosons. These distributions are obtained after applying the selection criteria described in Section 4 and the reconstructed jets, lepton, and an imbalance in transverse momentum of a W' boson with mass 1.2 TeV to the generator level object. These distributions show a resonant structure around the generated W' mass. However, the invariant mass distributions for $W'_L$ and $W'_{LR}$ bosons also include the contribution from s-channel single top quark production and show a minimum corresponding to the destructive interference between the amplitudes for production of left-handed fermions via the W and W' bosons. The width of a W' boson with a mass of 0.8 (2.1) TeV is about 25 (80) GeV, which
Electroweak diboson events are generated using MadGraph simulated using the powheg and hadronization and the response of the detector was verified using a control sample of multijet events from data. All samples of simulated events. The W background is reduced by requiring \( p_T > 35 \text{ GeV} \) and are initially identified by matching a track to a cluster of energy in the ECAL. Events are removed whenever the electron is determined to originate from a converted photon. Events containing a second lepton with relative isolation requirement less than 0.2 and a minimum \( p_T \) requirement for muons (electrons) of 10 GeV (15 GeV) are also rejected. Additionally, the cosmic-ray background is reduced by requiring the transverse impact parameter of the lepton with respect to the beam spot to be less than 0.2 mm.

Jets are clustered using the anti-\( k_T \) algorithm with a size parameter \( \Delta R = 0.5 \) [33] and are required to have \( p_T > 30 \text{ GeV} \) and \( |\eta| < 2.4 \). Corrections are applied to account for the dependence of the jet response as a function of \( p_T \) and \( \eta \) [34] and the effects of multiple primary collisions at high instantaneous luminosity. At least two jets are required in the event with the leading jet \( p_T > 100 \text{ GeV} \) and second leading jet \( p_T > 40 \text{ GeV} \). Given that there would be two b-quarks in the final state, at least one of the two leading jets is required to be tagged as a b-jet. Events with more than one b-tagged jet are allowed. The combined secondary vertex tagger [35] with the medium operating point is used for this analysis. The chosen operating point is found to provide best sensitivity based on signal acceptance and expected limits [36].

The QCD multijet background is reduced by requiring \( E_T^{\text{miss}} > 20 \text{ GeV} \) for the muon + jets channel. Since the multijet background from events in which a jet is misidentified as a lepton is larger for the electron + jets channel, and because of the presence of a \( E_T^{\text{miss}} \) requirement in the electron trigger, a tighter \( E_T^{\text{miss}} > 35 \text{ GeV} \) requirement is imposed for this channel. To estimate the \( W' \) signal and background yields, data-to-MC scale factors (\( g \)) measured using Drell–Yan data are applied in order to account for the differences in the lepton trigger and in the identification and isolation efficiencies. Scale factors related to the b-tagging efficiency and the light-quark tag rate (misidentification rate), with a jet \( p_T \) and \( \eta \) dependency, are applied on a jet-by-jet basis to all b-, c-, and light quark jets in the various MC samples [36].

Additional scale factors are applied to W + jets events in which a b-quark, a charm quark, or a light quark is produced in association with the W boson. The overall W + jets yield is normalized to the NNLO cross section [37] before requiring a b-tagged jet. The fraction of heavy flavor events (Wbb, Wcc) is scaled by an additional empirical correction derived using lepton + jets samples with various jet multiplicities [38]. Since this correction was obtained for events with a different topology than those selected...
in this analysis, an additional correction factor is derived using two data samples: events containing zero b-quark jets (0-b-tagged sample) and the inclusive sample after all the selection criteria, excluding any b-tagging requirement (preselection sample). Both samples are background dominated with negligible signal contribution. By comparing the W + jets background prediction with observed data in these two samples, through an iterative process, we extract W + light-flavor jets (Wlf) and W + heavy-flavor jets (Whf) scale factors. The value of the W + heavy-flavor jets scale factor determined via this method is within the uncertainties of the Whf corrections derived in Ref. [38]. Both Wlf and Whf scale factors are applied to obtain the expected number of W + jets events.

The observed number of events and the expected background yields after applying the above selection criteria and scale factors are listed in Table 2. These numbers are in agreement between the observed data and the expected background yields. The signal efficiency ranges from 87% to 67% for W' masses from 0.8 to 1.9 TeV respectively.

5. Data analysis

In this section, we describe two analyses to search for W' bosons. The reconstructed tb invariant mass analysis is used to search for W' bosons with arbitrary combinations of left- and right-handed couplings while a multivariate analysis is optimized for the search of W' bosons with purely right-handed couplings.

5.1. The tb invariant mass analysis

The distinguishing feature of a W' signal is a resonant structure in the tb invariant mass. However, we cannot directly measure the tb invariant mass. Instead we reconstruct the invariant mass from the combination of the charged lepton, the neutrino, and the jet that gives the best top-quark mass reconstruction, and the highest pT jet that is not associated with the top-quark. The E_T^miss is used to obtain the xy-components of the neutrino momentum. The z-component is calculated by constraining the E_T^miss and lepton momentum to the W-boson mass (80.4 GeV). This constraint leads to a quadratic equation in |p_T^z|. When the W reconstruction yields two real solutions, both solutions are used to reconstruct the top candidates. When the solution is complex, the E_T^miss is minimally modified to give one real solution. In order to reconstruct the top quark momentum vector, the neutrino solutions are used to compute the possible W momentum vectors. The top-quark candidates are then reconstructed using the possible W solutions and all of the selected jets in the event. The candidate with mass closest to 172.5 GeV is chosen as the best representation of the top quark (M(W, best jet)). The W' invariant mass (M(best jet, jet2, W')) is obtained by combining the "best" top-quark candidate with the highest pT jet (jet2) remaining after the top-quark reconstruction.

Fig. 2 shows the reconstructed tb invariant mass distribution for the data and simulated W' signal samples generated at four different mass values (0.8, 1.2, 1.6, and 1.9 TeV). Also included in the plots are the main background contributions. The data and background distributions are shown for sub-samples with one or more b-tags, separately for the electron and muon channels. Three additional criteria are used in defining the ≥ 1 b-tagged jet sample to improve the signal-to-background discrimination: the pT of the best top candidate must be greater than 75 GeV, the pT of the system comprising of the two leading jets pT(jet1,jet2) must be greater than 100 GeV, and the best top candidate must have a mass M(W, best jet) greater than 130 GeV and less than 210 GeV.

Since the W + jets process is one of the major backgrounds to the W' signal (see Table 2), a study is performed to verify that the W' + jets shape is modeled realistically in the simulation. Events with zero b-tagged jets in data that satisfy all other selection criteria are expected to originate predominantly from the W' + jets background. These events are used to verify the shape of the W' + jets background invariant mass distribution in data. The shape is obtained by subtracting the backgrounds other than W' + jets from the data. The invariant mass distribution with zero b-tagged jets derived from data using this method is compared with that from the W' + jets MC sample. They were found to be in agreement, validating the simulation. Any small residual difference is taken into account as a systematic uncertainty. The difference between the distributions is included as a systematic uncertainty on the shape of the W' + jets background. Using MC samples, it was also checked that the shape of W' + jets background does not depend on the number of b-tagged jets by comparing the tb invariant mass distribution with and without b-tagged jets with the distribution produced by requiring one or more b-tagged jets.

5.2. The boosted decision tree analysis

The boosted decision tree (BDT) multivariate analysis technique [39–41] is also used to distinguish between the W' signal and the background. For the BDT analysis we apply all the selection criteria described in Section 4, except the additional selection given in Table 2. This method, based on judicious selection of
Table 2
Number of events observed, and number of signal and background events predicted. For the background samples, the expectation is computed corresponding to an integrated luminosity of 5.0 fb⁻¹. The total background yields include the normalisation uncertainty on the predicted backgrounds. "Additional selection" corresponds to requirements of the W⁺ invariant mass analysis (described in Section 5.1) and are: p_T(top) > 75 GeV, p_T(jet1,jet2) > 100 GeV, 130 < M(top) < 210 GeV.

<table>
<thead>
<tr>
<th>Process</th>
<th>Signal</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+ jets</td>
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<td></td>
</tr>
<tr>
<td>b-tagged jets</td>
<td>= 1</td>
<td>405</td>
</tr>
<tr>
<td>additional selection</td>
<td>≥ 1</td>
<td>631</td>
</tr>
<tr>
<td>b-tagged jets</td>
<td>= 1</td>
<td>463</td>
</tr>
<tr>
<td>additional selection</td>
<td>≥ 1</td>
<td>539</td>
</tr>
<tr>
<td>W⁺ (0.8 TeV)</td>
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<td>605</td>
</tr>
<tr>
<td>W⁺ (1.2 TeV)</td>
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<td>838</td>
</tr>
<tr>
<td>W⁺ (1.6 TeV)</td>
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<td>11</td>
</tr>
<tr>
<td>W⁺ (1.9 TeV)</td>
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<tr>
<td>Background</td>
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</tr>
<tr>
<td>tt</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>t-channel</td>
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<tr>
<td>s-channel</td>
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<tr>
<td>tW-channel</td>
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<td>3</td>
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<tr>
<td>W⁺(→τν + jets)</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Z⁺(→ e⁺ e⁻) + jets</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Diboson</td>
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<td>3</td>
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<tr>
<td>Multijet QCD</td>
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<td>3</td>
</tr>
<tr>
<td>Total background</td>
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<tr>
<td>Data</td>
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Table 3
Variables used for the multivariate analysis in four different categories. For the angular variables, the subscript indicates the reference frame.

<table>
<thead>
<tr>
<th>Object kinematics</th>
<th>Event kinematics</th>
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<tbody>
<tr>
<td>η(jet1)</td>
<td>Aplanarity(alljets)</td>
</tr>
<tr>
<td>p_T(jet1)</td>
<td>Sphericity(alljets)</td>
</tr>
<tr>
<td>π(jet2)</td>
<td>Centrality(alljets)</td>
</tr>
<tr>
<td>p_T(jet2)</td>
<td>M(btag1,btag2,W)</td>
</tr>
<tr>
<td>π(jet3)</td>
<td>M(jet1,jet2,W)</td>
</tr>
<tr>
<td>π(jet4)</td>
<td>M(jet1,jet2,W)</td>
</tr>
<tr>
<td>π(jet1,lepton)</td>
<td>M(jet1,lepton, p_Tmiss)</td>
</tr>
<tr>
<td>p_T(lep+jet)</td>
<td>M(jet1,jet2)</td>
</tr>
<tr>
<td>π(ν(jet1,2))</td>
<td>M(ν, W)</td>
</tr>
<tr>
<td>π(ν(jet3,4))</td>
<td>p_T(ν, jet1,jet2)</td>
</tr>
<tr>
<td>p_T(ν, jet1,2, W)</td>
<td>p_T(ν, jet1,jet2,W)</td>
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<tr>
<td>p_T(ν, jet1,2, W)</td>
<td>p_T(ν, jet1,jet2,W)</td>
</tr>
</tbody>
</table>

The BDTs are trained at each W⁺ mass. We use the Adaptive Boost Algorithm (AdaBoost) with value 0.2 and 400 trees for training. We use the Gini index [42] as the criterion for node splitting. The training to distinguish between signal and the total expected background is performed separately for the electron and muon event samples, after requiring the presence of one or more b-tagged jets. In order to avoid training bias, the background and signal samples are split into two statistically independent samples. The first sample is used for training of the BDT and the second sample is used to obtain the final results for the W⁺ signal expectations. Cross checks are performed by comparing the data and MC for various BDT input variables and the output discriminants in two control regions, one dominated by W + jets background events and the other by tt background events. Fig. 3 shows data and background comparison for a W⁺ with mass of 1 TeV, for both e + jets and μ + jets events.
rate scale factors. For the W’ boson with mass of 1 TeV. The shape-changing category includes the uncertainty from data [38]. In the limit estimation, these are defined through the factorization scale uncertainty has the largest impact in the limit estimation. The variation of the factorization scale \(Q^2\) used in the strong coupling constant \(\alpha_s(Q^2)\), and the jet-parton matching scale [44] uncertainties are evaluated for the \(t\bar{t}\) background sample. In the case of W’ + jets, there is an additional systematic uncertainty due to the shape difference between data and simulation as observed in the 0-b-tagged sample. These shape uncertainties are evaluated by raising and lowering the corresponding correction by one standard deviation and repeating the complete analysis. Then, a bin-wise interpolation using a cubic spline between histogram templates at the different variations is performed. A nuisance parameter is associated to the interpolation and included in the limit estimation. Systematic uncertainties from a mismodeling of the number of simultaneous primary interactions is found to be negligible in this analysis.

7. Results

The observed W’ mass distribution (Fig. 2) and the BDT discriminant distributions (Fig. 3) in the data agree with the prediction for the total expected background within uncertainties. We proceed to set upper limits on the W’ boson production cross section for different W’ masses.

7.1. Cross section limits

The limits are computed using a variant of the CLs statistic [45,46]. A binned likelihood is used to calculate upper limits on the signal production cross section times branching fraction: \(\sigma(pp \rightarrow W’)(W’ \rightarrow t\bar{b} \rightarrow t\bar{c}b)\). The procedure accounts for the effects on normalization and shape from systematic uncertainties, see Section 6, as well as for the limited number of events in the background templates. Expected cross section limits for each W’ boson mass are also computed as a measure of the sensitivity of the analysis. To obtain the best sensitivity, we combine the muon and electron samples.

The BDT discriminant distributions, trained for every mass point, are also used to set upper limits on the production cross section of the W’ boson. The expected and measured 95% CL upper limits on the production cross section times decay branching fraction for the W’ bosons are shown in Fig. 4. The sensitivity achieved using the BDT output discriminant is greater than that obtained using the shape of the distribution of the W’ boson invariant mass.

In all the plots shown in Fig. 4, the black solid line denotes the observed limit and the red solid line and dot-dashed lines represent the theoretical cross section predictions for the two scenarios \(M_{W’} > M_W\), where W’ can decay only to quarks and \(M_{W’} \ll M_W\), where all decays of W’ are allowed.

We define the lower limit on the W’ mass by the point where the measured cross section limit crosses the theoretical cross section curves [14,16]. The observed lower limit on the mass of the W’ boson with purely right-handed coupling to fermions is listed in Table 4.

In the electron channel, we observe 2 events with a mass above 2 TeV with an expected background of 3.0 ± 1.5 events. In the muon channel, we observe 6 events with an expected background of 1.4 ± 0.9 events. This gives a total of 8 events with an expected background of 4.4 ± 1.7 events with a mass above 2 TeV. The significance of the excursion in the muon channel is 2.2 standard deviations. The dominant contributions to the expected background above 2 TeV come from W + jets and top-quark production.

7.2. Limits on coupling strengths

From the effective Lagrangian given in Eq. (1), it can be shown that the cross section for single-top quark production in the presence of a W’ boson can be expressed, for arbitrary combinations of left-handed (\(a^L\)) or right-handed (\(a^R\)) coupling strengths, in terms of four cross sections, \(\sigma_L\), \(\sigma_R\), \(\sigma_{LR}\), and \(\sigma_{SM}\) of the four simulated samples, listed in Table 1, as

\[
\sigma = \sigma_{SM} + a^L_{ud}a^L_{tb}(\sigma_L - \sigma_R - \sigma_{SM}) + (a^L_{ud}a^L_{tb})^2 + (a^R_{ud}a^R_{tb})^2)\sigma_R + \frac{1}{2}((a^L_{ud}a^R_{tb})^2 + (a^R_{ud}a^L_{tb})^2)(\sigma_{LR} - \sigma_L - \sigma_R).
\]
Fig. 4. The expected and measured 95% CL upper limits on the production cross section \(\sigma(pp \to W')B(W' \to tb \to \ell
b\bar{b})\) of right handed \(W'\) bosons obtained using the BDT discriminant for \(\geq 1\) b-tagged electron+jets events (a), muon+jets events (b), and combined (c). Also shown (d) is a comparison of the expected 95% CL upper cross section limits obtained using invariant mass distribution and BDT output for right handed \(W'\) bosons for \(\geq 1\) b-tagged muon+jets, electron+jets, and combined. The \(\pm 1\sigma\) and \(\pm 2\sigma\) excursions from expected limits are also shown. The solid and dot-dashed red lines represent the theoretical cross section predictions for the two scenarios \(M_\nu R > M_{W'}\), where \(W'\) can decay only to quarks and \(M_\nu R \ll M_{W'}\), where all decays of \(W'\) are allowed [16–18]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

Table 4

<table>
<thead>
<tr>
<th>Analysis</th>
<th>((a_L, a_R) = (0, 1))</th>
<th>((a_L, a_R) = (1, 0))</th>
<th>((a_L, a_R) = (1, 1))</th>
</tr>
</thead>
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<tr>
<td>BDT</td>
<td>(1.91) TeV</td>
<td>(1.85) TeV</td>
<td>(-)</td>
</tr>
<tr>
<td>Invariant mass</td>
<td>(-)</td>
<td>(-)</td>
<td>(1.51) TeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1.64) TeV</td>
</tr>
</tbody>
</table>

We assume that the couplings to first-generation quarks, \(a_{ud}\), which are important for the production of the \(W'\) boson, and the couplings to third-generation quarks, \(a_{tb}\), which are important for the decay of the \(W'\) boson, are equal. For given values of \(a^L\) and \(a^R\), the distributions are obtained by combining the four signal samples according to Eq. (2).

We vary both \(a^L\) and \(a^R\) between 0 and 1 in steps of 0.1, for a series of values of the mass of the \(W'\) boson. Templates of the reconstructed \(W'\) invariant mass distributions are generated for each set of \(a^L\), \(a^R\), and \(M(W')\) values by weighting the events from the four simulated samples, as described in Section 3, according to Eq. (2). For each of these combinations of \(a^L\), \(a^R\), and \(M(W')\), we determine the expected and observed 95% CL upper limits on the cross section. We then assume values for \(a^L\) and \(a^R\), and interpolate the cross section limit in the mass value. Fig. 5 shows the contours for the \(W'\) boson mass in the \((a^L, a^R)\) plane for which the cross section limit equals the predicted cross section. For each contour of \(W'\) mass, combinations of the couplings \(a^R\) and \(a^L\) above and to the right of the curve are excluded. The contours are obtained using the \(W'\) invariant mass distribution. For this analysis, we make the conservative assumption that \(M_\nu R \ll M_{W'}\). The observed lower limit on the mass of the \(W'\) boson with coupling to purely left-handed fermions and with couplings to both left- and right-handed fermions with equal strength is listed in Table 4.

8. Summary

A search for \(W'\) boson production in the \(tb\) decay channel has been performed in \(pp\) collisions at \(\sqrt{s} = 7\) TeV using data corresponding to an integrated luminosity of 5.0 fb\(^{-1}\) collected during 2011 by the CMS experiment at the LHC. Two analyses have searched for \(W'\) bosons, one uses the reconstructed \(tb\) invariant mass analysis to search for \(W'\) bosons with arbitrary combinations of left- and right-handed couplings while a multi-
significant improvement over previously published limits in the case of the \( t \bar{b} \) final state.

**Acknowledgements**

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COCINCIAS (Colombia); MSES (Croatia); RPF (Cypus); MEYS (Czech Republic); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); FODER and PCP (Morocco); NWO (Netherlands); NSC (Taipei); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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