Search for $W' \rightarrow tb$ resonances with left- and right-handed couplings to fermions


(The D0 Collaboration)

1Universidad de Buenos Aires, Buenos Aires, Argentina
2LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4Universidade Federal do ABC, Santo André, Brazil
5Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6Simon Fraser University, Vancouver, British Columbia, and York University, Toronto, Ontario, Canada
7University of Science and Technology of China, Hefei, People’s Republic of China
8Universidad de los Andes, Bogotá, Colombia
9Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
10Czech Technical University in Prague, Prague, Czech Republic
11Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
12Universidad San Francisco de Quito, Quito, Ecuador
13LCPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
14LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
15CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
16LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
17LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
18CEA, Ifra, SPP, Saclay, France
19IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
20IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
21III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
22Physikalisches Institut, Universität Freiburg, Freiburg, Germany
23II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
24Institut für Physik, Universität Mainz, Mainz, Germany
25Ludwig-Maximilians-Universität München, München, Germany
26Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany
27Panjab University, Chandigarh, India
28Delhi University, Delhi, India
29Tata Institute of Fundamental Research, Mumbai, India
30University College Dublin, Dublin, Ireland
31Korea Detector Laboratory, Korea University, Seoul, Korea
32CINVESTAV, Mexico City, Mexico
33FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
34Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
35Joint Institute for Nuclear Research, Dubna, Russia
36Institute for Theoretical and Experimental Physics, Moscow, Russia
37Moscow State University, Moscow, Russia
38Institute for High Energy Physics, Protvino, Russia
39Petersburg Nuclear Physics Institute, St. Petersburg, Russia
40Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden
41Lancaster University, Lancaster LA1 4YB, United Kingdom
42Imperial College London, London SW7 2AZ, United Kingdom
43The University of Manchester, Manchester M13 9PL, United Kingdom
44University of Arizona, Tucson, Arizona 85721, USA
45University of California Riverside, Riverside, California 92521, USA
46Florida State University, Tallahassee, Florida 32306, USA
47Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
In the standard model (SM), the charged weak current is mediated by $W$ bosons. Many models of physics beyond the standard model predict the existence of additional charged bosons, generally called $W'$, that are more massive than the $W$ boson of the standard model. The chiral structure of the couplings of the $W'$ boson to fermions depends on the details of the model.

In models of universal extra dimensions, the $W'$ is the lowest Kaluza-Klein excitation of the $W$ boson. It therefore has the same couplings to fermions as the $W$ boson and couples exclusively to left-handed fermions. Left-right symmetric models add an additional group $SU(2)_L$ to the SM. Thus there are two bosons, $W_L$ and $W_R$, associated with the SM $SU(2)_L$ group and the additional $SU(2)_R$ group that would mix to form the physical states. One of these physical states is identified with the $W$ boson. Since the $W'$ boson is known experimentally to couple only to left-handed fermions, the other state, $W'$, would have to almost exclusively couple to right-handed fermions. If there exists a light right-handed neutrino $\nu_R$, the decay $W' \rightarrow \ell \nu_R$ (where $\ell$ is a charged lepton) is allowed. Otherwise, the $W'$ can only decay to quarks, making it harder to observe.

Independent of specific models, the most general,
lowest-dimensional Lagrangian for the interaction of a $W'$ boson with fermion fields $f$ is given by

$$\mathcal{L} = \frac{V_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_{\mu} \left( a_{ij}^L (1 + \gamma^5) + a_{ij}^R (1 - \gamma^5) \right) W^{'\mu} f_j + \text{h.c.},$$

(1)

where $a_{ij}^{L/R}$ are the left/right-handed couplings of the $W'$ boson to the fermion doublet $f_i$ and $f_j$ and $g_{\nu}$ is the weak coupling constant of the SM. If the fermions are quarks, the $V_{ij}$ are the elements of the CKM matrix for quark flavors $i, j$. If the fermions are leptons, the $V_{ij}$ are the elements of a $3 \times 3$ identity matrix.

In this Letter, we report on a search for a $W'$ boson that decays to a top quark and an anti-bottom quark (or charge conjugates) using 2.3 fb$^{-1}$ of integrated luminosity from proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV, accumulated by the D0 experiment at the Fermilab Tevatron Collider between 2002 and 2007. This is the same dataset used in the observation of single top quark production by the D0 Collaboration. We use the notation $tb$ to represent the sum of the $t$ and $b$ final states. The $tb$ decay channel is sensitive to $W'$ bosons with left- and right-handed couplings regardless of the existence of a light right-handed neutrino. For left-handed couplings, the process $pp \rightarrow W' + X \rightarrow tb + X$ interferes with SM single top quark production $pp \rightarrow W^* + X \rightarrow t\bar{b} + X$.

We set limits on the production cross section for such $W'$ bosons and translate them into limits on left- and right-handed gauge couplings. We have previously excluded $W'$ bosons with masses of $M(W') < 731$ GeV for purely left-handed couplings and $M(W') < 739$ (768) GeV for the case of purely right-handed couplings with (without) a light right-handed neutrino. The CDF Collaboration has published similar limits, neglecting the interference with SM single top quark production. Relative to our earlier publication, we use more than twice the integrated luminosity and improve the overall sensitivity of the analysis to a $W'$ boson signal by using boosted decision trees (BDT). In Ref. [1], it was demonstrated that a single top quark signal at the level of a few percent was clearly identifiable by the BDT technique. For the first time, we perform a general analysis of the left- and right-handed gauge couplings $a_{ij}^L, a_{ij}^R$ of the $W'$ boson, $0 < a_{ij}^{L/R} < 1$. For comparison with the earlier work, we also quote results for three special cases: (1) purely left-handed couplings, $a_{ij}^L = a, a_{ij}^R = 0 \forall i, j$; (2) purely right-handed couplings, $a_{ij}^L = 0, a_{ij}^R = a \forall i, j$; and (3) an equal mixture of left- and right-handed couplings, $a_{ij}^L = a_{ij}^R = a \forall i, j$.

Finally, we set limits on the mass of such $W'$ bosons under the assumption of a “SM-like” coupling strength, i.e., $a = 1$.

We search for events in which a $W'$ boson is produced and subsequently decays into $tb$. The top quark decays to $Wb$ and the $W$ boson is required to decay to $e\nu$ or $\mu\nu$. $W$ boson decays into $\tau$-leptons or quarks suffer from an overwhelming background. Thus our final state contains an electron or muon, missing transverse momentum from the undetected neutrino, and two jets from the fragmentation of the two $b$-quarks. Additional jets may arise from initial- or final-state radiation. We acquire these events using a logical OR of many trigger conditions that require a combination of jets, electrons and muons.

Object selections and definitions are identical to Ref. [7]. Events are selected with exactly one isolated electron with $p_T > 15$ GeV for two-jet events or $p_T > 20$ GeV for three- and four-jet events, and $|\eta| < 1.1$ or one isolated muon with $p_T > 15$ GeV and $|\eta| < 2.0$, where $\eta$ is the pseudorapidity. The leading jet must have $p_T > 25$ GeV and there must be a total of two, three, or four jets with $p_T > 15$ GeV and $|\eta| < 3.4$. Jets are defined using a cone algorithm with a cone radius $\Delta R = \sqrt{\Delta\phi^2 + (\Delta\eta)^2} = 0.5$, where $\eta$ is the rapidity. Missing $p_T$ is required to be greater than 20 (25) GeV for two-jet (three- or four-jet) events. To enhance the signal content of the selected data sample, one or two of the jets are required to be identified as originating from the fragmentation of a $b$ quark. We call these jets $b$-tagged. In order to minimize the effect of interference with SM single top quark production, we require the invariant mass, $\sqrt{s}$, of the reconstructed charged lepton, the jets, and missing $p_T$ to be greater than 400 GeV.

We simulate the complete chain of $W'$ decays, taking into account finite widths and spin correlations between the production of resonance states and their decay using the SINGLETOP Monte Carlo package based on the SINGLETOP event generator. We set the top quark mass to 172.5 GeV; the factorization scale is set to $M(W')$ and we use the CTEQ6M parton distribution functions. The SINGLETOP generator reproduces the next-to-leading-order (NLO) kinematic distributions, and the interference term between the $W'$ boson signal and the SM $W$ boson. The width of the $W'$ boson varies between 20 and 30 GeV for $W'$ masses between 600 and 900 GeV. It is 25% smaller without a light right-handed neutrino. The width does not have a significant effect on our search because it is smaller than the detector resolution. Therefore, the only relevant effect of a massive neutrino is the larger branching fraction for $W' \rightarrow tb$. Unless mentioned otherwise we will assume in the following that there is a right-handed neutrino with $M(W') > m(\nu_R)$. In this case the limits for right-handed couplings will be weaker than for $M(W') < m(\nu_R)$ because of the smaller branching fraction for $W' \rightarrow tb$. In the absence of interference between $W$ and $W'$ bosons and in the presence of a light right-handed neutrino, there is no difference between $W'$ bosons with left- and right-handed couplings for our search. To probe for $W'$ bosons with masses above the currently published limits, we simulate $W'$ bosons at nine mass values from 600 to 1000 GeV.
Table I: Data and SM background event yields with systematic uncertainties.

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>tQb</td>
<td>26.4 ± 2.5</td>
</tr>
<tr>
<td>tt</td>
<td>424.7 ± 58.4</td>
</tr>
<tr>
<td>W+jets</td>
<td>279.5 ± 18.3</td>
</tr>
<tr>
<td>Z+jets</td>
<td>26.0 ± 3.2</td>
</tr>
<tr>
<td>Dibosons</td>
<td>13.0 ± 1.6</td>
</tr>
<tr>
<td>Multijets</td>
<td>60.5 ± 10.8</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td><strong>830 ± 62</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td><strong>831</strong></td>
</tr>
</tbody>
</table>

At this stage, the expected W’ boson signal would constitute only a small fraction of the selected data sample. To improve discrimination, we calculate a multivariate discriminant based on BDTs that separates the W’ boson signal from background and thus enhances the probability to observe W’ boson production. We compute the discriminant independently in each of the 24 channels. The input variables used to train the BDT discriminants take into account the kinematic properties and angular correlations of the reconstructed objects and the topology of the event. A BDT is trained for each W’ boson mass value using the Monte Carlo sample generated with $a^L = a^R = 1$. The final discriminant for all 24 channels combined is shown in Fig. 1(a). To represent the discriminant distribution expected from an arbitrary combination of couplings, we combine samples of W’ decays generated with left-handed, right-handed and mixed couplings and SM s-channel tb production based on theoretical expectations from Ref. 3. Background events preferentially populate the low discriminant region whereas signal events are clustered towards high discriminant values. We observe good agreement between background prediction and data in all channels. The data show no deviation from background only expectations and we set 95% C.L. upper limits on the cross section for the process $W' \rightarrow tb \rightarrow ℓνbb$ using Bayesian statistics 10. A Poisson distribution for the observed counts and a flat non-negative prior probability for the signal cross section are assumed. Systematic uncertainties are taken into account with Gaussian priors.

The systematic uncertainties that affect the signal and background models are described in Ref. 20. The largest sources of systematic uncertainties are the jet energy scale calibration and the modeling of b-tagging performance. Smaller uncertainties arise from the finite size of the MC samples, the corrections of the flavor composition of W+jets events, and from the normalization of the background. The total uncertainty in the background yield varies between 8% and 10% for the different channels. In determining the effect of the uncertainties from jet energy scale calibration, b-tag modeling, and W+jets modeling, we take into account changes in the shape of the discriminant distributions in addition to normalization effects.

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 $σ_L$ for purely left-handed couplings $(a^L, a^R) = (1, 0)$, $σ_R$ for purely right-handed couplings $(a^L, a^R) = (0, 1)$, $σ_{LR}$ for mixed couplings $(a^L, a^R) = (1, 1)$, and $σ_{SM}$ for SM couplings $(a^L, a^R) = (0, 0)$. It is given by:

$$σ = σ_{SM} + a^L_{ud}a^L_{tb}(σ_L - σ_R)$$

$$+ \left( (a^L_{ud}a^L_{tb})^2 + (a^R_{ud}a^R_{tb})^2 \right) (σ_R - σ_{SM})$$

$$+ \frac{1}{2} \left( (a^L_{ud}a^R_{tb})^2 + (a^R_{ud}a^L_{tb})^2 \right) (σ_{LR} - σ_L - σ_R + σ_{SM}).$$

The background yields are estimated using both Monte Carlo samples and data. The procedure is identical to that used in Ref. 2. The multijet background arises from events in which a jet mimics the signature of an isolated charged lepton. It is modeled using control data samples with non isolated leptons. The dominant background for our search originates from W+jets production. Smaller sources of backgrounds are from ℓℓ pair, t-channel single top quark (tqb), diboson, and Z+jets events. The diboson (WW, WZ, ZZ) backgrounds are modeled using PYTHIA 13. The other background processes are modeled using the ALPGEN 14 event generator and subsequently hadronized using PYTHIA. The fraction of W+heavy flavor events (Wbb, and Wcc) is obtained by scaling the cross sections calculated by ALPGEN to the NLO cross section by a factor of 1.47. An additional correction factor of 0.95 ± 0.13, derived from data samples with different number of b-tagged jets, is applied. The Wc+light jet cross sections are scaled by a factor of 1.38. All processes except the W+jets and multijets background are normalized to their expected cross sections 15, 18. The W+jets and multijets yields are obtained by normalizing to the data sample after subtracting all other backgrounds and before selecting events based on b-tagged jets. At this point in the selection, the data are completely dominated by background and any contamination from a W’ boson signal is negligible.

The sensitivity of the search is maximized by dividing the data into 24 independent channels based on lepton flavor (e, µ), jet multiplicity (2, 3, 4), number of b-tagged jets (1, 2), and two data collection periods, to take into account different signal acceptances and signal-to-background ratios 7. After applying all selections, we find the event yields for data and backgrounds as shown in Table I. The requirement $\sqrt{s} > 400$ GeV accepts most of the W’ contribution but eliminates most of the W boson contribution. As the mass of the W’ boson increases, its contribution to the tb final state decreases relative to that of the W boson, and therefore, the efficiency of this requirement decreases between 3.5% and 0.5% for W’ boson masses between 600 and 1000 GeV.
The predicted cross section for SM single top quark production through s-channel W boson exchange is $\sigma_{SM} = 1.12 \pm 0.05 \text{ pb}$\[8\]. The predicted cross sections $\sigma_L$, $\sigma_R$, and $\sigma_{LR}$ as a function of $W'$ boson mass are listed in Table I. 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 samples according to Eq. (2).

We vary both $a_L$ and $a_R$ between 0 and 1 in steps of 0.1, for each $W'$ boson mass value. We consider each of these 121 combinations of $a_L$, $a_R$, and $M(W')$ as a model. For each of these models, the ratio of the $s$-channel and the $W'$ cross sections is fixed. We then vary the total cross section to determine the expected and observed 95% C.L. upper limits for the three special cases. As the $W'$ boson mass increases, the selection efficiency decreases and the upper limits on the cross section increase.

In conclusion, we have carried out a search for a massive charged gauge boson, $W'$, that decays to $tb$. We considered a model-independent approach in which the $W'$ boson may couple to fermions with any combination of left- and right-handed couplings. We do not observe any deviations from SM expectations and set upper limits on the cross section for the production of $W'$ bosons. We compare upper limits to theory cross sections to extract the following limits for $M(W') > m(\nu_R)$: $M(W') > 863 \text{ GeV}$ for purely left-handed couplings, $M(W') > 885 \text{ GeV}$ for purely right-handed couplings, and $M(W') > 916 \text{ GeV}$ if both left- and right-handed couplings are present. The limit for right-handed couplings improves for $M(W') < m(\nu_R)$ to $M(W') > 890 \text{ GeV}$. These mass limits improve previously published results by more than 100 GeV.

TABLE II: NLO production cross section times branching fraction, $\sigma(pp \rightarrow W'/W \rightarrow tb)$, and expected and observed 95% C.L. upper limits for different W' boson masses, assuming $M(W') > m(\nu_R)$, in pb.

<table>
<thead>
<tr>
<th>$M(W')$ (GeV)</th>
<th>$(a_L^+, a_R^+)$</th>
<th>$(a_L^-, a_R^-)$</th>
<th>$(a_L^+, a_R^-)$</th>
<th>$(a_L^-, a_R^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>3.22 0.12 0.31</td>
<td>2.16 0.09 0.22</td>
<td>4.13 0.09 0.21</td>
<td></td>
</tr>
<tr>
<td>650</td>
<td>2.37 0.16 0.37</td>
<td>1.43 0.10 0.23</td>
<td>2.62 0.10 0.26</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>1.86 0.32 0.46</td>
<td>1.03 0.18 0.26</td>
<td>1.74 0.15 0.23</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>1.56 0.60 0.64</td>
<td>0.80 0.37 0.36</td>
<td>1.24 0.27 0.28</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>1.38 0.64 0.92</td>
<td>0.68 0.39 0.51</td>
<td>0.95 0.24 0.34</td>
<td></td>
</tr>
<tr>
<td>850</td>
<td>1.28 0.85 1.44</td>
<td>0.61 0.48 0.78</td>
<td>0.78 0.28 0.46</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>1.21 1.39 2.06</td>
<td>0.58 0.93 1.23</td>
<td>0.69 0.56 0.57</td>
<td></td>
</tr>
<tr>
<td>950</td>
<td>1.18 2.23 2.81</td>
<td>0.57 1.50 2.05</td>
<td>0.64 0.90 1.17</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>1.15 2.39 3.22</td>
<td>0.57 2.23 3.06</td>
<td>0.62 1.24 1.80</td>
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FIG. 1: (a) Distribution of the discriminant for data (points) compared to the background model summed over all analysis channels (filled histograms) and expected W' boson signal with mixed couplings \((a^L, a^R) = (1, 1)\) (open histogram). (b) Contour plots of 95% C.L. lower limits on \(M(W')\) in the \((a^L, a^R)\) plane, and (c) 95% C.L. upper limits on the coupling \(a^L\) in the \((a^R, M(W'))\) plane. Here \(M(W') > m(\nu_R)\).

FIG. 2: Expected and observed upper limits and theory prediction for the production cross section (the shaded band indicates the uncertainty \(\Delta\)) for W’ bosons with (a) left-handed couplings \((a^L, a^R) = (1, 0)\), (b) right-handed couplings \((a^L, a^R) = (0, 1)\) and, (c) mixed couplings \((a^L, a^R) = (1, 1)\) as a function of the W’ boson mass. Here \(M(W') > m(\nu_R)\).