FERMILAB-PUB-11/004-E

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

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(Dated: Jan 4, 2011)

We present a search for the production of a heavy gauge boson, W', that decays to third-generation quarks, by the D0 Collaboration in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We set 95% confidence level upper limits on the production cross section times branching fraction. For the first time, we set limits for arbitrary combinations of left- and right-handed couplings of the W' boson to fermions. For couplings with the same strength as the standard model W boson, we set the following limits for $M(W') > m(\nu_R)$: $M(W') > 863$ GeV for purely left-handed couplings, $M(W') > 885$ GeV for purely right-handed couplings, and $M(W') > 916$ GeV if both left- and right-handed couplings are present. The limit for right-handed couplings improves for $M(W') < m(\nu_R)$ to $M(W') > 890$ GeV.

PACS numbers: 13.85.Rm; 14.65.Ha; 14.70.Pw; 12.15.Ji; 13.85 Qk

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 [1], 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 [2] add an additional group $SU(2)_R$ 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 ν_R, the decay $W' \to \ell\nu_R$ (where ℓ 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,

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lowest-dimension Lagrangian for the interaction of a W' boson with fermion fields f is given by [3]

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

where $a^{L/R}_{ij}$ are the left/right-handed couplings of the W' boson to the fermion doublet f_i and f_j and g_w 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 3×3 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) [3–5] using 2.3 fb^{-1} of integrated luminosity from proton-antiproton collisions at $\sqrt{s}$ = 1.96 TeV, accumulated by the D0 experiment [6] 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 [7]. We use the notation tb to represent the sum of the $t\bar{b}$ and the $\bar{t}b$ 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 $p\bar{p} \to W' + X \to tb + X$ interferes with SM single top quark production $p\bar{p} \to W^* + X \to tb + X$.

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 [8]. The CDF Collaboration has published similar limits [9], 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). For the first time, we perform a general analysis of the left- and right-handed gauge couplings a^L_{ij}, a^R_{ij} of the W' boson. For comparison with the earlier work, we also quote results for three special cases: (1) purely left-handed couplings, $a^L_{ij} = a, a^R_{ij} = 0 \ \forall i,\ j$; (2) purely right-handed couplings, $a^L_{ij} = 0, a^R_{ij} = a \ \forall i,\ j$; and (3) an equal mixture of left- and right-handed couplings, $a^L_{ij} = a^R_{ij} = a \ \forall i,\ j$. 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 τ-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 where η 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 [10] with a cone radius $\Delta\mathcal{R} = \sqrt{(\Delta\phi)^2 + (\Delta y)^2} = 0.5$, where y 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 [11]. 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, $\sqrt{\hat{s}}$, 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 [12] based on the SINGLETOP event generator [13]. 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 [14]. 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 [3, 5]. 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 $W' \to tb$. 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 $W' \to tb$. 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.

Background yields are estimated using both Monte Carlo samples and data. The procedure is identical to that used in Ref. [7]. 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 $t\bar{t}$ pair, t-channel single top quark (tqb), diboson, and Z+jets events. The diboson (WW, WZ, ZZ) backgrounds are modeled using PYTHIA [15]. The other background processes are modeled using the ALPGEN [16] event generator and subsequently hadronized using PYTHIA. The fraction of W+heavy flavor events ($Wb\bar{b}$, and $Wc\bar{c}$) 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 parton 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 [17, 18]. The W+jets and multijets yield 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 $\sqrt{\hat{s}} > 400$ 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.

TABLE I: Data and SM background event yields with systematic uncertainties.

Process	Events
tqb	26.4 ± 2.5
$t\bar{t}$	424.7 ± 58.4
W+jets	279.5 ± 18.3
Z+jets	26.0 ± 3.2
Dibosons	13.0 ± 1.6
Multijets	60.5 ± 10.8
Total background	830 ± 62
Data	831

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 $W' \to tb \to \ell\nu bb$ using Bayesian statistics [19]. 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:

$$\begin{aligned}\sigma &= \sigma_{SM} + a^L_{ud}a^L_{tb}\left(\sigma_L - \sigma_R\right) \\ &+ \left(\left(a^L_{ud}a^L_{tb}\right)^2 + \left(a^R_{ud}a^R_{tb}\right)^2\right)\left(\sigma_R - \sigma_{SM}\right) \\ &+ \frac{1}{2}\left(\left(a^L_{ud}a^R_{tb}\right)^2 + \left(a^R_{ud}a^L_{tb}\right)^2\right)\left(\sigma_{LR} - \sigma_L - \sigma_R + \sigma_{SM}\right).\end{aligned} \tag{2}$$

The predicted cross section for SM single top quark

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

$M(W')$	$(a^L, a^R) = (1,0)$			$(a^L, a^R) = (0,1)$			$(a^L, a^R) = (1,1)$		
(GeV)	σ_L	obs	exp	σ_R	obs	exp	σ_{LR}	obs	exp
600	3.22	0.12	0.31	2.16	0.09	0.22	4.13	0.09	0.21
650	1.43	0.16	0.37	2.37	0.10	0.23	2.62	0.10	0.26
700	1.03	0.32	0.46	1.86	0.18	0.26	1.74	0.15	0.23
750	0.80	0.60	0.64	1.56	0.37	0.36	1.24	0.27	0.28
800	0.68	0.64	0.92	1.38	0.39	0.51	0.95	0.24	0.34
850	0.61	0.85	1.44	1.28	0.48	0.78	0.78	0.28	0.46
900	0.58	1.39	2.06	1.21	0.93	1.23	0.69	0.56	0.57
950	0.57	2.23	2.81	1.18	1.50	2.05	0.64	0.90	1.17
1000	0.57	2.39	3.22	1.15	2.23	3.06	0.62	1.24	1.80

production through s-channel W boson exchange is $\sigma_{SM} = 1.12 \pm 0.05$ pb [18]. The predicted cross sections σ_L, σ_R, and σ_{LR} as a function of W' boson mass are listed in Table II. 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. For each of these 121 combinations of a^L, a^R, and $M(W')$, we determine the expected and observed 95% C.L. upper limits on the cross section. For the three special cases $(a^L, a^R) = (1,0)$, $(0,1)$, and $(1,1)$, the measurements are listed along with the theoretical cross sections in Table II. We can now assume values for any two of the three parameters, a^L, a^R, and $M(W')$, and interpolate the cross section limit in the third parameter value. The value of the third parameter at which the cross section limit equals the theory cross section [3] represents the limit on the third parameter. Figure 1(b) shows exclusion contours for the W' boson mass in the (a^L, a^R) plane, and Fig. 1(c) shows exclusion contours for the coupling a^L in the $(a^R, M(W'))$ plane for $M(W') > m(\nu_R)$. If the third parameter is one of the couplings, it is an upper limit. If the third parameter is the W' boson mass, it is a lower limit. This is shown for the three special cases in Fig. 2. The cross section limits are for all s-channel single top-quark production processes. 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 $M(W') > m(\nu_R)$: $M(W') > 863$ GeV for purely left-handed couplings, $M(W') > 885$ GeV for purely right-handed couplings, and $M(W') > 916$ GeV if both left- and right-handed couplings are present. The limit for right-handed couplings improves for $M(W') < m(\nu_R)$ to $M(W') > 890$ GeV. These mass limits improve previously published results by more than 100 GeV.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program and NSERC (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

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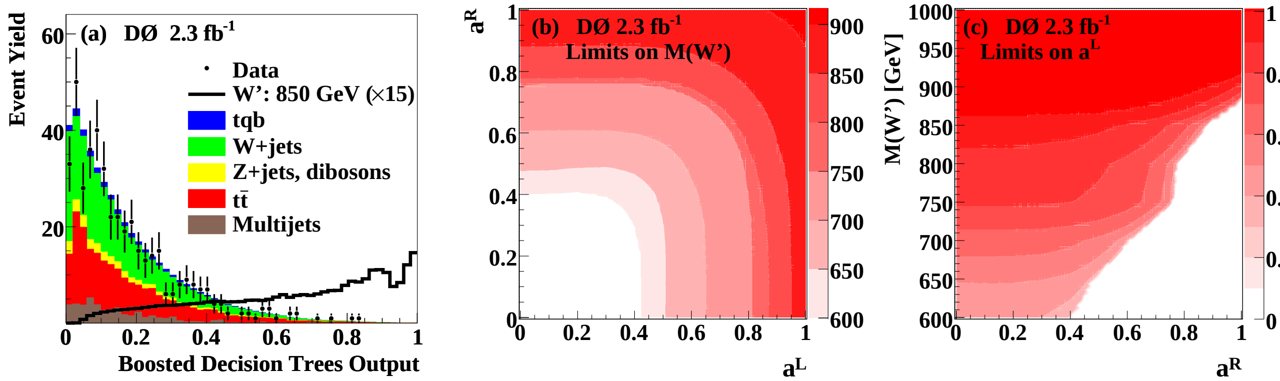

FIG. 1: (a) Distribution of the discriminant for data (points) compared to the background model summed over all analysis channels (filled histograms) and expected W' boson signal with mixed couplings $(a^L, a^R) = (1, 1)$ (open histogram), (b) Contour plots of 95% C.L. lower limits on $M(W')$ in the (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 $M(W') > m(\nu_R)$.

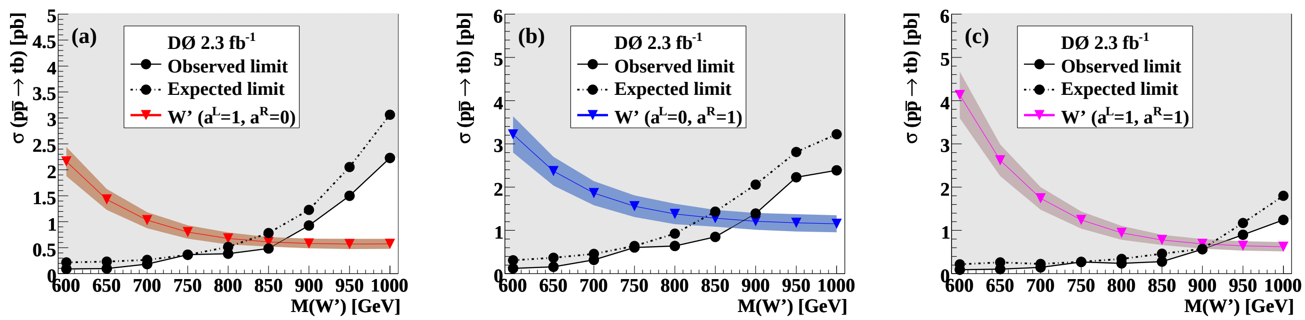

FIG. 2: Expected and observed upper limits and theory prediction for the production cross section (the shaded band indicates the uncertainty [5]) for W' bosons with (a) left-handed couplings $(a^L, a^R) = (1, 0)$, (b) right-handed couplings $(a^L, a^R) = (0, 1)$ and, (c) mixed couplings $(a^L, a^R) = (1, 1)$ as a function of the W' boson mass. Here $M(W') > m(\nu_R)$.

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