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Search for W' Boson Resonances Decaying to a Top Quark and a Bottom Quark

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We search for the production of a heavy W' gauge boson that decays to third generation quarks in 0.9 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, collected with the D0 detector at the Fermilab Tevatron collider. We find no significant excess in the final-state invariant mass distribution and set upper limits on the production cross section times branching fraction. For a left-handed W' boson with SM couplings, we set a lower mass limit of 731 GeV. For right-handed W' bosons, we set lower mass limits of 739 GeV if the W' boson decays to both leptons and quarks and 768 GeV if the W' boson decays only to quarks. We also set limits on the coupling of the W' boson to fermions as a function of its mass.

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New massive charged gauge bosons, usually called W', are predicted by various extensions of the standard model (SM). Noncommuting extended technicolor, little Higgs, composite gauge bosons, grand unification, and superstring theories represent examples in which an extension of the gauge group leads to the appearance of a W' boson [1].

Direct searches for such W' bosons in leptonic final states ($\ell\nu$) lead to the lower limit $M_{W'} > 1.0$ TeV [2], assuming the W' boson couples to fermions in the same way as the SM W boson. W' bosons that couple to right-handed fermions may not be able to decay to leptonic final states if the corresponding right-handed neutrinos are too massive. In this case, only decays to $q\bar{q}'$ final states are possible, and the best limit, based on decays of the W' boson to two light quark jets is $M_{W'} > 800$ GeV [3]. There are model-dependent upper limits on the mass of W' bosons, based on cosmological and astrophysical data, that range from 549 GeV to 23 TeV [4].

In this Letter, we report a search for a W' boson that decays to third generation quarks ($W' \to t\bar{b}$ or $\bar{t}b$). For brevity, we will use the notation tb to represent the sum of the $t\bar{b}$ and the $\bar{t}b$ decay modes.

A W' boson that decays to tb contributes to single top quark production [5] for which evidence has been reported recently [6]. Since the SM W boson and a hypothetical W' boson with left-handed couplings both couple to the same fermion multiplets, they interfere with each other. The interference term may reduce the total rate by as much as (16–33)%, depending on the mass of the W' boson and its couplings [1]. Previous searches [7] in this channel (neglecting interference effects) at the Tevatron have led to the 95% C.L. limits $M_{W'} > 536$ GeV if the W' decays to $\ell\nu$ and to $q\bar{q}'$ and $M_{W'} > 566$ GeV if it only decays to $q\bar{q}'$. A recent D0 analysis [8], which takes into account the interference, excludes masses between 200 and 610 GeV for a W' boson with left-handed SM-like couplings, between 200 and 630 GeV for a W' boson with right-handed couplings that decays to $\ell\nu$ and $q\bar{q}'$, and between 200 and 670 GeV for a W' boson with right-handed couplings that can only decay to $q\bar{q}'$.

The most general lowest-order effective Lagrangian for the interactions of a W' boson with SM fermions f with generation indices i and j, is

$$\mathcal{L} = \frac{V_{ij}}{2\sqrt{2}} g_w \bar{f}_i \gamma^\mu [a_{ij}^R(1+\gamma^5) + a_{ij}^L(1-\gamma^5)] W'_\mu f_j + \text{H.c.},$$

where V_{ij} is the Cabibbo-Kobayashi-Maskawa [9] matrix element if the fermion is a quark, and $V_{ij} = \delta_{ij}$ if it is a lepton, δ_{ij} is the Kronecker delta, g_w is the weak coupling constant of the SM, and a_{ij}^L, a_{ij}^R are coefficients. In this notation, $a_{ij}^L = 1$ and $a_{ij}^R = 0$ for a so-called SM-like W' boson. This effective Lagrangian has been incorporated into the COMPHEP package [10] and used by the SINGLETOP event generator [11]. SINGLETOP is used to simulate SM single top quark production via the exchange of a W boson in the s- and t-channel, and the s-channel W' signal, including interference with the SM W boson. We simulate the complete chain of W', top quark, and W boson decays, taking into account finite widths and all spin correlations between the production of resonance states and their decay. The top quark mass is set to 175 GeV, the CTEQ6L1 parton distribution functions [12] 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 not only the rates, but also the shapes of distributions at NLO [13], are reproduced.

We generate samples of purely left-handed W'_L bosons with $a_{ij}^L = 1$ and $a_{ij}^R = 0$, and purely right-handed W'_R bosons with $a_{ij}^L = 0$ and $a_{ij}^R = 1$. W'_L bosons interfere with the standard W boson, but W'_R bosons couple to different final-state particles and therefore do not interfere with the standard W boson. The $\ell\nu$ decays of W'_R bosons involve a right-handed neutrino of unknown mass, assumed to be $M_{\nu_R} > M_{W'}$ or $M_{\nu_R} < M_{W'}$. The W' width varies between 20 and 30 GeV for W' masses between 600 and 900 GeV [1,13]. If $M_{\nu_R} > M_{W'}$ and only $q\bar{q}'$ final states are open, the width is about 25% smaller. This does not have a significant effect on our search as the experimental resolution for the tb invariant mass is much larger (≈ 90 GeV). The branching fraction for $W' \to tb$ is around 0.32 (0.24) for decays only to quarks (quarks and leptons) for a W' boson with a mass of 700 GeV and varies slightly with the mass. In the absence of interference between W and W' bosons, and if $M_{\nu_R} < M_{W'}$, there is no difference between W'_L and W'_R for our search. Since the current lower limit on the mass of the W' boson is around 600 GeV [8], we simulate W'_L and W'_R bosons at seven mass values from 600 to 900 GeV to probe for W' bosons with higher masses.

We analyze events with leptons, jets, and missing transverse momentum, $\not{p}_T$, in the final state. The data were recorded by the D0 detector [14] between 2002 and 2005 using triggers that required a jet and an electron or a muon. They correspond to 0.9 fb^{-1} of integrated luminosity. The event selection and trigger criteria are very similar to those in Ref. [6] and require exactly one isolated electron (muon) with a momentum component transverse to the beam direction $p_T > 15(20)$ GeV and pseudorapidity $|\eta| < 1.1(2.0)$, $15 < \not{p}_T < 200$ GeV, a leading jet with $p_T > 25$ GeV and $|\eta| < 2.5$, and a second leading jet with $p_T > 20$ GeV and $|\eta| < 3.4$. We select events with two or three jets, counting all jets with $p_T > 15$ GeV and $|\eta| < 3.4$. Events with more than three jets are excluded to reduce the $t\bar{t}$ background. Jets are reconstructed using the Run II

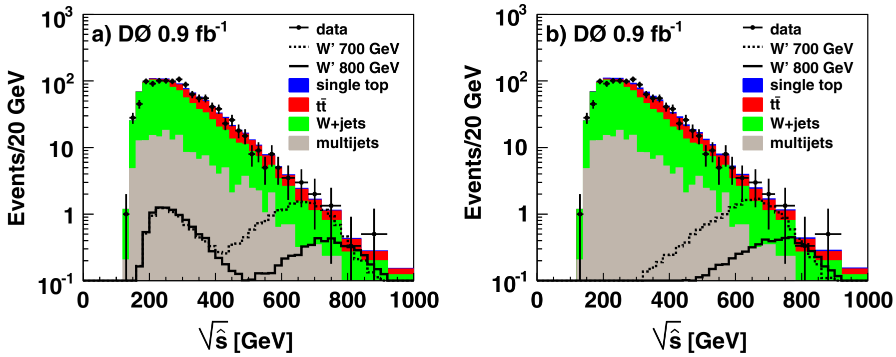

FIG. 1 (color online). $\sqrt{\hat{s}}$ distributions for the data and the SM background. Plot (a) shows the W_L' signal, and plot (b) shows the W_R' signal at two different masses, normalized to the NLO prediction (Table II). Events in the eight subsamples (electron, muon, two and three jets, single-tagged, and double-tagged) are combined.

midpoint cone algorithm [15] with cone size 0.5. Since we expect two b quarks in the $W' \to tb$ decay, we require at least one jet to be classified (“tagged”) as a b jet [16]. The data are divided into eight independent channels based on lepton flavor (e, μ), jet multiplicity (2, 3), and number of b-tagged jets (1, ≥ 2) to take into account the different signal acceptances and signal-to-background ratios, which increases the sensitivity of the search.

Background yields are estimated using both Monte Carlo (MC) samples and data in the same way as in Ref. [6]. Control data samples are used to determine the multijet background from events in which a jet is misidentified as an electron, or a muon from a semileptonic heavy flavor quark decay is considered to be from the decay of a W boson. The $t\bar{t}$ background is estimated using the ALPGEN [17] MC event generator, normalized to the theoretical cross section of 6.8 ± 1.2 pb [18]. The W + jets background is modeled using ALPGEN, and its yield is normalized together with the multijet background, so that the total background yield equals the observed number of events in data before requiring a b-tagged jet. The fraction of W + jets events with heavy flavors ($Wb\bar{b}$, $Wc\bar{c}$) is measured using data. In this way, the small contributions from Z + jets and diboson processes (WW, WZ, ZZ) are absorbed into the W + jets background normalization. For the W_R' search, the SM single top quark production is included in the background. Because of their interference, the s-channel single top quark production is considered part of the signal for the W_L' search, and only the t-channel single top quark production is included in the background. All parton-level MC samples are further processed with PYTHIA [19] and a GEANT [20]-based simulation of the D0 detector. Lepton and jet energies are corrected to reproduce the resolutions observed in data.

TABLE I. Data and SM background event yields.

Process	Events SM + W_L' search	Events W_R' search
Single top	6.4 ± 1.4	10.2 ± 2.2
$t\bar{t}$	59.1 ± 14.4	
W + jets	91.0 ± 18.8	
Multijets	29.7 ± 5.9	
Total background	186.1 ± 40.4	190.0 ± 41.2
Data	182	

The distinguishing feature of a W' signal is a resonance structure in the tb invariant mass. However, we cannot directly measure the tb invariant mass. Instead, we reconstruct the invariant mass $\sqrt{\hat{s}}$ of the leading two jets, the charged lepton, and the neutrino by adding their measured momentum four-vectors. The missing transverse momentum is used to obtain the x and y-components of the neutrino momentum, and the z-component is the smaller of the two $|p_z^\nu|$ values that makes the $\ell\nu$ mass equal the W boson mass.

The observed $\sqrt{\hat{s}}$ distribution in the data is consistent with the background prediction within uncertainties and shows no evidence for a signal (see Fig. 1). Since we search for W' bosons with masses greater than 600 GeV, we set upper limits on the W' boson production cross section times branching fraction to the tb final state, $\sigma(p\bar{p} \to W') \times B(W' \to tb)$, using the high tail of the $\sqrt{\hat{s}}$ distribution. Table I gives the observed number of data events and the expected background yields for events with $\sqrt{\hat{s}} >$ 400 GeV (chosen to improve the signal-to-background ratio). The signal yields corresponding to the same selec-

TABLE II. NLO production cross sections × branching fraction to tb in pb (theory), expected signal event yields (evts), and expected (exp) and observed (obs) 95% C.L. upper limits for $\sigma(p\bar{p} \to W') \times B(W' \to tb)$ in pb. Theory I (II) corresponds to the case $M_{\nu_R} < M_{W'}$ ($M_{\nu_R} > M_{W'}$). The uncertainty on signal yields are around 20%.

$M_{W'}$	W_L'				W_R'				
(GeV)	Theory	Evts	Exp	Obs	Theory (I)	(II)	Evts	Exp	Obs
600	2.17	58	0.69	0.66	2.10	2.79	61	0.67	0.58
650	1.43	33	0.65	0.69	1.25	1.65	35	0.55	0.59
700	1.01	19	0.69	0.74	0.74	0.97	20	0.50	0.54
750	0.76	11	0.80	0.93	0.44	0.57	12	0.44	0.50
800	0.62	6	1.04	1.23	0.26	0.34	7	0.42	0.47
850	0.55	4	1.46	1.77	0.16	0.20	4	0.42	0.48
900	0.51	3	2.35	2.79	0.09	0.12	2	0.40	0.44

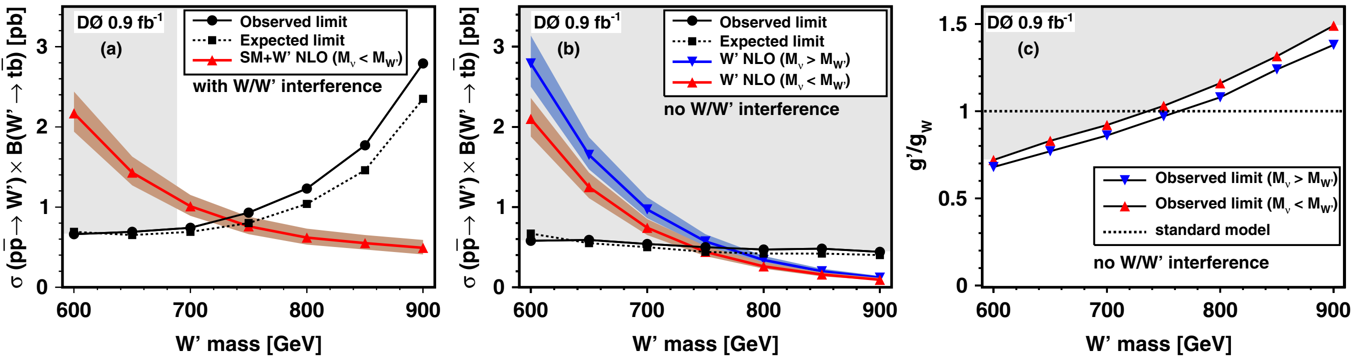

FIG. 2 (color online). NLO theory cross sections and 95% C.L. limits for $\sigma_{W'} \times B(W' \to tb)$ as a function of W' mass for (a) W'_L production and (b) W'_R production. Observed limits on the ratio of coupling constants g'/g_w are shown in (c). The shaded regions are excluded by this analysis.

tion are listed in Table II. We use a Bayesian method [21] with a flat nonnegative prior for the signal cross section. The limits are derived using a binned likelihood constructed from the $\sqrt{\hat{s}}$ spectrum above 400 GeV, taking into account all systematic uncertainties, and their correlations. We also compute expected upper limits as a measure of the sensitivity of the analysis. We combine the eight independent subsamples to obtain the limits listed in Table II.

In the evaluation of the systematic uncertainties, we take into account the uncertainties in both the background normalization and the shape of the $\sqrt{\hat{s}}$ distribution. Uncertainties in the integrated luminosity (6.1%), theoretical cross sections [(15–18)%], branching fractions (1%), object identification efficiencies [(1–7.5)%], trigger efficiencies [(3–6)%], jet fragmentation modeling (5%), and the uncertainty in the fraction of $W +$ jets events with heavy quarks affect only the normalization [6]. Uncertainties in the b-jet simulation [(12–17)%] and the jet energy scale calibration [(1–20)%] affect both shape and normalization. Ranges represent the variations among the eight subsamples.

The observed 95% C.L. upper limit of $\sigma(p\bar{p} \to W') \times B(W' \to tb)$ compared to the NLO theory predictions are shown in Fig. 2 for (a) W'_L and (b) W'_R production cross sections. For the W'_L boson, we show the total cross section for s-channel single top quark production including the SM diagram, the W' diagram, and their interference [1]. In this case, the limit applies to the total s-channel single top production. The k-factors needed to scale the W'_L cross section to NLO, the NLO cross sections for the W'_R boson, and the expected theoretical uncertainty are taken from Ref. [13]. Using the nominal (nominal-1σ) values of the theoretical cross section, the lower limit for W'_L mass is 731 (718) GeV. For W'_R bosons that decay only to $q\bar{q}$, the limit is 768 (750) GeV; 739 (725) GeV if the leptonic decay is also allowed.

Limits for the gauge couplings $g' = g_w a^L_{ij}$ or $g' = g_w a^R_{ij}$, depending on the model, of the W' boson can be derived from the cross section limits. Since the leading-order s-channel production diagram has two $W'q\bar{q}'$ vertices, $\sigma(p\bar{p} \to W') \times B(W' \to tb)$ is proportional to g'^4. Figure 2(c) shows the observed limit for g'/g_w. We exclude gauge couplings above 0.68 (0.72) g_w for W' bosons with a mass of 600 GeV for the case $M_{\nu_R} > M_{W'}$ ($M_{\nu_R} < M_{W'}$).

We have performed a search for W' bosons that decay to tb, using 0.9 fb^{-1} of data recorded by the D0 detector. We find no evidence for W' boson production and set 95% C.L. upper limits on $\sigma(p\bar{p} \to W') \times B(W' \to tb)$. We use the nominal value of the theoretical cross section to set limits on the mass of the W' bosons. We exclude W'_L bosons with left-handed, SM-like couplings with masses below 731 GeV. For W'_R bosons with right-handed couplings, we set a lower mass limit of 739 GeV if the W' boson can decay to leptons and to quarks. If the W' decays only to quarks, the lower mass limit is 768 GeV. We also constrain the W' gauge coupling and exclude couplings above 0.68 (0.72) g_w for W' bosons with a mass of 600 GeV that only decay to quarks (leptons and quarks). These limits represent a significant improvement over previously published results [7,8].

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