Search for the Production of Narrow $t\bar{b}$ Resonances in 1.9 fb^{-1} of $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present new limits on resonant $t\bar{b}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$, using $1.9\,\mathrm{fb}^{-1}$ of data recorded with the CDF II detector at the Fermilab Tevatron. We reconstruct a candidate mass in events with a lepton, neutrino candidate, and two or three jets, and search for anomalous $t\bar{b}$ production as modeled by $W' \to t\bar{b}$. We set a new limit on a right-handed W' with standard model-like coupling, excluding any mass below $800\,\mathrm{GeV}/c^2$ at 95% C.L. The cross-section for any narrow, resonant $t\bar{b}$ production between 750 and $950\,\mathrm{GeV}/c^2$ is found to be less than 0.28 pb at

95% C.L. We also present an exclusion of the W' coupling strength versus W' mass over the range 300 to 950 GeV/c^2.

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Many modifications of the standard model (SM) of particle physics include new, massive, short-lived particles with two-body decays to known fermion pairs. A classic search strategy for these states looks for resonant signals in the spectra of two-body mass distributions. Recent techniques developed to observe electroweak single-top production are well-suited to a search for unexpected $t\bar{b}$ resonances [1]. A $t\bar{b}$ resonance (inclusion of the charge conjugate is implied throughout the text) is predicted by a wide range of models containing a massive charged vector boson, generically referred to as W'. The classic model is a simple extension of the SM to the left-right symmetric group $\mathrm{SU(2)_L \times SU(2)_R \times U(1)}$ [2], which adds a right-handed charged boson W_R with universal weak coupling strength and unknown mass. The W' may arise in models with other symmetry extensions: as the excitation of the W-boson in Kaluza-Klein extra dimensions [3], as the techni-ρ of technicolor theories [4], or as a bosonic partner in little Higgs scenarios [5].

The classic limits on W' are derived from searches in the $W' \to l\nu$ decay channel [6]. For large W' masses, the sensitivity in this channel is diminished by the broad Jacobian lineshapes for the lepton momentum and W' transverse mass. Searches in the $t\bar{b}$ channel [7] avoid this difficulty and also probe models where the couplings are free parameters and the leptonic decay modes may be suppressed. Although we quantify our results using the model of a right-handed W' with SM-like coupling [8], this analysis is sensitive to any narrow state decaying to $t\bar{b}$, including *e.g.* a charged Higgs boson or bound states arising from new dynamics in the third generation. Searches in the $t\bar{b}$ channel complement searches for neutral states coupling to $t\bar{t}$ [9].

In this Letter we present a new search for an s-channel $W' \to t\bar{b}$ resonance produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$ at the Fermilab Tevatron. The dataset of $1.9\,\mathrm{fb}^{-1}$ was recorded with the CDF II detector; a standard coordinate system [10] is used. A detailed explanation of this analysis can be found in [11]. Our selection is based on the leptonic decay mode $t\bar{b} \to (\ell\nu b)\bar{b}$, which has been well understood in the search for electroweak single-top production [1]. Events are expected to have a high transverse momentum (p_T) electron or muon candidate, missing transverse energy ($\not\!\!E_\mathrm{T}$) from a neutrino [12], and two or three jets, at least one of which is a b-quark candidate. The dominant background is from $W+$jet processes and electroweak top-quark production. We reconstruct each event according to our signal hypothesis $W' \to t\bar{b} \to (\ell\nu b)\bar{b}$, then search the mass spectrum for a narrow resonance. If no signal is detected, we set limits on $\sigma(p\bar{p} \to W') \times \mathrm{BR}(W' \to t\bar{b})$ and on the W' coupling strength $g_{W'}$.

The CDF II detector [13] is a cylindrically-symmetric general-purpose detector. Precision charged-particle tracking is accomplished by layers of silicon microstrip detectors surrounded by a large open-cell drift chamber within a 1.4 T solenoidal magnetic field. Outside the magnet are the electromagnetic and hadronic calorimeters, steel for hadronic shielding, and an exterior layer of muon detectors. The luminosity of the $p\bar{p}$ collisions is measured using gas Cherenkov detectors at small angles.

We select data using online selection criteria which require a high-p_T lepton or large $\not\!\!E_\mathrm{T}$ [14]. We identify $t\bar{b} \to \ell\nu b\bar{b}$ candidates as having an electron or muon with $p_\mathrm{T} \geq 20\,\mathrm{GeV}/c$. We also require $\not\!\!E_\mathrm{T} \geq 25\,\mathrm{GeV}$ and two or three hadronic jets with $p_\mathrm{T} \geq 20\,\mathrm{GeV}/c$ and $|\eta| \leq 2.8$. Jets are clustered in cones of fixed radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$, and at least one jet is required to be "b-tagged", *i.e.* the jet contains a secondary vertex consistent with the decay of a hadron containing a b-quark [15]. We reduce Z-decays and $t\bar{t}$ contamination by excluding events with a second charged lepton. Events consistent with cosmic ray or photon interactions are also excluded. QCD multi-jet background, which does not involve a W boson, is rejected with a specific set of requirements [11].

The primary background process is the associated production of a W boson and jets with subsequent leptonic decay of the W boson ($W+$jets). Approximately 70% of our sample are $W+$ jets events containing heavy fla-

*Deceased
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vor ($Wb\bar{b}$, $Wc\bar{c}$, Wcj) or incorrectly b-tagged light flavor (mistags). We establish the normalization of these processes from data, and estimate the fraction of the candidate events with bottom or charm flavor using the ALPGEN Monte Carlo event generator [16]. The mistagging rate for light-flavor jets is estimated from inclusive generic jet data [17]. Additional backgrounds including $t\bar{t}$ pair production, s-channel and t-channel single-top production, and diboson processes (WW,WZ,ZZ) are modeled using the PYTHIA Monte Carlo event generator [18] and are normalized to the next-to-leading-order cross-sections predicted by theory. A small multi-jet background without leptonic W decay ("non-W") arises when a jet is misidentified as a lepton and $\not\!\!E_{\mathrm{T}}$ results from jet energy mismeasurement; this background is modeled using data. The predicted SM background is detailed in Table I. The uncertainties are dominated by imprecise knowledge of the heavy flavor fraction and pertain to background rate estimates only; other systematic uncertainties are discussed later. In data we observe 1362 events with two jets and 617 events with three jets.

TABLE I: Predicted SM background contribution with two jets and with three jets.

Background	2 Jets	3 Jets
$Wb\bar{b}$	409.4 ± 123.4	125.6 ± 37.9
$Wc\bar{c} + Wcj$	412.4 ± 127.2	109.3 ± 33.6
Mistags	276.5 ± 35.0	82.5 ± 10.7
Non-W	53.2 ± 21.3	17.3 ± 6.9
$t\bar{t}$	126.5 ± 13.4	291.8 ± 36.7
Single Top (t-channel)	53.3 ± 7.8	15.7 ± 2.3
Single Top (s-channel)	35.4 ± 5.0	11.6 ± 1.6
$WW + WZ + ZZ$	54.4 ± 4.2	18.4 ± 1.5
Z+jets	22.6 ± 3.3	9.3 ± 1.4
Total BG Prediction	1443.8 ± 254.6	681.6 ± 83.0
Observed	1362	617

According to the proposed W' hypothesis, the W' mass is given by reconstructing $M_{t\bar{b}}$ from the four-momenta of the lepton, neutrino, and two jets. The unmeasured longitudinal neutrino momentum p_z^ν is quadratically constrained by assigning $M_{l\nu} = M_W = 80.448\,\mathrm{GeV}/c^2$ [19]. We assign p_z^ν to the smallest real solution or to the real part of complex solutions [20]. We assume the two highest E_{T} jets arise from the b-quarks, even for the three-jet case in which the third jet has been b-tagged. The reconstructed W is then combined with these two leading jets, corrected to reproduce parton-level energies, to form $M_{t\bar{b}}$.

Our signal model is a W' with purely right-handed decays and SM-like coupling, simulated using PYTHIA. The model assumes a top quark mass of $175\,\mathrm{GeV}/c^2$. The left-handed case is not considered since the consequent $W - W'$ interference has not been observed in any precision W measurements. Figure 1 shows the $M_{t\bar{b}}$ distribution in data superimposed with the expected signal shape for a $600\,\mathrm{GeV}/c^2$ W' produced with a total cross-section of 9 pb ($\sim 4\times$ the prediction for a W' with SM-like coupling [8]). The reconstructed width of the signal is dominated by resolution effects, particularly the jet energy resolution [21] and the incorrect assignment of jets from initial or final state radiation. Our test signal is therefore applicable for any W'-like object whose width is small compared to the experimental resolution. The binning is chosen so that background models have a sufficient number of entries in each bin, including the overflow bin for all values above $700\,\mathrm{GeV}/c^2$.

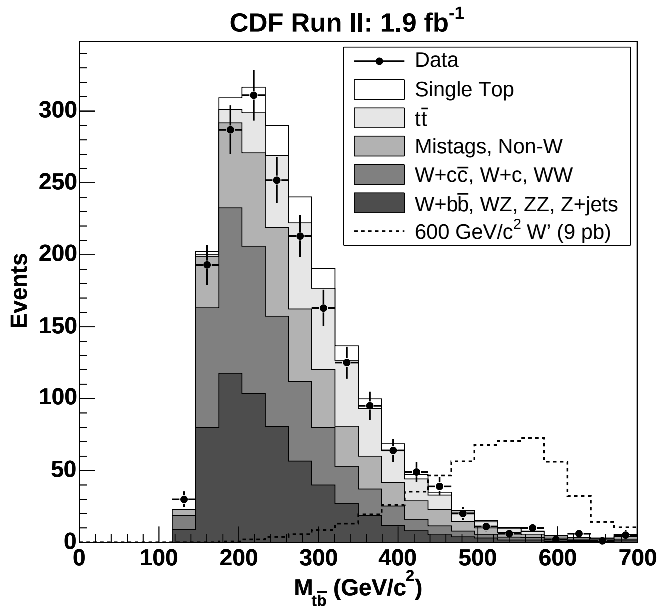

FIG. 1: $M_{t\bar{b}}$ for events with two jets and one b-tag, comparing the shapes between background and signal. Backgrounds are stacked and grouped according to similar shape. A $600\,\mathrm{GeV}/c^2$ W' model is shown with $\sigma \times \mathrm{BR}(W' \to t\bar{b}) = 9\,\mathrm{pb}$ ($\sim 4\times$ the prediction for a W' with SM-like coupling).

Unlike single-top production, W' production is entirely an s-channel process; contributions from the t and u channels are suppressed by the large W' mass. We simulate a narrow right-handed W' with SM-like coupling and a mass between $300\,\mathrm{GeV}/c^2$ and $950\,\mathrm{GeV}/c^2$ in steps of $100\,\mathrm{GeV}/c^2$ below $600\,\mathrm{GeV}/c^2$ and steps of $50\,\mathrm{GeV}/c^2$ above. This is the mass range to which our analysis is sensitive to changes in the signal distribution: above $950\,\mathrm{GeV}/c^2$ the signal events simply pile into the $M_{t\bar{b}}$ overflow bin. Since there is very little high-mass background, we are sensitive to excesses of just a few events in the tail. For $M_{W'} = 800\,\mathrm{GeV}/c^2$, our selection efficiency in the $t\bar{b}$ channel is approximately $2.8 \pm 1.0\%$. An excess of ten events, for example, would correspond to a Tevatron cross-section of 0.18 pb.

The branching ratios of a right-handed W' depend on whether decay to ν_{R} is allowed; we consider both possibilities. If leptonic decay is forbidden, as for a leptophobic W' or when $M_{W'} < M_{\nu_R}$, the $M_{t\bar{b}}$ prediction simply has a slightly larger normalization. For example, if $M_{W'} = 800\,\mathrm{GeV}/c^2$, $\sigma \times \mathrm{BR}(W' \to t\bar{b})$ is predicted to be 0.337 pb if leptonic decays are forbidden and 0.262 pb if they are allowed.

We set frequentist limits on $W' \to t\bar{b}$ using the measure CL_s from [22], which is defined as the probability of background plus a specified signal fraction matching the data ($P_{\mathrm{S+B}}$) divided by the probability of a background-only model matching the data (P_{B}). Sources of uncertainty are treated using a large series of trials (∼50k) for both cases. Each trial is produced by randomly varying all uncertain parameters in the model prediction within a Gaussian constraint about their nominal values. $P_{\mathrm{S+B}}$ is determined from the fraction of the S+B trials with a minimized $\Delta\chi^2 = \chi^2(\mathrm{Data}|\mathrm{S+B}) - \chi^2(\mathrm{Data}|\mathrm{B})$ larger than in data; P_{B} is analogous. The 95% C.L. limit is set by adjusting the signal fraction assumed in the S+B model until $CL_{\mathrm{s}} = 0.05$.

Our event selection introduces various sources of systematic uncertainty. These are manifest as errors in both the rates and shapes the mass distributions for our signal and background models. They include: jet-energy scale (JES), b-tagging efficiencies, lepton identification and trigger efficiencies, recorded luminosity, quantity of initial and final state radiation, parton distribution functions, factorization and renormalization scale, and MC modeling. Our limit procedure evaluates their impact by making reasonable variations in the model parameters and re-simulating the analysis [11].

The systematic uncertainties are dominated by JES and the b-tagging rate uncertainties for the signal. JES uncertainty is modeled by calculating 1σ shifts in each jet-energy correction and adding the results in quadrature. The uncertainty in b-tagging efficiency is determined by binning the b-tagging rate as a function of energy for multi-jet data. The uncertainty is found to be proportional to the jet energy, allowing extrapolation to the higher energies common for our W' signal. This jet-energy weighted uncertainty on the b-tagging rate leads to acceptance errors as large as 40% for a $950\,\mathrm{GeV}/c^2$ W'. Including all such sources of uncertainty in our model results in the expected upper limit on the cross-section increasing by 30-40%.

Applying the full limit procedure, we set 95% C.L. upper limits on $\sigma \times \mathrm{BR}(W' \to t\bar{b})$ as listed in Table II for a right-handed W' with SM-like coupling. Predicted cross-sections for such a W' [8] are shown in Figure 2: we set new 95% C.L. limits of $M_{W'} > 800\,\mathrm{GeV}/c^2$ including leptonic decays, and $M_{W'} > 825\,\mathrm{GeV}/c^2$ if leptonic decays are forbidden. The best prior result used $0.9\,\mathrm{fb}^{-1}$ and found $M_{W'} \geq 768\,\mathrm{GeV}/c^2$ if leptonic decays are forbidden [7]. These results are quoted for a top quark mass of $175\,\mathrm{GeV}/c^2$ and thus are slightly conservative: using the smaller world-average would increase the $t\bar{b}$ branching fraction.

TABLE II: 95% C.L. limits on $\sigma \times \mathrm{BR}(W' \to t\bar{b})$ as function of $M_{W'}$ for a right-handed W' with SM-like coupling. The expected limit is quoted with the range of values into which our observation should fall 68% of the time assuming no signal is present.

$M_{W'}$ (GeV/c^2)	Expected Limit (pb)	Observed Limit (pb)
300	$1.56^{+0.62}_{-0.45}$	1.59
400	$1.04^{+0.44}_{-0.30}$	1.17
500	$0.74^{+0.35}_{-0.22}$	0.84
600	$0.54^{+0.24}_{-0.17}$	0.44
650	$0.46^{+0.21}_{-0.13}$	0.39
700	$0.40^{+0.17}_{-0.12}$	0.32
750	$0.33^{+0.15}_{-0.09}$	0.28
800	$0.30^{+0.13}_{-0.09}$	0.26
850	$0.28^{+0.13}_{-0.08}$	0.25
900	$0.28^{+0.13}_{-0.08}$	0.26
950	$0.30^{+0.13}_{-0.09}$	0.28

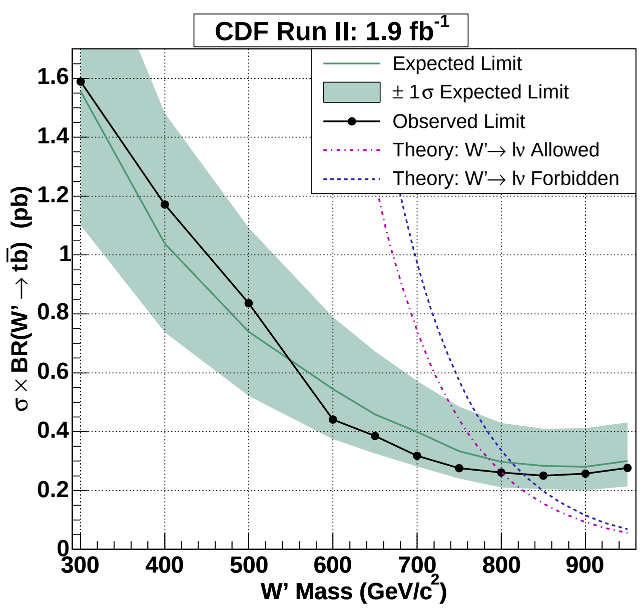

FIG. 2: Expected and observed 95% C.L. limits on $\sigma \times \mathrm{BR}(W' \to t\bar{b})$ as function of $M_{W'}$ for $1.9\,\mathrm{fb}^{-1}$, along with theoretical predictions. A right-handed W' with SM-like couplings is excluded for W' masses below $800\,\mathrm{GeV}/c^2$.

For a simple s-channel model with effective coupling $g_{W'}$, the cross-section is proportional to $g^4_{W'}$. Relaxing the assumption of the universal weak coupling, our cross-section limits can be rewritten as upper limits on $g_{W'}$ as a function of $M_{W'}$. The excluded region of the $g_{W'} - M_{W'}$ plane is shown in Figure 3, with $g_{W'}$ in units of g_W. At $M_{W'} = 300\ \mathrm{GeV}/c^2$, we limit (95% C.L.) the effective coupling to be less than 0.40 of the W boson coupling. In this more general case, the effective cross-section for any narrow, resonant $t\bar{b}$ production between 750 and 950 GeV/c^2 is found to be less than 0.28 pb at 95% C.L.

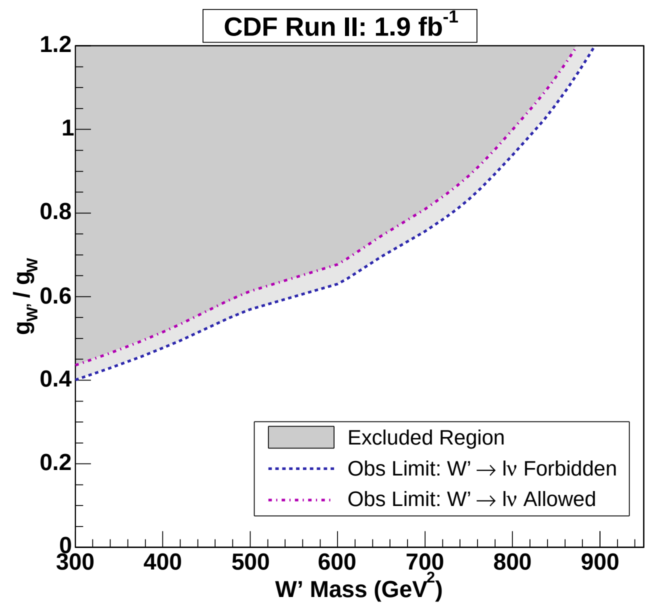

FIG. 3: Observed 95% C.L. limits on the coupling strength of a right-handed W' compared to the SM W boson coupling, $g_{W'}/g_W$, as function of $M_{W'}$ for 1.9 fb^{-1}. The shaded region above the dashed lines are excluded.

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