Search for a Heavy Toplike Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present the results of a search for pair production of a heavy toplike (t') quark decaying to Wq final states using data corresponding to an integrated luminosity of 5.6 fb^{-1} collected by the CDF II detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We perform parallel searches for $t' \to Wb$ and $t' \to Wq$ (where q is a generic down-type quark) in events containing a lepton and four or more jets. By performing a fit to the two-dimensional distribution of total transverse energy versus reconstructed t' quark mass, we set upper limits on the $t'\bar{t}'$ production cross section and exclude a standard model fourth-generation t' quark decaying to Wb (Wq) with mass below 358 (340) GeV/c^2 at 95% C.L.

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The top quark is one of the most recently discovered particles of the standard model (SM), and since its discovery [1,2], the data collected at the Tevatron have been actively used to test the validity of the SM predictions of the top quark's properties. The top quark is unique because of its large mass of $173.3 \pm 1.1\ \mathrm{GeV}/c^2$ [3], which distinguishes it from the other fermions of the SM. It is similar in mass to the weak force carriers (W and Z) as well as the expected mass range for the proposed SM Higgs boson [4]. One of the simplest extensions of the SM is a fourth chiral generation of massive fermions. A fourth generation is predicted in a number of theories [5,6] and is compatible with precision electroweak data [7,8]. Furthermore, its existence would allow for a higher Higgs boson mass [9] and relax the tension between indirect predictions which point to very low masses [4] and direct searches [10,11].

Fourth-generation fermions with masses much higher than current lower bounds [12] would have sizable radiative corrections to the quark scattering amplitude [13], so the masses of heavy toplike (t') quark and heavy down-type (b') quarks should be in the range of a few hundred GeV/c^2 [8]. These ranges are accessible at the Tevatron collider. In addition, a small mass splitting between t' and b' is preferred, such that $m(b') + m(W) > m(t')$, and t' decays predominantly to Wq (a W boson and a down-type quark $q = d, s, b$) [8,12,14]. Previously published limits have excluded a b' at masses below 372 GeV/c^2 [15] and a t' at masses below 285 GeV/c^2, assuming that the t' decays to Wq [16].

In this Letter we report on a search for a t' quark decaying to Wq, where q can be either a generic down-type quark or specifically a b quark. We analyze a data set of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV corresponding to an integrated luminosity of 5.6 fb^{-1} collected by the Collider Detector at Fermilab (CDF II) which is described elsewhere [17]. We search for pair production of such quarks using events characterized by a high-p_T lepton, large missing transverse energy $\not{E}_T$ [18], and multiple hadronic jets. We assume that the new quark is heavier than the top quark and it is produced by strong interaction processes. With respect to [16] the analysis described herein utilizes a data sample approximately 7 times larger, and adds a parallel search wherein it is assumed that the t' decays to Wb.

The data events used in the analysis are collected by triggers that identify at least one high-p_T e or μ candidate [19] or by a trigger requiring $\not{E}_T$ plus jets [20]. Events are retained only if the electron or muon candidate has $p_T \geq 20$ (25 for the $t' \to Wq$ search) GeV/c and satisfies the typical CDF identification and isolation requirements [19]. Jets are reconstructed using a fixed cone algorithm of radius 0.4 in azimuth (ϕ) pseudorapidity (η) space [18] and their energy is corrected for detector effects [21]. We require at least four jets with $E_T \geq 20$ GeV and $|\eta| < 2.0$. Missing transverse energy is reconstructed using fully corrected calorimeter and muon information [19] and required to have magnitude ≥ 20 GeV. For the $t' \to Wb$ search at least one of the jets must be identified as having originated from a bottom quark (b tagged) by a secondary vertex tagging algorithm [22]. In order to reduce the contribution of the multijet (QCD) background for the $t' \to Wq$ search we make some additional requirements. We ask that at least two of the jets have $E_T \geq 25$ GeV, that $M_{T,W} > 20$ GeV/c^2, and that $\not{E}_{T,\mathrm{sig}} > -0.05 M_{T,W} + 3.5$, where $M_{T,W}$ is the transverse leptonically decaying W boson mass, and $\not{E}_{T,\mathrm{sig}}$ is the $\not{E}_T$ significance [23].

The main contribution to the selected sample of events comes from $t\bar{t}$ production, which is modeled using the PYTHIA V6.216 Monte Carlo (MC) generator [24] assuming $m_t = 172.5$ GeV/c^2. The ALPGEN [25] V2.10 matrix-element generator interfaced to PYTHIA V6.325 is used to simulate W + jets and Z/γ^* + jets events. The W + jets samples are generated separately for $W + b\bar{b}$ + jets, $W + c\bar{c}$ + jets, $W + c$ + jets, and W + light flavor. Other backgrounds include diboson production (WW, WZ, ZZ) modeled with PYTHIA, single top quark production simulated using MADGRAPH+PYTHIA [24,26] and multijet QCD events modeled using a jet-triggered data sample normalized to a background-dominated region at low $\not{E}_T$. The signal sample of $t'\bar{t}'$ production is generated with PYTHIA. The detector response in all MC samples is modeled by a GEANT3-based detector simulation [27].

When examining control regions for the $t' \to Wq$ search, defined by events having less than four jets but passing all the other selection criteria, it was observed that the MC simulations underpredicted events in the tails of jet E_T and lepton p_T distributions. For events with electrons this observed mismodeling was found in events with a high E_T lead (highest E_T) jet or high lepton p_T; for events with muons the discrepancy was present for high lepton p_T. Since for misreconstructed events a correlation between the misreconstructed object and the $\not{E}_T$ is expected, cuts are placed on the $\Delta\phi$ between the physics object in question and the $\not{E}_T$. For electron events with lead jet $\not{E}_T \geq 160$ GeV, it is required that the $\Delta\phi$ between the $\not{E}_T$ and the lead jet be at least 0.6. For electron events with lepton $p_T \geq 120$ GeV/c it is required that the $\Delta\phi$ between the lepton and the $\not{E}_T$ be less than 2.6. For muon events there are two categories: muons coming from high-p_T lepton triggers and muons from triggers based on high $\not{E}_T$ plus jets. For muons in the first category if the lepton p_T is greater than 120 GeV/c it is required that the $\Delta\phi$ between the lepton and the $\not{E}_T$ be less than 2.6. For muons in the second category if the lepton p_T is greater than 120 GeV/c it is required that the $\Delta\phi$ between the lepton and the $\not{E}_T$ be between 0.4 and 2.6. These cuts only reduce our signal efficiency by 0.5% and greatly improve our modeling of the tails of the kinematic distributions. Our selection requirements for both searches are summarized in Table I. After all selection and trigger requirements we observe 1441 (4390) events for the $t' \to Wb(Wq)$ search.

TABLE I. Summary of selection criteria.

Selection requirements by search	
$t' \to Wq$	$t' \to Wb$
Lepton $p_T \geq 25$ GeV/c	Lepton $p_T \geq 20$ GeV/c
≥ 4 jets with $E_T \geq 20$ GeV	≥ 4 jets with $E_T \geq 20$ GeV
2 jets with $E_T \geq 25$ GeV	
$\not{E}_T \geq 20$ GeV	$\not{E}_T \geq 20$ GeV
$M_{T,W} > 20$ GeV/c^2	≥ 1 jet identified
$\not{E}_{T,\mathrm{sig}} > -0.05 M_{T,W} + 3.5$	As coming from a b jet
Requirements on $\Delta\phi$ between lead jet E_T or lepton p_T and $\not{E}_T$	

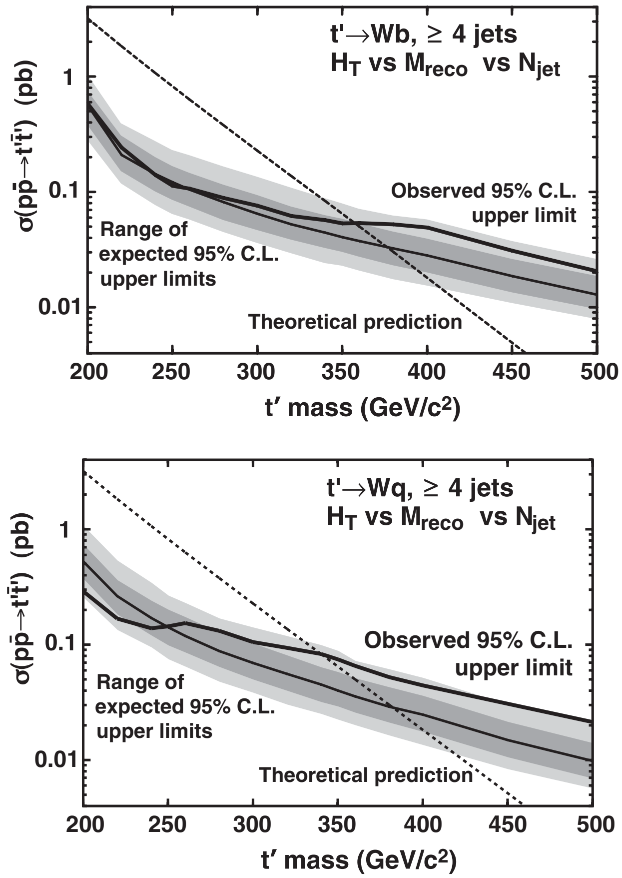

FIG. 1. Observed and expected 95% C.L. upper limits as a function of the mass of the t' quark, for a t' decaying to Wb (upper) and Wq (lower) with 100% branching ratio. The light and dark gray areas show the $\pm 1\sigma$ and $\pm 2\sigma$ areas around the expected limits. The dashed line is the theory expectation.

The total transverse energy (H_T), defined as

$$H_T = \sum_{\text{jets}} E_T + E_{T,\ell} + \not{E}_T, \qquad (1)$$

serves as a good discriminator between standard model and new physics processes associated with production of high mass particles. In addition we make use of the assumption that the t' decay chain is identical to the one of the top quark and reconstruct its mass (M_{reco}) using the standard χ^2-based fit of the kinematic properties of final t' decay products, the same technique utilized in top quark mass measurement analyses [28].

We perform the search for a t' signal by employing a two-dimensional binned likelihood fit in both H_T and M_{reco}. In order to improve the discrimination between potential t' signal and SM backgrounds, we split the events into four samples, based on the number of jets (exactly 4 or ≥ 5) and good or poor mass reconstruction χ^2 ($\chi^2 < 8$ and $\chi^2 \geq 8$). The sample with exactly 4 jets and good χ^2 has the largest sample size due to the fact that the majority of $t\bar{t}$ events [61% (65%) out of all ≥ 4 jet $t\bar{t}$ events when (not) requiring a jet tagged as a b quark] fall into this category. The t' mass reconstruction is best in this category, but the $t'\bar{t}'$ events are distributed more uniformly than $t\bar{t}$ events among all four categories of events. To ensure sufficient MC statistics on the high energy tails, we developed an algorithm that merges bins with low MC statistics together into superbins. The superbins are defined by the

TABLE II. Expected, with $\pm 1\sigma$ uncertainties, and observed limits on $t'\bar{t}'$ production cross section for a given mass assuming the t' quark decays to Wb.

$m(t')$ (GeV/c^2)	Expected limit (pb)	Observed limit (pb)
180	$1.757^{+0.729}_{-0.519}$	1.814
200	$0.563^{+0.198}_{-0.178}$	0.581
220	$0.209^{+0.099}_{-0.058}$	0.242
240	$0.142^{+0.059}_{-0.041}$	0.139
250	$0.121^{+0.047}_{-0.036}$	0.113
260	$0.104^{+0.043}_{-0.029}$	0.106
280	$0.082^{+0.034}_{-0.025}$	0.088
300	$0.065^{+0.029}_{-0.018}$	0.076
320	$0.052^{+0.023}_{-0.013}$	0.062
340	$0.044^{+0.019}_{-0.011}$	0.057
350	$0.040^{+0.019}_{-0.010}$	0.053
360	$0.037^{+0.017}_{-0.010}$	0.054
380	$0.032^{+0.013}_{-0.009}$	0.052
400	$0.028^{+0.011}_{-0.008}$	0.049
450	$0.019^{+0.007}_{-0.006}$	0.031
500	$0.013^{+0.006}_{-0.003}$	0.020

TABLE III. Expected, with $\pm 1\sigma$ uncertainties, and observed limits on $t'\bar{t}'$ production cross section for a given mass assuming the t' quark decays to Wq.

$m(t')$ (GeV/c^2)	Expected limit (pb)	Observed limit (pb)
180	$1.116^{+0.506}_{-0.332}$	0.369
200	$0.524^{+0.213}_{-0.153}$	0.290
220	$0.263^{+0.100}_{-0.081}$	0.167
240	$0.170^{+0.071}_{-0.050}$	0.138
250	$0.141^{+0.060}_{-0.042}$	0.144
260	$0.118^{+0.055}_{-0.032}$	0.153
280	$0.088^{+0.039}_{-0.024}$	0.131
300	$0.069^{+0.033}_{-0.019}$	0.105
320	$0.056^{+0.025}_{-0.016}$	0.094
340	$0.045^{+0.019}_{-0.013}$	0.083
350	$0.040^{+0.019}_{-0.011}$	0.074
360	$0.035^{+0.016}_{-0.009}$	0.065
380	$0.029^{+0.014}_{-0.008}$	0.052
400	$0.025^{+0.011}_{-0.008}$	0.044
450	$0.015^{+0.006}_{-0.004}$	0.031
500	$0.010^{+0.004}_{-0.003}$	0.021

requirement that each superbin in a template has a relative uncertainty due to MC statistics below 40%.

The fit is conducted simultaneously for four different sets of templates. The likelihood is defined as the product of the Poisson probabilities for observing $n_{i,k}$ events in the bin i, k of $(H_T, M_{\rm reco})$. The expected number of events in each bin, $\mu_{i,k}$, is given at base by the sum over all sources indexed by j:

$$\mu_{i,k} = \sum_j L_j \sigma_j \epsilon_{ikj}. \quad (2)$$

Here the L_j are the integrated luminosities, the σ_j are the cross sections, and the ϵ_{ikj} are the efficiencies per bin of $(H_T, M_{\rm reco})$. We calculate the likelihood as a function of the $t'\bar{t}'$ cross section and apply Bayes' theorem with a uniform prior in σ to obtain a 95% C.L. upper limit or measure the production rate of $t'\bar{t}'$ events.

The production rates for $t'\bar{t}'$ events, W + jets in the 4-jet bins, and W + jets events in the ≥ 5 jet bins are three unconstrained independent parameters in the fit. Production rates for $t\bar{t}$, single top, dibosons, and Z + jets [29–31] are constrained to their theoretically predicted

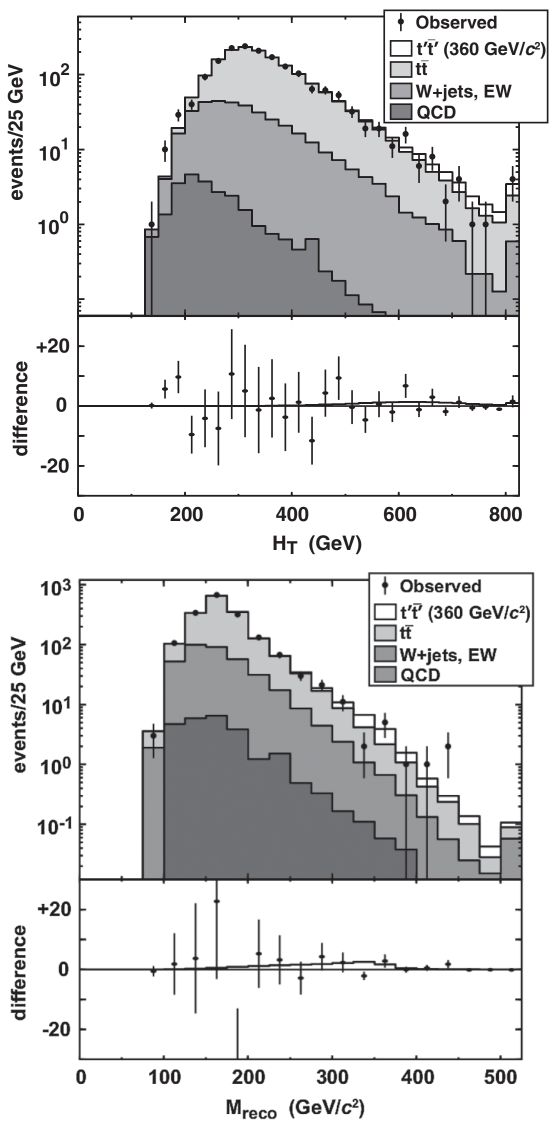

FIG. 2. Log scale distributions of H_T and $M_{\rm reco}$ comparing data (dots) with backgrounds (filled histograms) and signal (empty histogram). The $t'\bar{t}'$ signal is for a t' mass 360 GeV$/c^2$ and a $t'\bar{t}'$ cross section corresponding to the 95% C.L. upper limit. The amounts of all backgrounds are set to their fitted results from the fit assuming t' decays to Wb. In the lower plot the points are the difference between the data and the sum of all the backgrounds, the histograms are the signal contribution.

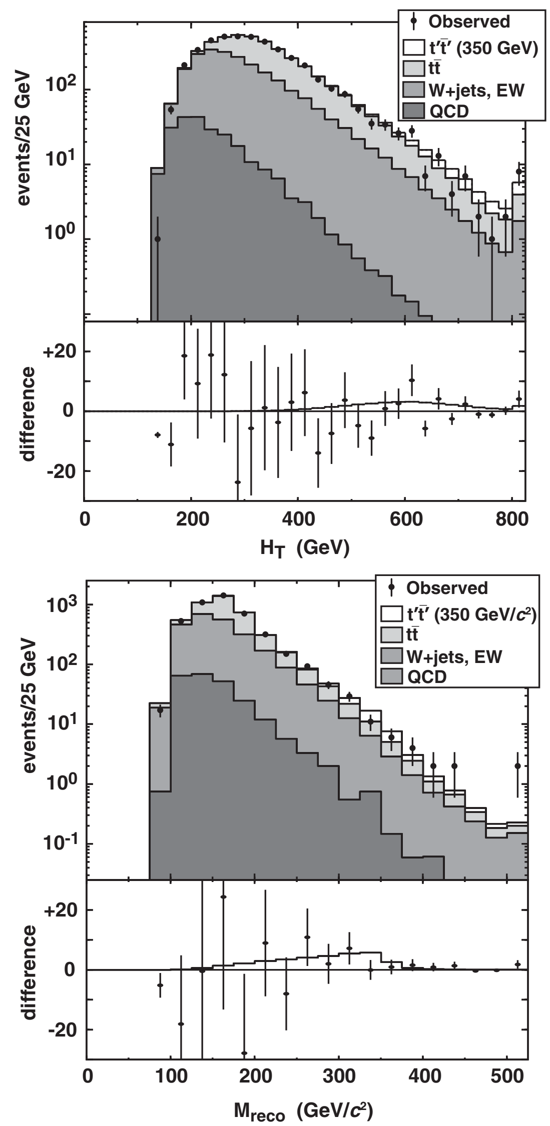

FIG. 3. Log scale distributions of H_T and $M_{\rm reco}$ comparing data (dots) with backgrounds (filled histograms) and signal (empty histogram). The $t'\bar{t}'$ signal is for a t' mass 350 GeV$/c^2$ and a $t'\bar{t}'$ cross section corresponding to the 95% C.L. upper limit. The amounts of all backgrounds are set to their fitted results from the fit assuming t' decays to Wq. In the lower plot the points are the difference between the data and the sum of all the backgrounds, the histograms are the signal contribution.

values and uncertainties. We consider systematic uncertainties that affect only the normalization as well as those affecting the normalization and shape of the distributions. The normalization uncertainties and their magnitudes are integrated luminosity (5.6%), lepton identification scale factors (1%), uncertainty on the parton distribution functions (1%), and wholly correlated theory uncertainty on the t' [32] and $t\bar{t}$ [29] cross section (10%). The shape and normalization systematics and their impact on the expected limit at a t' mass of 360 GeV$/c^2$ (near the observed limit) are jet energy scale (2.5%), the Q^2 scale at which W + jets MC events are generated (2.5%), initial and final state radiation (2.5%), and, for the $t' \to Wb$ search only, uncertainty on the b tagging of jets ($< 2.5\%$). All of the sources of systematic errors are treated in the likelihood as nuisance parameters constrained within their expected distributions. We adopt the profiling method [33] for dealing with these parameters; i.e., the likelihood is maximized with respect to the nuisance parameters. For normalization and shape uncertainties we use a vertical morphing technique [33] to change both shape and normalization when fitting. For these parameters we interpolate quadratically for less than one σ variance and extrapolate linearly for beyond one σ variance in the expectation value. Taking this into account the likelihood takes the following expression:

$$\mathcal{L}(\sigma_{t'\bar{t}'}|n_{i,k}) = \prod_{i,k,m,j} P(n_{i,k}|\mu_{i,k}) G(\nu_m|\tilde{\nu}_m, \sigma_{\nu_m}) \times f_X(\nu_j|\tilde{\nu}_j, \sigma_{\nu_j}), \tag{3}$$

where ν_m are the nuisance parameters used in the morphing parameters (constrained by Gaussian G terms to their expectation) and ν_j are the nuisance parameters used in nonmorphing parameters (constrained by log normal f_X terms to their expectations), such as $\sigma_{t\bar{t}}$, L_j, etc., $\tilde{\nu}_{m,j}$ are their central nominal values, and $\sigma_{\nu_{m,j}}$ are their uncertainties.

We test the sensitivity of our method by drawing pseudoexperiments from standard model distributions, i.e., assuming no t' contribution. The expected 95% C.L. upper limits on the $t'\bar{t}'$ production rate as a function of t' mass, for a t' decaying to Wb and Wq (assuming in either case a 100% branching ratio), are shown in Fig. 1. The dashed line is the theoretical prediction for a fourth-generation t' with SM couplings [32].

We perform the analysis fit on the data which shows no significant excess from $t'\bar{t}'$ production. Results expressed as a 95% C.L. upper limit on the cross section are shown in Fig. 1. The individual limits along with the expected ones from pseudoexperiments are listed in Tables II and III.

Distributions of H_T and $M_{\rm reco}$ comparing the data with the fit to the backgrounds plus a signal contribution are shown in Figs. 2 and 3. The backgrounds are normalized to their fitted results and the t' signal with mass of 360 (350 for $t' \to Wq$) GeV$/c^2$ is normalized to its 95% C.L. upper limit value.

In conclusion, we present a search for pair production of a t' quark decaying to Wq, where q can be a generic down-type quark or specifically a b quark. Having observed no excess attributable to $t'\bar{t}'$ production, we exclude at 95% C.L. a t' quark with mass below 358 (340) GeV$/c^2$ for $t' \to Wb(Wq)$. Examining the results separately for the cases where the W decays to e or μ, we see no significant difference between them, obtaining separate limits of 292 (307 expected) GeV$/c^2$ for $t' \to Wb$ in the μ case and 306 (336 expected) GeV$/c^2$ for $t' \to Wb$ in the e case. These are the most stringent limits set on such a quark at this time. While these direct limits are set on a fourth-generation massive uplike quark t', this analysis is sensitive to models of other massive quarks with similar signatures.

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