

## Search for Heavy Toplike Quarks Using Lepton Plus Jets Events in 1.96 TeV $p\bar{p}$ Collisions

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We present the results of a search for pair production of a new heavy top-like quark  $t'$  decaying to a  $W$  boson and another quark using the Collider Detector at Fermilab II detector in run II of the Tevatron  $p\bar{p}$  collider. Using a data sample corresponding to  $760 \text{ pb}^{-1}$  of integrated luminosity, we fit the observed spectrum of total transverse energy and reconstructed  $t'$  quark mass to a combination of standard model processes and  $t'$  pair production. We see no evidence for  $t'\bar{t}'$  production, and we infer a lower limit of  $256 \text{ GeV}/c^2$  on the mass of the  $t'$  at 95% C.L. assuming standard strong couplings for the  $t'$ .

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The discovery of the top quark in 1995 [1] completed the third generation of fundamental fermions in the quark sector in the standard model (SM) of particle physics. A fourth chiral generation of massive fermions with the same quantum numbers as the known fermions is predicted in a number of models. It is favored by flavor democracy [2], for example, and arises by unifying spins and charges in the GUT  $\text{SO}(1,13)$  framework [3].

Precise measurements from LEP exclude a light fourth neutrino  $\nu_4$  with mass  $m(\nu_4) < m_Z/2$ , where  $m_Z$  is the mass of the  $Z$  boson. On the other hand a fourth-generation neutrino cannot be too heavy due to sizable radiative corrections [4], although  $m(\nu_4) \approx 100 \text{ GeV}/c^2$  is still consistent with electroweak data [5]. If  $m(\nu_4) \geq m_Z/2$  the radiative corrections become small [6], such a neutrino may explain some of the astrophysical puzzles [7], and

one extra chiral family of fermions with quark masses as high as  $400 \text{ GeV}/c^2$  is viable [5,8]. Additional fermion families can also be accommodated in two-Higgs-doublet scenarios and  $N = 2$  SUSY models [9].

In all of the above scenarios the present bounds on the Higgs boson are relaxed; the Higgs boson mass could be as large as  $500 \text{ GeV}/c^2$  with enhanced production at the Tevatron and LHC. In addition, a small mass splitting between new heavy quarks  $t'$  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  $q = d, s, b$ ) [10].

Other models with heavy exotic quarks decaying to  $Wq$  with vector couplings to the  $W$  boson are possible. Contributions to radiative corrections from such quarks with mass  $M$  decouple as  $1/M^2$  and preserve the agreement with precision data. For example, the “beautiful mirrors” model [11] improves the fit to the precision electroweak observables by eliminating the observed discrepancy in the  $b\bar{b}$  forward-backward asymmetry [4,12]. It introduces a new fermion doublet, a mirror copy of the standard quark doublets with a heavier version of the SM top decaying to  $Wb$ .

A heavy toplike quark also appears in little Higgs (LH) models [13], which evade the hierarchy problem by introducing a minimal set of gauge and fermion fields in the context of a large-extra-dimension framework. In particular, LH models in which  $T$  parity is conserved suggest a massive toplike quark which can decay to  $Wq$ , as do LH models requiring two scales ( $f_{1,2}$ ); these have been shown to prefer a toplike quark having a mass of approximately  $500 \text{ GeV}$  [14,15].

In this Letter we present the results of a search for pair production of a new massive strongly interacting up-type quark  $t'$  with its associated antiquark, each decaying to  $Wq$ , using the large data set collected by the upgraded Collider Detector at Fermilab (CDF II) in Run II of the Tevatron. The data come from  $p\bar{p}$  collisions at a center of mass energy of  $1.96 \text{ TeV}$ , corresponding to an integrated luminosity of  $760 \text{ pb}^{-1}$ .

As in the case of  $t\bar{t}$  production, the case when one  $W$  decays leptonically leads to events with a lepton, a neutrino, and four quarks via the chain  $t'\bar{t}' \rightarrow WqWq \rightarrow \ell\nu qqqq$ . Employing a selection based on event kinematics avoids imposing a  $b$ -quark tagging requirement, which would limit our search to the decay mode  $t' \rightarrow Wb$ . We select events with a lepton ( $e$  or  $\mu$ ), missing transverse energy [16], and four or more hadronic jets. The observed distributions of the scalar sum of the transverse energy ( $H_T$ ) of all reconstructed leptons, jets, and missing transverse energy in these events, together with the distribution of reconstructed  $t'$  mass ( $M_{\text{rec}}$ ), allow discrimination of the  $t'\bar{t}'$  signal from the standard model backgrounds discussed below.

CDF II [17] is a large general purpose detector with an overall cylindrical geometry surrounding the  $p\bar{p}$  interac-

tion region. The three-dimensional trajectories of charged particles produced in  $p\bar{p}$  collisions are measured using multiple layers of silicon microstrip detectors, and at outer radii with an axial-stereo wire drift chamber. The tracking system lies inside a uniform  $1.4 \text{ T}$  solenoidal magnetic field oriented along the beam direction. Outside the solenoid lie the electromagnetic and hadronic calorimeters, which are segmented in pseudorapidity ( $\eta$ ) and azimuth in a projective “tower” geometry. Muons are identified by a system of drift chambers placed outside the calorimeter steel, which acts as an absorber for hadrons. The integrated luminosity of the  $p\bar{p}$  collisions is measured using Čerenkov luminosity counters [18].

Events with a high- $p_T$  ( $18 \text{ GeV}/c$  or more)  $e$  or  $\mu$  candidate are identified using high-speed trigger electronics and recorded for later analysis. The performance of the trigger and lepton identification algorithms is described in detail elsewhere [19].

Jet clustering employs an iterative cone-based technique, which associates calorimeter energy deposits within a cone of radius  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ . The energies of reconstructed jets and the missing transverse energy are corrected for detector nonuniformity and other effects [20].

Selected events must contain an  $e$  or  $\mu$  having  $p_T > 20 \text{ GeV}/c$ , four or more jets with  $E_T > 15 \text{ GeV}$  and  $|\eta| < 2.0$ , and missing transverse energy  $\cancel{E}_T > 20 \text{ GeV}$ . To ensure that leptons come from  $W$  boson decay they must be isolated; there can be no significant energy deposit within  $\Delta R < 0.4$  of the lepton momentum. Also, to ensure that leptons and jets are reconstructed from the same interaction, the event vertex is required to be within  $5 \text{ cm}$  of the  $z$  position of the lepton track’s point of closest approach to the beam axis. We observe 451 events in the recorded sample.

The main SM contributions to the selected event sample come from  $t\bar{t}$  events,  $W$  plus hadronic jets events, and hadronic multijet (“QCD”) events having large  $\cancel{E}_T$  in which one jet is misreconstructed as a lepton. We use observed data with nonisolated leptons to estimate the QCD contribution, following the same method as in the  $t\bar{t}$  cross section measurement [19]. We use the ALPGEN [21] Monte Carlo generator to simulate  $W$  plus jets events with HERWIG [22] used for modeling parton showers, and the PYTHIA [23] event generator to simulate both  $t\bar{t}$  and  $t'\bar{t}'$  events. These events pass through a full detector simulation and reconstruction.

The backgrounds from single top, diboson, and  $Z$  + jets production contribute about 10% of the accepted events. However, the kinematic distributions of interest in this analysis in these processes differ negligibly from those in  $W$  + jets events, allowing use of just the  $W$  + jets simulation to model all the non- $t\bar{t}$  background with real leptons.

For each event we calculate the mass  $M_{\text{rec}}$  of the hypothetical  $t'$  and of the  $\bar{t}'$  using the same type of kinematic fit

used in a measurement of the top quark mass [24]. Of all possible lepton-jet combinations of the four highest- $E_T$  jets, we select the one with the lowest  $\chi^2$  for the hypothesis  $t' \rightarrow Wq$ , having equal reconstructed  $t'$  and  $\bar{t}'$  masses, and having the  $W$  mass hypothesis satisfied by the relevant jet pair on one side and by the lepton and  $\cancel{E}_T$  on the other. This procedure selects the correct combination about 30% of the time.

We perform a binned likelihood fit of background and signal to the observed two-dimensional distribution of  $H_T$  and  $M_{\text{rec}}$ . The  $t'\bar{t}'$  events would have larger  $H_T$  and  $M_{\text{rec}}$  than the backgrounds, especially as the  $t'$  mass gets larger. Fitting this two-dimensional distribution brings up to 20% more sensitivity than fitting either one alone, particularly at lower  $t'$  masses.

Imperfect knowledge of various experimental parameters leads to systematic uncertainties which degrade our sensitivity to a  $t'\bar{t}'$  signal. All systematic effects are represented by Gaussian-constrained “nuisance” parameters in the likelihood. The Gaussian width is equal to the systematic uncertainty, except the rate for  $W + \text{jets}$ -like events, which floats freely in the fit. We calculate the likelihood maximized with respect to the nuisance parameters as a function of a hypothetical  $t'\bar{t}'$  signal cross section  $\sigma$  (assuming a 100% branching ratio of  $t' \rightarrow Wq$ ) and apply Bayes’ theorem with a uniform prior in  $\sigma$  to obtain a 95% C.L. upper limit.

The systematic uncertainty with the largest effect on the final result is that due to the 3% uncertainty on the jet energy scale. The nuisance parameter representing this effect controls how the  $H_T$ - $M_{\text{rec}}$  distribution is modified as the jet energy scale changes within its uncertainty. We calculate the bin-by-bin dependence for each background and signal source distribution from simulated samples in which the jet energy scale has been altered from its nominal value.

Another systematic uncertainty is due to the lack of knowledge of the appropriate  $Q^2$  scale at which the  $W$  plus jets processes should be evaluated. The magnitude of this uncertainty comes from changing the  $Q^2$  scale by a factor of 2 up and down from the nominal choice, and assigning the larger of the two apparent shifts in  $\sigma$  as a systematic uncertainty. The effect of this is substantially smaller than that of the jet energy scale uncertainty. We also include along with this effect the uncertainty in the amounts of initial- and final-state radiation.

Other systematic effects include those due to a 6% uncertainty in the integrated luminosity, the 0.7% uncertainty in lepton identification efficiencies, and the 27% uncertainty in QCD background normalization. All these have a small effect on the final result.

We constrain the value of the  $t\bar{t}$  production cross section in the likelihood fit to its theoretical value of 6.7 pb at 175 GeV/ $c^2$  [25]. We assume a 7% uncertainty in the cross section, which is predominantly due to uncertainties in the

TABLE I. The 95% C.L. upper limits on  $\sigma(t'\bar{t}')$  as a function of  $t'$  mass.

Mass (GeV/ $c^2$ )	175	200	225	250	275	300	350	400
Upper limit (pb)	5.21	2.57	1.13	0.72	0.59	0.41	0.32	0.25

parton density functions. We assume that this effect is correlated positively between the  $t'\bar{t}'$  and  $t\bar{t}$  production processes.

The likelihoods reveal no significant excess attributable to  $t'\bar{t}'$  production, and in fact the observed distributions agree well with the zero-signal hypothesis. Table I shows the result for the 95% C.L. upper limit on  $\sigma(p\bar{p} \rightarrow t'\bar{t}')$  as a function of  $t'$  mass, assuming that the branching ratio  $t' \rightarrow Wq$  is 100%. Figure 1 shows the observed distributions projected onto the  $M_{\text{rec}}$  and  $H_T$  dimensions. The figures compare the observed distributions with the fit to the background plus a 250 GeV/ $c^2$   $t'$  signal.

To obtain a lower bound on the mass of the  $t'$ , we compare our upper limit on  $\sigma$  to the theoretical cross section for a fourth-generation  $t'$  with SM couplings [25], assuming a 100% branching ratio  $B(t' \rightarrow Wq)$ ; this is illustrated in Fig. 2. We take the point in  $t'$  mass where the observed limit crosses the theoretical cross section as the lower bound on the mass of the  $t'$ :  $m(t') > 256$  GeV/ $c^2$ , at 95% C.L.

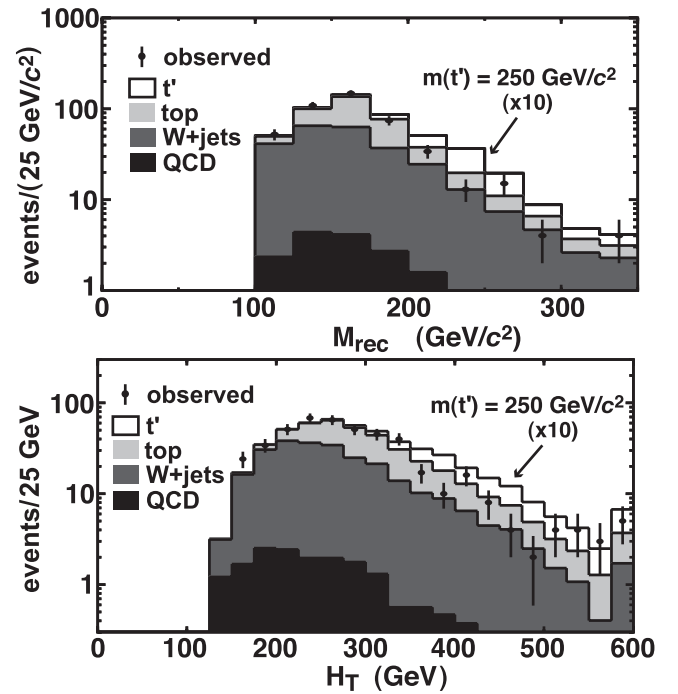


FIG. 1. Observed and predicted distributions of  $M_{\text{rec}}$  (above) and  $H_T$  (below). The predicted distribution corresponds to that for a 250 GeV/ $c^2$  mass  $t'\bar{t}'$  signal assuming a value of the cross section at 10 times the theoretical one. Note that in each plot the last bin is an overflow bin, and that the  $W + \text{jets}$  contribution also represents other similar backgrounds.

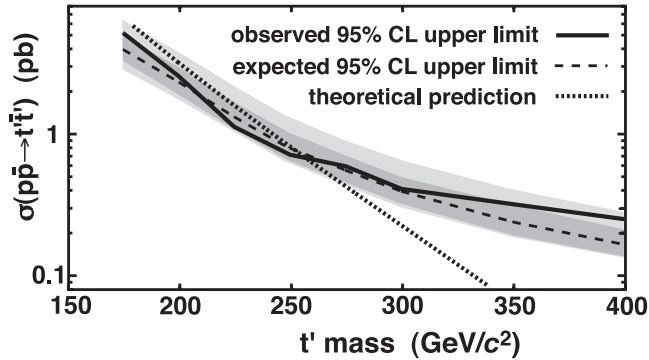


FIG. 2. Observed and expected 95% C.L. upper limits on the cross section for  $t'\bar{t}'$  production as a function of  $t'$  mass. The gray bands around the median expected limit show the  $\pm 1$ - and  $\pm 2$ -standard-deviation ranges. The theoretical prediction is also shown (assuming a 100% branching ratio to  $Wq$ ).

In conclusion, we present here the result of a search for a new heavy toplike quark  $t'$  decaying to  $Wq$ , using a data sample from  $760 \text{ pb}^{-1}$  integrated luminosity of  $p\bar{p}$  collisions at 1.96 TeV center of mass energy. Our fit of the observed  $H_T$ - $M_{\text{rec}}$  distribution reveals no excess from  $t'\bar{t}'$  production, and so we conclude that the mass of the  $t'$ , if it exists, must exceed  $256 \text{ GeV}/c^2$  at 95% C.L. or the  $t'$  must decay to a different final state.

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where  $E$  is the energy measured by the calorimeter and  $p$  is the momentum measured in the tracking system. The missing transverse energy is defined as  $\cancel{E}_T = |-\sum_i E_T^i \vec{n}_i|$  where  $\vec{n}_i$  is a unit vector in the transverse plane that points from the event vertex to the  $i$ th calorimeter tower.

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