Search for Heavy Top-like Quarks $t' \to Wq$ 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 a new heavy top-like quark, $t'$, decaying to a $W$ boson and another quark using the CDF II Detector in Run II of the Tevatron $p\bar{p}$ collider. New top-like quarks are predicted in a number of models of new physics. Using a data sample corresponding to 2.8 fb$^{-1}$ of integrated luminosity we fit the observed spectrum of total transverse energy and reconstructed quark mass to a combination of background plus signal. We see no evidence for $t'$ production, so use this result to set limits on the $t'\bar{t}'$ production cross section times the branching ratio of $t'$ to $Wq$ and infer a lower limit of 311 GeV$/c^2$ on the mass of the $t'$ at 95% CL.

1. INTRODUCTION

We present the result of a search for a new heavy top-like quark, $t'$, assumed to decay to $Wq$. Such would be the case with a “sequential” fourth generation in which the bottom-like quark, $b'$, has mass such that $m(b') + m(W) > m(t')$. 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, for example, and arises by unifying spins and charges in the GUT SO(1,13) framework. Many theoretical models, some of which are discussed in the $t'$ search using 0.76 fb$^{-1}$ of data, predict the presence of new heavy quarks that decay predominantly to $Wq$. For this reason, we keep the analysis scope broad and do not focus on a specific model.

The mass limits on $t'$ production quoted assume 100% branching ratio to $Wq$.

2. ANALYSIS METHOD

We search for strong pair production of a new heavy $t'$ quark with its associated antiquark, each decaying to $Wq$, using the large data set in CDF from Run II of the Tevatron. As in the case of $t\bar{t}$ production, this would lead to events with leptons, jets, and missing transverse energy. Employing a technique based on event kinematics avoids imposing a $b$-quark tagging requirement, which would limit us to the decay mode $t' \to Wb$. We select events with a lepton ($e$ or $\mu$), missing transverse energy, and four or more hadronic jets. In the standard model these events topologies can arise from $t\bar{t}$ production, $W$ plus jets production, and multi-hadronic-jet production from QCD processes. The observed distribution of total transverse energy, $H_T$, and reconstructed $t'$ mass, $M_{rec}$, allows discrimination of the $t'$ signal from these backgrounds.

We perform a binned likelihood fit of background and signal to the observed two-dimensional distribution of $H_T$ and $M_{rec}$. In this plane, the $t'\bar{t}'$ events tend to have larger $H_T$ and $M_{rec}$ than the backgrounds, especially as the $t'$ mass gets larger. We calculate the likelihood as a function of $t'$ signal cross section times branching ratio $(\sigma \cdot B)$ and apply Bayes’ Theorem assuming a uniform prior in $\sigma \cdot B$ to obtain a 95% CL limit on the rate.

3. EVENT SELECTION

Selected lepton plus jets events must have an $e$ or $\mu$ having reconstructed $p_T$ above 20 GeV$/c$, four or more jets with $E_T$ exceeding 15 GeV, having $|\eta| < 2.5$, and missing transverse energy $E_T > 20$ GeV. To insure that leptons and jets are reconstructed from the same interaction, the event $z$ vertex is required to be within 5 cm of that of the lepton. In addition, we require that the muons should not be back-to-back with the missing transverse energy.
∆φ(µ → ET) ≤ 3.05; this cut removes possibly mis-measured muons. A cut on the leading jet ET is applied at 60 GeV which removes a large fraction of the QCD and W plus jets backgrounds yet keeps over 95% of the signal.

For each event we calculate the mass M_{rec} of the t' and ¯t' using the same approach as in the measurement of the top quark mass [3]. Of the possible combinations, we select the one with the lowest χ² for the hypothesis t' → Wq', demanding that the transverse momenta of the t' and ¯t' balance, the reconstructed t' and ¯t' masses are equal, and the W mass hypothesis is satisfied by the relevant jet pair on one side and by the lepton and ET on the other.

We use observed data to estimate the QCD contribution, following the same method as in the top cross section measurement. [4] We use the ALPGEN [7] Monte Carlo generator to simulate W plus jets events, and the PYTHIA event generator to simulate both tt and t't' events.

4. SYSTEMATIC UNCERTAINTIES

Imperfect knowledge of various experimental parameters leads to systematic uncertainties which degrade our sensitivity to a t' signal. All systematic uncertainties are represented by “nuisance” parameters in the likelihood, and at each point in σ · B we maximize the likelihood with respect to the values of the nuisance parameters, most of which are gaussian-constrained to particular values.

The largest systematic uncertainty is that due to imperfect knowledge of the jet energy scale. The nuisance parameter representing this effect controls how the H_T-M_{rec} distribution changes (“morphs”) as the jet energy scale changes within its uncertainties. This morphing includes both shape and normalization uncertainties simultaneously.

Another important 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. We take the larger of the shifts in apparent σ · B due to changing the Q^2 scale from the nominal choice of p_T by a factor of two as the magnitude of this uncertainty.

Other systematic effects include those due to imperfect knowledge of the integrated luminosity (5.9%), the lepton identification efficiencies (0.7%), and the QCD background normalization (50%). As we have poor knowledge of the W plus jets cross section, this parameter is free to float in the binned likelihood fit.

5. RESULTS

The likelihoods as a function of σ · B reveal no significant excess attributable to t't' production. Figure 1 shows the observed data distributions projected into the M_{rec} and H_T dimensions. The figures compare the observed distributions with the fit to the background plus a 300 GeV/c^2 t', where the σ · B of the t' signal corresponds to that which we exclude with 95% confidence.

To obtain a limit on the mass of the t' we compare our upper limit on σ · B to the theoretical cross section assuming a 100% branching ratio B(t' → Wq). Figure 2 shows these curves, and compres our observed limits to the range of those expected. 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', 311 GeV/c^2, at 95% CL.

So we conclude that the mass of the t', if it exists, must exceed 311 GeV/c^2 or the t' must decay to some other final state.

References

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[4] We define the pseudorapidity η of a particle three-momentum as η ≡ − ln(tan θ/2), where θ is the polar angle of the momentum to the beam direction.
Figure 1: Observed and predicted distribution of $M_{\text{rec}}$ (left) and $H_T$ (right). The predicted distribution corresponds to that for a 300 GeV/$c^2$ mass $t'$ signal with a cross section times branching ratio at the 95% CL upper limit.

Figure 2: Observed and expected 95% CL upper limits on the cross section times branching ratio as a function of $t'$ mass. The one and two sigma bands around the expected limits are also shown. The theoretical prediction is shown assuming a 100% branching ratio to $Wq$.

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