Search for New Heavy Quarks in Electron-Muon Events at the Fermilab Tevatron Collider

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A search for $t\bar{t} \rightarrow e\mu + X$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV is described. The production and decay of top-quark–antiquark pairs is considered in the context of the standard model. The analysis is based on data with an integrated luminosity of 4.4 pb^{-1} recorded with the Collider Detector at Fermilab. An upper limit on the $t\bar{t}$ cross section is obtained and the top quark in the mass range 28–72 GeV/c^2 is excluded at the 95% C.L. The same limits apply to a possible fourth-generation, charge $-\frac{1}{3}$, b' quark, decaying via the charged current.

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The sixth quark (t, or top) postulated by the standard model has not yet been observed. The absence of t-quark production in e^+e^- collisions places a lower limit on the t-quark mass (M_{top}) of 29 GeV/c^2.[1] Searches at the CERN $p\bar{p}$ collider provide a lower limit of 41 GeV/c^2 at the 95% confidence level (C.L.).[2,3] This paper describes a search performed with the Collider Detector at Fermilab (CDF) for $t\bar{t}$ pair production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV.

In the standard model, top quarks may be produced via the processes $p\bar{p} \rightarrow t\bar{t}$ and $p\bar{p} \rightarrow W \rightarrow t\bar{b}$. The t quark decays via the weak charged current into a b quark plus either a charged lepton and a neutrino (ν), or two light quarks. The $t\bar{t}$ signature employed in this analysis is the presence of both an electron and a muon with high transverse momenta (P_T) and with opposite electric charges. At $\sqrt{s} = 1.8$ TeV, the decay of the W boson ($W \rightarrow t\bar{b} \rightarrow e\mu + X$) contributes less than 3% to the signal and is not considered further in the analysis. The double-semileptonic decay of a $t\bar{t}$ pair (one top quark to $e\nu b$ and the other to $\mu\nu b$), with an assumed branching ratio of $\frac{2}{81}$, contributes over 80% of the signal. The remaining contributions from sequential decays of a daughter b or c quark or τ lepton are also considered. By requiring two leptons from different families, backgrounds from Drell-Yan and Z^0 production and QCD production of W+jets are strongly suppressed. The $e\mu$ signature can also be used to search for the production of a pair of fourth-generation bottom quarks ($b'\bar{b}'$) which decay semileptonically via the weak charged current.

The CDF detector has been described in detail.[4] Here we summarize features relevant to this analysis. A vertex time-projection chamber (VTPC) provides tracking information up to a radius of 22 cm from the beam axis for $|\eta| < 3.25$, where η is the pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the proton-beam direction. At larger radii, an 84-layer central tracking chamber (CTC) measures charged-particle momenta for $|\eta| \lesssim 1.2$, in a 1.4-T magnetic field with a precision of $\Delta P_T/P_T^2 \simeq 0.001\ (\text{GeV}/c)^{-1}$.[5] Outside the tracking chambers, electromagnetic (EM) and hadronic calorimeters are arranged in a fine-grained, projective tower geometry covering most of the 4π solid angle. In the region $|\eta| < 1.1$, the EM calorimeters have strip chambers (wire chambers with cathode strips perpendicular to the wires) imbedded at a depth of six radiation lengths. The strip chambers measure the lateral shape and position of EM showers. The region $|\eta| < 0.63$ is instrumented with drift chambers for muon detection outside of the hadron calorimeter.

An inclusive electron trigger was used to collect the events for this analysis. This trigger required a calorimeter cluster with EM transverse energy $E_T(e) > 12$ GeV, a ratio of hadronic to EM energy of less than 0.125, and an associated track of transverse momentum $P_T(e) > 6$ GeV/c. The efficiency of this trigger has been studied using data taken at lower trigger thresholds and using W and Z events from independent triggers. We find that this trigger is $(98.0 \pm 0.5)\%$ efficient for $E_T(e) > 15$ GeV.

Events with at least one electron candidate and one muon candidate are selected in the off-line analysis. Electron candidates must be inside the region $|\eta| < 1.0$ and must satisfy the following: (1) A calorimeter cluster must have $E_T(e) > 15$ GeV, a ratio of hadronic energy to EM energy of less than 0.05, and a lateral shape consistent with that of an electron shower. Fiducial cuts to avoid cracks between calorimeter modules are applied. (2) The ratio of the cluster energy to track momentum must be less than 1.5. (3) A strip-chamber cluster must have energy profiles in both the ϕ (azimuth) and z (along the beam direction) views consistent with an electron shower. (4) The distance between the strip-chamber shower position and the extrapolated track position must be less than 1.5 cm in the ϕ direction and less than 3.0 cm in the z direction.

The electron fiducial volume covers 84% of the solid angle in the region $|\eta| < 1.0$. For electrons inside the fiducial volume with $E_T(e) > 20$ GeV, the efficiency of the electron selection as measured using a sample of $Z^0 \rightarrow e^+e^-$ is 0.77 ± 0.03 and is consistent with test beam measurements. A total of 17500 events pass the electron selection requirements.

Electron candidates without a matching VTPC track or with a second nearby oppositely charged CTC track forming a low e^+e^- effective mass are rejected as photon conversion candidates. The low-mass pair cut also rejects electrons from Dalitz decays of neutral pions. The photon conversion cuts cause an inefficiency of 5% for identifying electrons. There remain 13300 electron candidates after these cuts.

Muon candidates are selected inside the region $|\eta| < 1.2$ and must satisfy the following: (1) A minimum ionization requirement is imposed. The calorimeter tower to which the CTC track points is required to contain less than 2 GeV of energy in the EM compartment, less than 6 GeV of energy in the hadronic compartment, but more than 0.1 GeV in the sum of the two compartments. (A minimum ionizing particle will deposit on the average 0.3 and 2 GeV of EM and hadronic energy, respectively.) Fiducial cuts are applied to avoid cracks between calorimeter modules. (2) A P_T threshold requirement is imposed. For candidates with an associated track in the muon chambers, $P_T(\mu)$ must be greater than 5 GeV/c and the azimuthal separation between the extrapolated CTC track and the muon chamber track must be less than 10 cm. In addition, candidates with $P_T(\mu) > 10$ GeV/c having no associated muon chamber track are accepted if the transverse energy in the towers within a cone of $R \equiv [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} = 0.4$, excluding the muon energy, is less than 5 GeV. This extends muon detection out to $|\eta| < 1.2$.

The muon fiducial volume covers 85% of the solid angle in the region $|\eta| < 1.2$. For muons inside the fiducial volume with $P_T(\mu) > 20$ GeV/c, the efficiency of the muon selection as measured using a sample of $Z^0 \rightarrow \mu^+\mu^-$ is 0.98 ± 0.02 and 0.96 ± 0.02 for muons with and without a muon chamber segment, respectively.

With the electron and muon selection criteria, 45 opposite-sign $e\mu$ candidate events are found in the data. Figure 1 shows the scatter plot of $E_T(e)$ vs $P_T(\mu)$ for these events.

The ISAJET Monte Carlo program[6] is used to generate samples of $b\bar{b}$ and $t\bar{t}$ events with full detector simulation[7] for comparison with the data and for the determination of acceptance and efficiencies. Figure 2 shows the expected number of events with $E_T(e) \geq P_T^{\text{min}}$ and $P_T(\mu) \geq P_T^{\text{min}}$ as a function of the threshold P_T^{min} for simulated $t\bar{t}$ and $b\bar{b}$ events. The t-quark decays generate leptons with large transverse momentum, while the leptons from b-quark decay are concentrated at much lower P_T. We have also analyzed a subset of the data with lower trigger and selection $E_T(e)$ thresholds for comparison with the expectations for $b\bar{b}$ events. We find good agreement between these data and the Monte Carlo predictions for the rates and for the shapes of distributions of several kinematic variables, including the azimuthal angular separation between the two leptons, missing transverse energy, and lepton isolation.

We define a top-quark signal region with $E_T(e) > 15$ GeV and $P_T(\mu) > 15$ GeV/c. The total $t\bar{t} \rightarrow e\mu + X$ detection efficiency in the signal region is shown in Fig. 3 as a function of M_{top}, together with the separate efficiencies due to the transverse-momentum cuts, geometric acceptance, and dilepton selection. The expected number of $t\bar{t} \rightarrow e\mu + X$ events detected in this region is 33 (7.5) events for $M_{\text{top}} = 28$ (70) GeV/c^2. Background leptons from $b\bar{b}$ and misidentified particles are dominantly nonisolated, and are concentrated near or below the P_T threshold. In the signal region we expect 1 $e\mu$ event from the process $Z^0 \rightarrow \tau\tau$ and 0.2 event from the process $Z^0 \rightarrow b\bar{b}$, 0.15 event from WW, and 0.05 event from WZ. Other sources such as Drell-Yan are negligible.

The data sample contains one event in the top-quark signal region. This event has an isolated electron with $E_T(e)$ of 31.7 GeV and an isolated opposite sign muon with $P_T(\mu)$ of 42.5 GeV/c with a dilepton azimuthal opening angle of 137°. With leptons at such high transverse momenta, the interpretation of this event as background from Z^0 decays is unlikely. Other characteristics of the event include the presence of a second muon can-

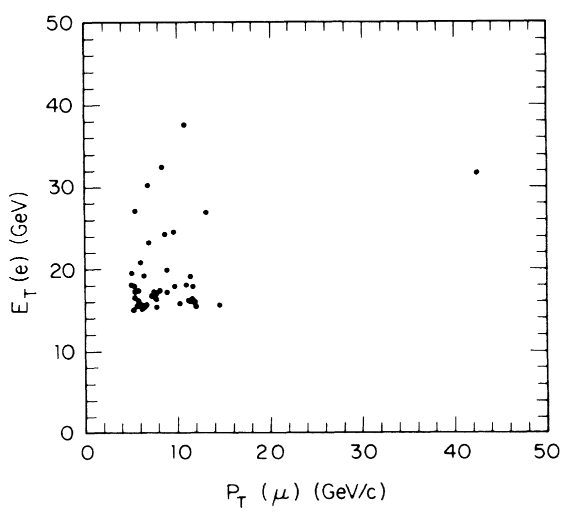

FIG. 1. Electron transverse energy vs muon transverse momentum for the CDF data with an integrated luminosity of 4.4 pb^{-1}.

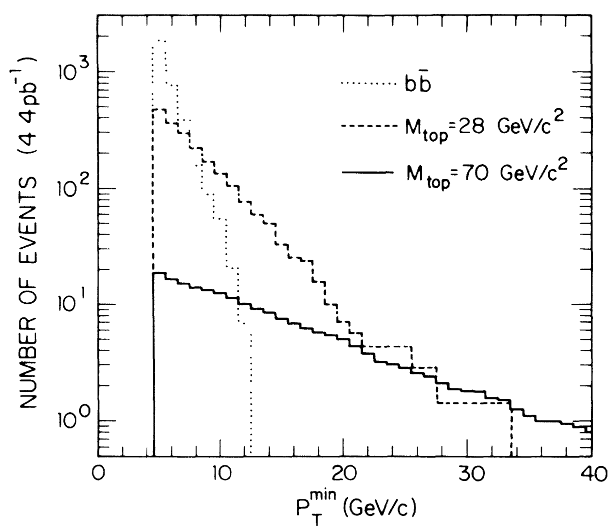

FIG. 2. The expected number of opposite-sign events for 4.4 pb^{-1} with $E_T(e) \geq P_T^{\text{min}}$ and $P_T(\mu) \geq P_T^{\text{min}}$ as a function of the threshold P_T^{min} for simulated $t\bar{t}$ events with $M_{\text{top}} = 70$ GeV/c^2, $M_{\text{top}} = 28$ GeV/c^2 and for simulated $b\bar{b}$ events. The analysis P_T thresholds have been lowered to 5 GeV/c for this plot in order to show the shape of $b\bar{b}$ background at low P_T.

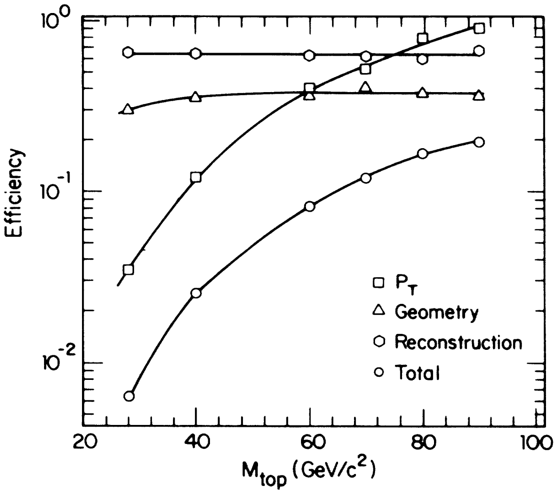

FIG. 3. The $t\bar{t} \rightarrow e\mu + X$ efficiencies for (i) the P_T requirement, (ii) geometric acceptance (after the P_T requirement), (iii) dilepton reconstruction (after P_T and geometric cuts), and (iv) total. The efficiency of the P_T cuts and the total efficiency have been normalized to the assumed double-semileptonic branching ratio of $\frac{2}{81}$.

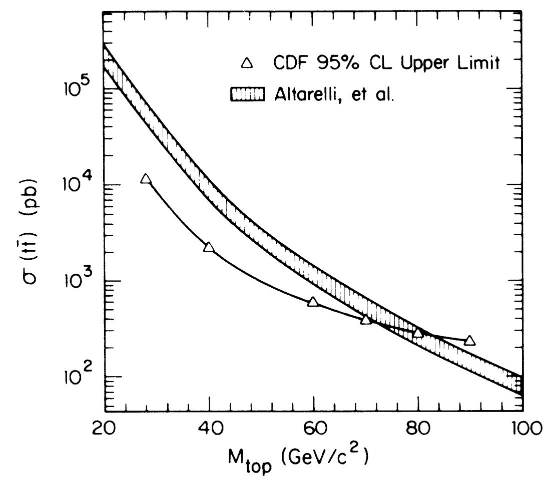

FIG. 4. The 95%-C.L. upper limit on the $t\bar{t}$ production cross section as a function of top-quark mass. The shaded band shows the result of a theoretical calculation of the $t\bar{t}$ production cross section (Refs. 3 and 10).

didate with a transverse momentum of 10 GeV/c in the forward muon detector,[4] and a jet with calorimeter transverse-energy deposition of 14 GeV. A firm conclusion about the identity of this event is not possible.

Given one event in the signal region, an upper limit on the $t\bar{t}$ cross section is obtained as a function of top-quark mass M_{top}. This upper-limit cross section takes into account systematic uncertainties in lepton identification efficiencies, the t-quark P_T distribution, t-quark fragmentation, and integrated luminosity. Theoretical uncertainty in t-quark fragmentation affects the lepton isolation and results in an uncertainty in the detection efficiency of 30 (10)% for $M_{top}=28$ (70) GeV/c^2, as determined by varying the ϵ parameter in the Peterson parametrization in the range 0.5–1.5.[8] The uncertainty in the acceptance due to uncertainties in the t-quark and the lepton P_T distributions is 30 (4)% for $M_{top}=28$ (70) GeV/c^2, as obtained by comparing the ISAJET and PAPAGENO (Ref. 9) Monte Carlo calculations. The systematic uncertainty in the CDF luminosity measurement is 15%.

The systematic uncertainties are added in quadrature and then used as the standard deviation of a Gaussian distribution which is covoluted with the Poisson statistical probability. The resulting distribution is used to obtain the 95%-C.L. upper limit on the expected number of events in the signal region as a function of M_{top}. This number is used along with the Monte Carlo calculation of the $t\bar{t}$ detection efficiency as a function of M_{top}, the integrated luminosity, and the semileptonic branching ratio to provide an upper limit on the $t\bar{t}$ production cross section. The result is shown in Fig. 4, together with a theoretical calculation of the $t\bar{t}$ production cross section.[3,10] The 95%-C.L. upper-limit cross-section curve intersects the lower edge of the theoretical calculation band at $M_{top}=72$ GeV/c^2. We have chosen to terminate the analysis at 28 GeV/c^2 at the low end. Below this mass, the efficiency for detecting the t quark becomes small and the systematic uncertainties become large. Top quarks in the mass range 28–72 GeV/c^2 are thus excluded at the 95% confidence level. Comparable t-quark mass limits were obtained from a CDF search for $t\bar{t}$ decaying into electron +jets.[11]

A fourth generation of quarks is possible in the standard model. The cross section for pair production of charge $-\frac{1}{3}$, b' quarks would be the same as that for $t\bar{t}$.[12] Assuming the b' decays via the charged-current interaction into a virtual W and a light quark (u or c), the lepton spectrum would be slightly harder resulting in higher detection efficiency. Our limit on the t-quark mass is then applicable to the b' if it is lighter than the top quark, and has a decay lifetime sufficiently short that its decay products appear to come from the interaction vertex. Previous lower limits on the mass of the b' quark were near 30 GeV/c^2.[1–3] With the assumptions stated above, a b' quark in the mass range 28–72 GeV/c^2 is excluded at the 95% confidence level.

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