Search for the Top Quark in the Reaction $\bar{p}p \to$ Electron + Jets at $\sqrt{s} = 1.8$ TeV

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A search for the top quark in $\bar{p}p$ collisions at a center-of-mass energy of 1.8 TeV using the Collider Detector at Fermilab is described. A study of events selected by requiring an energetic electron, missing transverse energy, and two or more jets excludes at 95% confidence level the standard-model prediction and decay of $t\bar{t}$ pairs if the top-quark mass is between 40 and 77 GeV/c^2. The observed electron+multijet data are consistent with W-boson production.

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The standard model of the electroweak and strong interactions requires the existence of the top quark, the SU(2) partner to the bottom quark. Previous searches[1-3] have established a lower limit on the top-quark mass ($M_{\rm top}$) of 41 GeV/c^2. This Letter reports the results of a search for the top quark in $\bar{p}p$ interactions at a center-of-mass energy ($\sqrt{s}$) of 1.8 TeV.

Calculations[4] predict that $t\bar{t}$ pair production is the most copious source of top quarks at $\sqrt{s}=1.8$ TeV. The decay modes yielding an electron, neutrino, and jets provide an excellent signature. The presence of both a lepton and missing transverse energy yields substantial rejection against QCD multijet backgrounds. We have searched for such events in a data sample with an integrated luminosity of 4.4 pb^{-1} accumulated with the Collider Detector at Fermilab (CDF). We have also performed a parallel search for events with both an energetic muon and electron.[5]

Features of the CDF detector[6] pertinent to this study include a vertex time-projection chamber (VTPC) for charged-particle tracking out to a radius of 22 cm from the interaction point and an 84-layer drift chamber extending to a radius of 1.3 m. These chambers are inside an axial magnetic field (1.412 T) and provide momentum measurement in a pseudorapidity interval $-1.0 \lesssim \eta \equiv -\ln[\tan(\theta/2)] \lesssim 1.0$ (θ is the polar angle relative to the beam axis). Electromagnetic (CEM) and hadronic calorimeters outside the solenoid cover the interval $|\eta| < 1.1$, and are composed of towers of size $\Delta\eta \times \Delta\phi \sim 0.1 \times 15°$ (ϕ is the azimuthal angle about the proton-beam axis). Proportional wire chambers are located in the CEM at a depth of six radiation lengths. Additional calorimeters cover the interval $1.1 \le |\eta| \le 4.2$.

We select events that pass an inclusive electron trigger that requires a cluster of CEM transverse energy $E_T^{\rm em} > 12$ GeV and an associated track. The transverse energy is defined as $E_T \equiv E \sin\theta$, where E is the energy detected in the calorimeter. We require each event to have an electron candidate, defined as a cluster of energy in the CEM (1–3 adjacent towers) with (i) $E_T^{\rm em} > 15$ GeV and a hadronic-to-electromagnetic energy ratio less than 0.05, (ii) a track that points to the CEM cluster with transverse momentum P_T such that $E_T^{\rm em} < 1.5 P_T$, and (iii) a shower in the CEM wire chamber whose centroid is within 1.5 cm in R-ϕ and 3.0 cm in the beam direction of the extrapolated track. We fit the shower profiles observed in the CEM wire chamber to the distributions for electrons from test beam measurements and required that $\chi^2 < 10$ for each fit. We also require the distribution of energy in the towers to be consistent with that expected for an electron shower. This results in a sample of 17 500 events. The total efficiency of the cuts, evaluated using electrons from W- and Z-boson decays, is $(77\pm5)\%$. The trigger is $(98\pm0.5)\%$ efficient for events with at least one electron candidate satisfying this selection.

We reject electrons from phonon conversions and π^0 decays by requiring that the electron candidate have a VTPC track and that a second oppositely charged track forming an effective e^+e^- mass less than 0.5 GeV/c^2 is not present. This selection is 95% efficient for prompt electrons. We remove events with a Z^0 boson by rejecting those in which a second electromagnetic cluster and the electron candidate form an e^+e^--pair mass greater than 70 GeV/c^2. In addition, the location of the event vertex along the beam axis is required to be within 60 cm of the center of the detector. This selection results in 10 837 events.

After this selection, the majority of events contain electrons with $E_T < 20$ GeV. QCD calculations predict that b-quark, rather than c-quark, production is the dominant source of electrons in this range of transverse energy, given the above selection criteria. The rate of observed events and distributions of the transverse-energy flow and energy surrounding the electron in this sample are in good agreement with an ISAJET (Ref. 7) QCD Monte Carlo (MC) calculation of b-quark production, including a full detector simulation. In particular, the distribution of $E_T^{\rm iso}$, the transverse energy in the 8–12 calorimeter towers adjacent to the CEM cluster, is well modeled by the calculation and has a mean value of ~ 2.5 GeV for these low-energy electrons.

Because of the greater mass of the top quark, electrons from top-quark decay typically have $E_T^{\rm iso} \lesssim 1$ GeV, as is observed for electrons produced in the decay of W bosons.[8] Hence, we impose the isolation requirement $E_T^{\rm iso} < 2.0$ GeV to reduce the background from b quarks; this yields a sample of 6070 events. The efficiency of this cut, as determined by Monte Carlo calculations, is 80% for electrons from top quarks.

In a $t\bar{t}$ event with one semileptonic top-quark decay, four quark jets are expected in addition to the electron and neutrino. Jets are identified as clusters of energy in the calorimeter using a cone clustering algorithm with a cluster radius $R = [(\Delta\eta)^2 + (\Delta\phi)^2]^{1/2}$ of 0.7.[9] For the top search we select events with two or more jets each having observed $E_T > 10$ GeV and $|\eta| < 2$. Studies of MC $t\bar{t}$ events show that of those events passing the elec-

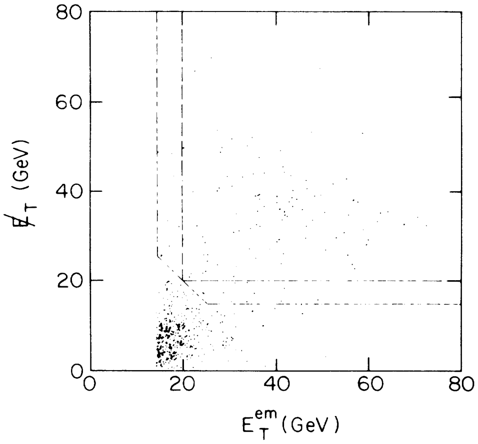

FIG. 1. The distribution of $\not{E}_T$ vs E_T^{em} for electron + $\geq$ two-jet events. The dashed (dot-dashed) lines show the tight (loose) event selection discussed in the text.

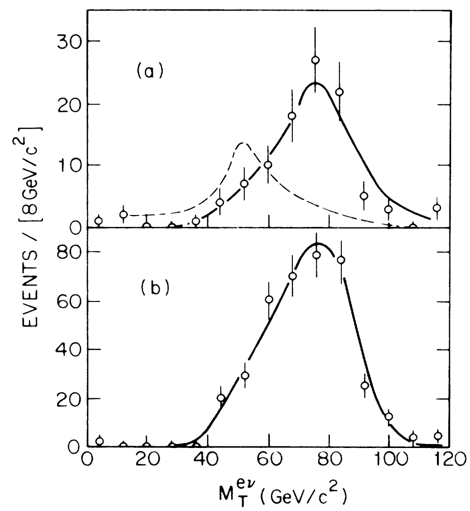

FIG. 2. (a) The $M_T^{e\nu}$ distributions for the electron + $\geq$ two-jet data (points), W+two-jet (solid curve), and $t\bar{t}$ production with M_{top}=70 GeV/c^2 (dashed curve). The solid and dashed curves correspond to the T and W functions discussed in the text. (b) The $M_T^{e\nu}$ distribution for the electron + $\geq$ one-jet data with the W+one-jet prediction normalized to equal area.

tron selection, 50% (80%) survive this jet requirement for M_{top}=40 (80) GeV/c^2. This cut leaves 512 events.

We define the missing transverse energy $\not{E}_T$ as the magnitude of the vector sum of the E_T deposited in each calorimeter tower in the region $|\eta| < 3.6$. The distribution of $\not{E}_T$ vs E_T^{em} is shown in Fig. 1 for the electron + $\geq$ two-jet sample. Events from semileptonic b decays typically have low values of $\not{E}_T$ and E_T and would show up in the bottom-left corner of Fig. 1, where the dense cluster of events is observed. Events from W-boson production populate the higher E_T^{em} and $\not{E}_T$ region. The cuts $E_T^{em} > 20$ GeV and $\not{E}_T > 20$ GeV are reasonably efficient for $M_{top} \gtrsim 50$ GeV/c^2 as they retain at least 20% of the electron + $\geq$ two-jet events, and leave an estimated b-quark, conversion-electron, and nonelectron background of ~12%. We have also analyzed the data with the looser cuts $E_T^{em} > 15$ GeV, $\not{E}_T > 15$ GeV, and $E_T^{em} + \not{E}_T > 40$ GeV. This selection increases our sensitivity to top-quark masses down to ~40 GeV/c^2 (see Fig. 3) but also increases the estimated b-quark and nonelectron background in the event sample to ~20%. There are 104 (123) events that satisfy the tight (loose) selection.

The $\not{E}_T$ vector, interpreted as the transverse momentum of an undetected neutrino, is used to compute the transverse mass $M_T^{e\nu}$,

$$M_T^{e\nu} = [2E_T^{em}\not{E}_T(1-\cos\phi^{e\nu})]^{1/2},$$

where $\phi^{e\nu}$ is the azimuthal angle between the electron and neutrino vectors. The transverse-mass distribution with the tight E_T^{em} and $\not{E}_T$ cuts is shown in Fig. 2(a). Shown for comparison are the expected $M_T^{e\nu}$ distributions for $t\bar{t}$ and W production, $T(M_T^{e\nu})$ and $W(M_T^{e\nu})$. The $t\bar{t}$ events come from an ISAJET calculation with M_{top}=70 GeV/c^2. We have used a $t \to be^+\nu_e$ branching ratio (BR) of $\frac{1}{9}$ in this calculation. The W+two-jet events were generated according to a QCD calculation[10] as implemented in the PAPAGENO Monte Carlo program,[11] which agree with independent W+two-jet calculations[12] (a W mass of 80 GeV/c^2 was used). The detector response was simulated for both MC event samples. The data are consistent with the W+two-jet predictions; there is no evidence for top-quark production. Distributions involving jet variables, including the E_T of the leading and second jet, the dijet effective mass, and the angles between the electron and the two leading jets also show the data to be consistent with the W+two-jet process.

The difference in shape between the W+two-jet and $t\bar{t}$ $M_T^{e\nu}$ distributions, which occurs when M_{top} is at least several GeV/c^2 below the combined mass of the W boson and the b quark,[13] enables us to determine the fraction of data that can be attributed to these two sources by fitting the observed $M_T^{e\nu}$ distribution to

$$dN/dM_T^{e\nu} = \alpha T(M_T^{e\nu}) + \beta W(M_T^{e\nu}).$$

The functions $T(M_T^{e\nu})$ and $W(M_T^{e\nu})$ depend on the $M_T^{e\nu}$ resolution, which we have studied using inclusive electrons, Z^0 events, and the electron + $\geq$ one-jet data. For example, the electron + $\geq$ one-jet sample, which is dominated by W+one-jet production, provides a good calibration because the contribution from top events is small (< 10%-20%). Figure 2(b) shows the electron + $\geq$ one-jet data together with the PAPAGENO W +one-jet calculation with full detector simulation; the agreement in shape is excellent and the normalization agrees within the theoretical uncertainty.

The functions $T(M_T^{e\nu})$ and $W(M_T^{e\nu})$ are normalized so that α=1.0 and β=1.0 correspond to observing the ex-

TABLE I. The number of predicted $t\bar{t}$ events, $n_{t\bar{t}}$, the fitted $t\bar{t}$ contribution to the electron + $\geq$ two-jet rate, α, and the 95%-C.L. upper limits on the $t\bar{t}$ production cross section.

$M_{\rm top}$ (GeV/c^2)	$n_{t\bar{t}}$ predicted	$\alpha \pm$ (stat) $\pm$ (syst)	$\sigma_{t\bar{t}}$ (pb)
40	130 ± 44	$0.07 \pm 0.05 \pm 0.02$	< 2410
50	123 ± 31	$0.06 \pm 0.05 \pm 0.03$	< 648
60	101 ± 22	$0.11 \pm 0.08 \pm 0.04$	< 408
70	43 ± 8	$0.00^{+0.12}_{-0.00} \pm 0.11$	< 266
80	32 ± 5	$0.00^{+0.27}_{-0.00} \pm 0.17$	< 281

pected number of events according to the $t\bar{t}$ cross section calculated by Altarelli *et al.*[2] using a next-to-leading-order QCD calculation,[14] and the PAPAGENO W+two-jet cross section. Contributions to $T(M_T^{e\nu})$ from $W \to t\bar{b}$ have been neglected, as they are small relative to the rate from $t\bar{t}$. The results of a maximum-likelihood fit in the interval $24 \leq M_T^{e\nu} \leq 120$ GeV/c^2 are summarized in Table I. The fits for $M_{\rm top} \geq 65$ GeV/c^2 were performed on the sample selected with the tight $E_T^{\rm em}$ and $\not{E}_T$ cuts while the fits to lower $M_{\rm top}$ were performed on the events passing the loose selection. The fits are in good agreement with the data, with the binned χ^2 per degree of freedom being ~ 1.0. The fitted values for β, typically 1.28 ± 0.15, agree with the predicted value within the theoretical uncertainty for the W+two-jet cross-section calculation.[12,15,16] The fitted top-quark contribution, however, is much smaller than that expected for $M_{\rm top} \lesssim 80$ GeV/c^2.

The events with $M_T^{e\nu} < 24$ GeV/c^2 have been excluded from the fits because few top events are expected in this interval due to the cuts on $E_T^{\rm em}$ and $\not{E}_T$. Any remaining backgrounds from b quarks, gluons, and light quarks contribute primarily at transverse masses below 50 GeV/c^2, and will increase the fitted $t\bar{t}$ fraction; therefore, α is an overestimate of the $t\bar{t}$ fraction.

Systematic uncertainties in the jet-energy scale and in the "underlying event" (energy flow in the event other than that contained in the electron and jet clusters) affect both the $M_T^{e\nu}$ distribution and the acceptance. The calorimeter response to hadrons was determined *in situ* using isolated, low-P_T particles reconstructed in the track chambers. We verified the resulting jet-energy scale[9] by studying inclusive high-P_T photon production, a process dominated by a photon recoiling against a single quark or gluon. In addition, we compared the electron sample with $12 < E_T^{\rm em} < 25$ GeV with the b-quark MC sample to ensure that the energy spectrum of the low-E_T jets agreed in the MC calculations and data. Based on these studies, we conservatively estimate the uncertainty on the jet-energy scale to be $\pm 20\%$. The corresponding uncertainty in α varies with $M_{\rm top}$, and is ± 0.13 for $M_{\rm top} = 80$ GeV/c^2. Differences in the underlying event in the data and the MC calculations correspond to a ± 0.05 uncertainty in α for $M_{\rm top} = 80$ GeV/c^2. An additional variation of ± 0.10 in α for $M_{\rm top} = 80$ GeV/c^2 results from changing the $M_T^{e\nu}$ interval of the fit. We add the individual uncertainties together in quadrature to yield the systematic uncertainties in α presented in Table I.

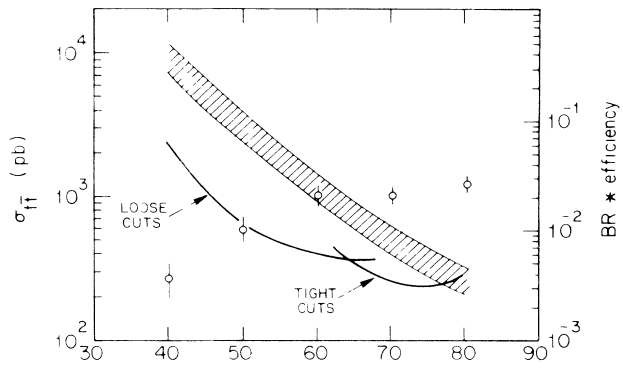

FIG. 3. The 95%-C.L. upper limit for the $t\bar{t}$ production cross section is given by the solid curve, and the predicted cross section (see text) is given by the shaded area. Plotted points show the $t\bar{t}$ branching ratio times efficiency as a function of $M_{\rm top}$ (right-hand scale).

Further systematic uncertainties, which do not significantly change the $M_T^{e\nu}$ distribution but do affect the derivation of an upper limit on the $t\bar{t}$ production cross section, arise from variations in (i) the models of top-quark production and fragmentation, and initial-state gluon radiation; (ii) electron detection efficiency; and (iii) integrated luminosity. We estimate the acceptance uncertainty due to changes in the model for $t\bar{t}$ production by comparing the ISAJET and PAPAGENO calculations. The top-quark fragmentation is modeled using the Peterson parametrization[17] with the ϵ parameter chosen to be $0.5/M_{\rm top}^2$. Although this model is in good agreement with data from charm- and bottom-quark decays, its uncertainties are difficult to determine. We estimate them by varying the ϵ parameter from $0.2/M_{\rm top}^2$ to $1.5/M_{\rm top}^2$. We estimate the acceptance uncertainty due to variations in the amount of initial-state radiation by halving the contribution predicted by ISAJET. The systematic uncertainty due to these effects is 30% (7%) for $M_{\rm top} = 40$ (80) GeV/c^2. The uncertainties in electron detection efficiency and integrated luminosity are 5% and 15%, respectively. We add these systematic uncertainties together in quadrature and present the results in Table I as the uncertainty in the predicted number of observed $t\bar{t}$ events.

We assume the systematic uncertainties on α and the acceptance and normalization to be Gaussian and convolute them with the likelihood functions for α from the fits. We extract the 95%-confidence-level (C.L.) limits on the $t\bar{t}$ cross section from the convoluted-likelihood functions and present them in Table I as a function of top-quark mass. These limits are shown in Fig. 3 along with the upper and lower bounds on the $t\bar{t}$ cross section ($\sigma_{t\bar{t}}$) calculated by Altarelli *et al.*[2,14] These upper limits compared with the theoretical lower bound exclude the existence of a top quark with a mass between 40 and 77 GeV/c^2 at 95% confidence level. The systematic uncertainties on jet detection efficiency and top fragmentation grow rapidly with decreasing M_{top}, and so we do not extend the lower mass limit below 40 GeV/c^2.

In conclusion, we have searched for the production and decay of the standard-model top quark into the electron+multijet final state. The observed data are consistent with Monte Carlo predictions for W+two-jet production. A fit to the electron-neutrino transverse-mass distribution excludes a top quark with mass between 40 and 77 GeV/c^2 at 95% C.L.

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