Search for the Top Quark in $p\bar{p}$ Collisions at $\sqrt{s}$ =1.8 TeV

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We have searched for evidence of top quark production in $p\bar{p}$ collisions at $\sqrt{s}$ =1.8 TeV using the D0 detector at the Fermilab Tevatron collider. For an integrated luminosity of 15 pb^{-1}, we report results of a search for $t\bar{t}$ pairs in the decay modes $t\bar{t} \rightarrow e\mu$+jets, ee+jets, e+jets, and μ+jets. From analyses of these modes we obtain a lower limit on the top quark mass of 131 GeV/c^2 at the 95% confidence level, assuming standard model branching fractions and a predicted cross section for $t\bar{t}$ production. We discuss the properties of an event for which expected backgrounds are small.

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The top quark is the only minimal standard model (SM) quark that has not yet been observed [1]. Assuming standard model decays, the present experimental lower limit for the top quark mass (m_t) is 91 GeV/c^2 [2]. In $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV the strong interaction production of $t\bar{t}$ pairs is expected to dominate single top creation. According to the SM, a top quark decays via the weak charged current into a b quark and a W boson. The W can decay into leptons [referred to as $W(e\nu)$, $W(\mu\nu)$, or $W(\tau\nu)$] or quarks [$W(q\bar{q})$].

We have searched for the dilepton decay modes $t\bar{t} \rightarrow W(e\nu)W(e\nu)b\bar{b}$, the ee mode, and $t\bar{t} \rightarrow W(e\nu)W(\mu\nu)b\bar{b}$, the $e\mu$ mode, which have expected branching fractions of 1/81, and 2/81, respectively. In addition, we have looked for the single lepton modes $t\bar{t} \rightarrow W(e\nu)\ W(q\bar{q})\ b\bar{b}$, the e + jets mode, and $t\bar{t} \rightarrow W(\mu\nu)\ W(q\bar{q})\ b\bar{b}$, the μ + jets mode, each of which has an expected branching fraction of 12/81. The signature for a dilepton event is two isolated leptons of high transverse momentum (p_T), jets and large missing transverse energy ($\not\!\!E_T$) due to the two neutrinos. Backgrounds from other physics processes are relatively small. Single lepton events have one high p_T lepton, jets, and large $\not{E}_T$. The dominant background is from production of $W +$ jets. The data presented were collected between August 1992 and May 1993 and correspond to an integrated luminosity of 15 pb^{-1}.

The D0 detector [3] has a hermetic, compensating sampling calorimeter with fine longitudinal and transverse segmentation in pseudorapidity (η) and azimuth (ϕ). The energy resolutions can be parametrized as $\sigma/E \approx A/\sqrt{E}$ (E in GeV), where A=0.15 for electrons, A=0.50 for single hadrons, and A=0.80 for jets [4]. For minimum bias events the resolution for either component of $\not{E}_T$ is about 1.1 GeV+0.02($\sum E_T$), where $\sum E_T$ is the scalar sum of all the transverse energy, E_T, in the calorimeter. There is no central magnetic field. We reconstruct charged particle tracks using drift chambers located between the interaction region and the calorimeter; a transition radiation detector identifies electrons. We detect muons by reconstructing tracks in proportional drift tubes before and behind magnetized iron toroids located outside of the calorimeter. The bending angle of the track in the toroid determines the muon momentum (p) with momentum resolution of $\sigma(1/p) = (0.2/p) + [0.01\ (\mathrm{GeV}/c)^{-1}]$, as obtained from $Z \rightarrow \mu\mu$ events.

We require that the muon track be consistent with coming from the primary interaction, and to deposit energy in the calorimeter consistent with minimum ionization. For these analyses we use isolated muons with $|\eta| < 1.7$. We identify electrons by the longitudinal and transverse shape of isolated energy clusters in the calorimeter [5] and by the requirement that there be a matching track in the drift chambers. We require electrons to be within a fiducial region of $|\eta| < 2.5$. We reconstruct jets using a cone algorithm with $\mathcal{R} = 0.5$, where $\mathcal{R} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$. We correct jet energies for calorimeter response, out of cone leakage, noise and for the underlying event; the correction is of the order of 15% and varies with jet energy and η. The missing transverse energy, as computed from energy deposited in the calorimeter after all corrections, is denoted by $\not{E}_T^{\mathrm{cal}}$. The missing transverse energy corrected also for observed muon momenta is denoted by $\not{E}_T$ [6].

We trigger on events with combinations of electron, muon, jet candidates, and $\not{E}_T^{\mathrm{cal}}$. We compute the efficiency for the triggers with a Monte Carlo (MC) simulation of each $t\bar{t}$ decay mode. It varies between 70% and 90% as m_t increases from 90 to 160 GeV/c^2.

In the off-line selection of $e\mu$ events, we require one electron with $E_T > 15$ GeV, one muon with $p_T > 15$ GeV/c, $\not{E}_T^{\mathrm{cal}} > 20$ GeV, and $\not{E}_T > 20$ GeV. To eliminate contributions from muon bremsstrahlung, the leptons must be well separated ($\mathcal{R}_{e\mu} > 0.25$). To reduce backgrounds from WW, W, and Z decays, we require at least one jet with $E_T > 15$ GeV. Figure 1 shows the distribution of muon p_T versus electron E_T for the $e\mu$ mode before jet requirement for data and for MC $t\bar{t} \rightarrow e\mu$. One event, denoted by a $\star$ in Fig. 1(a), survives all selection cuts.

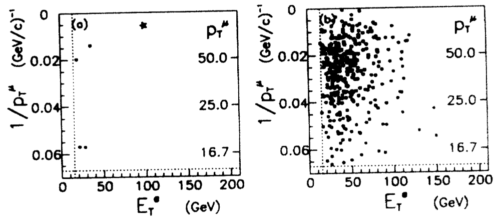

FIG. 1. Scatter plots of $1/p_T^\mu$ versus E_T^e prior to jet cut for $e\mu$ events from (a) data, and (b) $t\bar{t}$ MC simulation; $m_t = 160$ GeV/c^2 ($\int \mathcal{L}dt \approx 11\ \mathrm{fb}^{-1}$).

For ee candidates, we require two isolated electrons with $E_T > 20$ GeV and $\not{E}_T^{\mathrm{cal}} > 25$ GeV. To suppress backgrounds from $Z \rightarrow ee$, we require $\not{E}_T^{\mathrm{cal}} > 40$ GeV if $|m_{ee} - m_Z| < 12$ GeV/c^2, where m_{ee} is the dielectron invariant mass. As in the $e\mu$ mode, we require at least one jet with $E_T > 15$ GeV. Figure 2 shows the distribution of $\not{E}_T^{\mathrm{cal}}$ versus m_{ee} in the ee mode after the electron E_T and jet cuts for data and for MC $t\bar{t} \rightarrow ee$. One event, denoted by a $\star$ in Fig. 2(a), remains after all cuts.

We have calculated the efficiency of the selection cuts using the ISAJET MC program [7] for top samples with masses 90, 100, 120, 140, and 160 GeV/c^2, with subsequent detector simulation [3]. Table I shows the (efficiency) $\times$ (branching fraction) for dilepton cuts, including trigger and off-line selection and the expected yields for top production. The quoted yields do not include events from $t\bar{t}$ decays to τ, b, or c with subsequent secondary decays to dileptons. We estimate that the acceptance for m_t of 120 GeV/c^2 top quarks would be increased by about 10% from these secondary leptons. All errors on the efficiencies are dominated by systematics in detector simulation.

Extensive studies of backgrounds to the dilepton modes, including the dilepton continuum, $Z \rightarrow ee$, $Z \rightarrow \tau\tau$, $Z \rightarrow b\bar{b}$ or $c\bar{c}$, strong production of $b\bar{b}$ and $c\bar{c}$, WW, WZ, $W +$ jets, $Z +$ jets, and fake leptons, result in the background estimates summarized in Table I. We estimate physics backgrounds from MC samples and find that WW production and $Z \rightarrow \tau\tau$ decays are dominant. Using data, we evaluate the backgrounds arising from

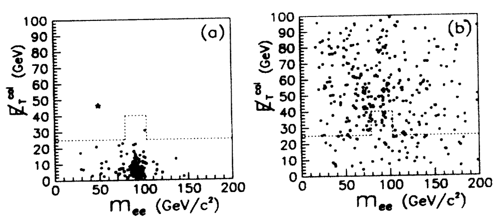

FIG. 2. Scatter plots of $\not{E}_T^{\mathrm{cal}}$ versus m_{ee} for ee events from (a) data, and (b)$t\bar{t}$ MC simulation; $m_t = 160$ GeV/c^2 ($\int \mathcal{L}dt \approx 19\ \mathrm{fb}^{-1}$).

TABLE I. (Efficiency) × (branching fraction) ($\varepsilon \times B$), expected number of events ($\langle N \rangle$) for signal [11] (errors do not include the $\sigma_{t\bar{t}}$ theoretical uncertainty) and background sources for the observed integrated luminosity ($\int \mathcal{L}dt$), and number of events observed in the data. The numbers in parentheses correspond to the stricter off-line cuts discussed in the text.

m_t (GeV/c^2)		$e\mu$		ee	$e+$jets	$\mu+$jets
	$\varepsilon \times B$ (%)	0.31 ± 0.06		0.15 ± 0.02	0.28 ± 0.08	0.15 ± 0.07
90	$\langle N \rangle$	8.5 ± 1.9		4.2 ± 0.7	7.7 ± 2.4	3.0 ± 1.5
	$\varepsilon \times B$ (%)	0.39 ± 0.07		0.18 ± 0.02	0.44 ± 0.12	0.19 ± 0.08
100	$\langle N \rangle$	6.1 ± 1.3	(1.3 ± 0.6)	2.8 ± 0.5	6.8 ± 2.0	2.2 ± 1.0
	$\varepsilon \times B$ (%)	0.42 ± 0.08		0.23 ± 0.03	1.13 ± 0.22	0.61 ± 0.20
120	$\langle N \rangle$	2.5 ± 0.6	(0.6 ± 0.1)	1.4 ± 0.3	6.7 ± 1.5	2.7 ± 0.9
	$\varepsilon \times B$ (%)	0.46 ± 0.09		0.24 ± 0.03	1.45 ± 0.19	0.90 ± 0.27
140	$\langle N \rangle$	1.2 ± 0.3	(0.4 ± 0.2)	0.6 ± 0.1	3.7 ± 0.7	1.7 ± 0.6
	$\varepsilon \times B$ (%)	0.48 ± 0.09		0.25 ± 0.03	1.69 ± 0.18	0.85 ± 0.24
160	$\langle N \rangle$	0.6 ± 0.1	(0.2 ± 0.1)	0.3 ± 0.1	2.1 ± 0.3	0.8 ± 0.2
$\int \mathcal{L}dt$ (pb^{-1})		15.2 ± 1.8	15.2 ± 1.8	15.2 ± 1.8	15.2 ± 1.8	11.0 ± 1.3
Data		1	(1)	1	1	0
Physics background		0.6 ± 0.1	(0.07 ± 0.04)	0.2 ± 0.1	2.4 ± 1.2	1.3 ± 0.8
Fake background		0.5 ± 0.2	(0.02 ± 0.02)	0.3 ± 0.2	0.3 ± 0.3	0.3 ± 0.1
Total background		1.1 ± 0.3	(0.09 ± 0.05)	0.5 ± 0.2	2.7 ± 1.3	1.6 ± 0.9

W + jets and multijet production with jets misidentified as an electron. The probability for a jet to fake an electron, as measured in multijet events, is about 0.05%. Backgrounds due to a jet faking a muon are negligible.

To select e+jets and μ+jets samples we require W boson selection (defined as one high p_T isolated electron or muon and $\not{E}_T$), jet counting (four or more jets), and event shape cuts (top events are more spherical than background processes). Event shape is characterized by the aplanarity $\mathcal{A}$ which is proportional to the lowest eigenvalue of the momentum tensor for observed objects [8]. In $\mu+$jets events we calculate $\mathcal{A}$ using only the jets ($\mathcal{A}_{\rm jets}$). In the e + jets case, where the electron momentum is measured precisely, we use the jets and reconstructed $W(e\nu)$ momenta ($\mathcal{A}_{W+\rm jets}$). We estimate the dominant $W+$jets background using the VECBOS MC program [9], which reproduces the properties of our $W+2,3$ jets sample moderately well. We use the measured probability of misidentifying a jet as an electron to determine the background from multijet events.

For the e + jets mode, we require one electron with $E_T > 20$ GeV, at least four jets with $E_T > 15$ GeV, and $\not{E}_T^{\rm cal} > 30$ GeV. Figure 3(a) shows the expected $\mathcal{A}_{W+\rm jets}$ distribution for W+jets and for $t\bar{t}$ events. Requiring $\mathcal{A}_{W+\rm jets} > 0.08$ reduces the expected W + jets background by a factor of 5 while accepting about half of the $t\bar{t}$ events. The $e+$jets data are also shown in Fig. 3(a). One event passes all cuts.

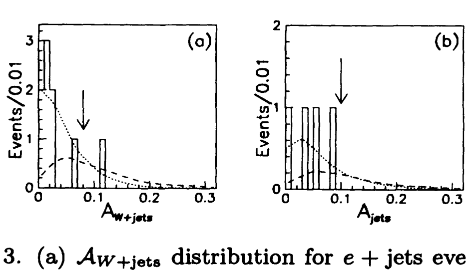

FIG. 3. (a) $\mathcal{A}_{W+\rm jets}$ distribution for e + jets events. The dotted curve corresponds to the expectation for $W+$jets, the dashed curve for $t\bar{t}$ ($m_t = 140$ GeV/c^2). (b) $\mathcal{A}_{\rm jets}$ distribution for $\mu+$jets events. Dotted curve corresponds to expectation for W + jets, dashed curve for $t\bar{t}$ ($m_t = 140$ GeV/c^2).

In the μ + jets mode, we require one muon with $p_T > 15$ GeV/c, $\not{E}_T^{\rm cal} > 20$ GeV, $\not{E}_T > 20$ GeV, and at least four jets with $E_T > 15$ GeV. Figure 3(b) shows the expected $\mathcal{A}_{\rm jets}$ distribution for $W+$jets and for $t\bar{t}$ events. To obtain a reduction from W + jets comparable to that achieved in the $e+$jets mode, we cut at $\mathcal{A}_{\rm jets} > 0.1$. No events remain after all cuts. Table I lists the selection (efficiency) × (branching fraction) and expected yields for $t\bar{t} \rightarrow e$ + jets and for $t\bar{t} \rightarrow \mu$ + jets as a function of the top mass. Background estimates are also listed; physics backgrounds due to $W+$jets are assigned a 40% theoretical error [10].

We determine a 95% confidence level (C.L.) upper limit on the $t\bar{t}$ cross section based on the observation of three events passing the analysis cuts. We calculate the limit by interpreting these as signal events and making no background subtraction. Poisson-distributed numbers of events are convoluted with the errors on efficiencies, acceptances, and luminosities as a function of m_t. Figure 4 shows the resulting 95% C.L. upper limit on the $t\bar{t}$ cross section as a function of m_t. The intersection of this curve with a predicted $t\bar{t}$ cross section lower bound [11] yields a lower limit on the top quark mass of 131 GeV/c^2. For comparison with previously published results [2], we use the same method with the next-to-leading order $t\bar{t}$ cross section [12] to obtain a lower limit on m_t of 122 GeV/c^2.

Backgrounds to $t\bar{t}$ production are smaller in the dilepton than in the single lepton modes. Imposing the more stringent requirements for the dilepton modes of $E_T^l > 30$ GeV (l=e or μ), $\not{E}_T > 40$ GeV, and requiring 2 jets with

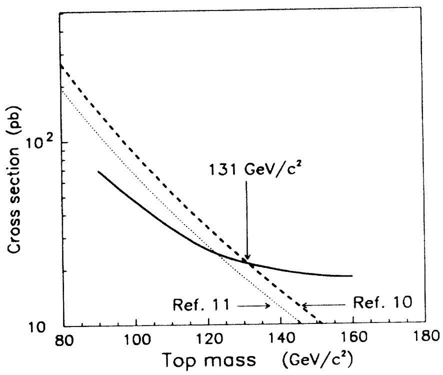

FIG. 4. The 95% C.L. limit on $\sigma_{t\bar{t}}$ from the combination of the four modes (solid curve) compared with two theoretical predictions.

$E_T > 15$ GeV, reduces the background to less than 0.1 event for each of the dilepton modes, and increases the signal to background ratio by a factor of about 4. With these cuts the significant backgrounds are from WW production and $Z \to \tau\tau$ decay. The effects of such cuts are shown in Table I for the $e\mu$ mode in which one event survives. No events survive in the ee mode. The single $e\mu$ event that survives has the following kinematic parameters: E_T^e=98.8±1.6 GeV, p_T^μ=195 GeV/c (>40 GeV/c at 95% C.L.), $E_T^{\rm jet1}$=24.9±4.3 GeV, $E_T^{\rm jet2}$=22.3±5.6 GeV, $E_T^{\rm jet3}$=6.7±3.6 GeV, and $\not{E}_T$ = 102 GeV. Although $\not{E}_T$ and p_T^μ are correlated, $\not{E}_T$ is greater than 54 GeV at 95% C.L. The interpretation of this event as a $Z \to \tau\tau \to e\mu$ decay is ruled out kinematically ($m_{e\mu\nu}$ >200 GeV/c at 95% C.L.).

We have analyzed the surviving $e\mu$ event under the hypothesis that it is due to $t\bar{t} \to W(e\nu)W(\mu\nu)b\bar{b}$ using an extension of the likelihood method based solely on the event topology as described in Ref. [13]. Our analysis [14] shows that this event is kinematically consistent with $t\bar{t}$ production over the mass range 100 to 200 GeV/c^2. Using a likelihood function based upon the parton distribution functions, partonic cross sections, and decay lepton distributions, we find that the peak likelihood for this event is near the median found in MC top samples. The likelihood distribution is maximized for a top mass of about 145 GeV/c^2, but masses as high as 200 GeV/c^2 cannot be excluded. This result is consistent with, but independent of, our lower limit on m_t described above.

We see no conclusive evidence for top production in the four modes presented here. The final event sample contains three candidate events, consistent with our background estimates, though the $e\mu$ event is in a relatively low background region. We obtain a 95% C.L. lower limit on the top quark mass of 131 GeV/c^2.

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