

Top Search at CDF

Milciades Contreras, University of Chicago
for the CDF Collaboration

ABSTRACT

We review top quark searches carried out at CDF with data collected during the 1988-1989 Collider Run. The latest analyses give a lower limit on the top quark mass of $91 \text{ GeV}/c^2$ at the 95 % confidence level, assuming Standard Model decays.

When the last Fermilab collider run started in 1988, the experimental lower bounds on the mass of the top quark (M_{top}) were $28 \text{ GeV}/c^2$ from the absence of $t\bar{t}$ production at the TRISTAN e^+e^- collider [1], and $41 \text{ GeV}/c^2$ at from searches at the CERN $p\bar{p}$ collider [2]. Since then, e^+e^- colliders with center-of-mass energies around the Z^0 mass at SLAC and LEP have become available, and lower bounds of about $46 \text{ GeV}/c^2$ have been reported [3]. Also, improved lower limits of up to $69 \text{ GeV}/c^2$ have resulted from the last runs at the CERN $p\bar{p}$ collider with $\sqrt{s} = 0.63 \text{ TeV}$ [5].

The Fermilab $p\bar{p}$ collider with $\sqrt{s} = 1.8 \text{ TeV}$, is the world's highest energy accelerator. This has allowed the CDF experiment to have the best sensitivity to top quarks at this time. In this paper we review CDF results from searches for the top quark based on a data sample with integrated luminosity of 4.1 pb^{-1} collected during 1988-1989.

Top quarks are expected to be produced at the Fermilab collider mainly via the process $p\bar{p} \rightarrow t\bar{t}$. The cross section for this process has been calculated to order α_s^3 [4] and is known with a theoretical uncertainty of $\sim 30\%$. Each top quark is expected to decay into a W boson and a bottom quark, $t \rightarrow Wb$ (charged current decay). The W , which can be real or virtual depending on the mass of the top quark, then decays into a pair of quarks ($u\bar{d}$ or $c\bar{s}$) or into leptons ($e\nu$, $\mu\nu$, or $\tau\nu$). The final states of the top quark decay are either three jets or a jet accompanied by a charged lepton and a neutrino. Assuming a semileptonic branching ratio of $\frac{1}{9}$ per lepton, purely hadronic final states are the most abundant but are very difficult to distinguish from large QCD multijet

backgrounds. Useful top quark signatures employ at least one lepton (e or μ). Figure 1 shows a list of final states and their branching ratios.

CDF is a solenoidal detector with good electron and muon identification capabilities. Electromagnetic and hadronic calorimeters with projective towers cover nearly the full solid angle. Inside the region $|\eta| < 1.2$ ¹ the central tracking chamber (CTC) measures charged particle momenta with precision $\delta p_T/p_T^2 \simeq 0.0011 (\text{GeV}/c)^{-1}$. A vertex time projection chamber (VTPC) located between the beam pipe and the central tracking chamber provides tracking information out to $|\eta| = 3.25$. Electrons are identified in the rapidity regions $|\eta| < 1.0$ (central calorimeter) and $1.26 < |\eta| < 2.2$ (plug calorimeter). Electron candidates have calorimeter clusters with mostly electromagnetic energy and with lateral shower profiles consistent with test beam electrons. They must be associated to a track extrapolating to the calorimeter shower position. For central electrons, the track momentum must be in good agreement with the calorimeter energy. In the plug region, where the CTC resolution and efficiency are degraded, energy-momentum matching is not required, and tracks in the VTPC are also used for position matching. Electron pairs from photon conversions and Dalitz decays can be rejected if a second nearby track forming a low mass pair is found in the CTC. Photon conversions can also be rejected if no track is found in the VTPC. Muons are identified in the region $|\eta| < 1.2$ by requiring that the tower to which the candidate track extrapolates has energy deposi-

¹ $\eta = -\ln(\tan(\theta/2))$. θ is the angle to the proton direction.

Published Proceedings Joint International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics, Geneva, Switzerland, July 25-August 1, 1991.

tion consistent with that of a minimum ionizing particle. The region $|\eta| < 0.6$ is instrumented with muon chambers, outside of the calorimeters, for triggering and improved muon identification.

The first CDF top results came from searches in the $e+jets$ [6] and $e\mu$ [7] channels. The $e+jets$ sample of 104 events was selected having a central electron candidate with $E_T^e > 20$ GeV, missing transverse energy $\cancel{E}_T > 20$ GeV, and at least two jets with $E_T > 10$ GeV. The major background after these cuts is from high P_T W events produced in association with jets. The transverse mass variable $M_T^{\pi} = \sqrt{2E_T^e \cancel{E}_T (1 - \cos \Delta\phi_{e\pi})}$, with E_T^e the electron transverse energy and $\Delta\phi_{e\pi}$ the azimuthal separation between the electron and missing transverse energy vectors, is used to distinguish the top signal from the $W+jets$ background. Figure 2 shows the transverse mass distribution for the CDF data, which is seen to be consistent with expectations from W boson decay alone. The top quark would show up as an excess of events in the low transverse mass region. The absence of such an excess implies that $M_{top} > 77$ GeV/c 2 at the 95% CL [6]. We note that this method of discrimination is no longer useful for top masses at or above the W mass, when the top quarks decay into real W bosons and the transverse mass distributions become indistinguishable.

The $e\mu$ signature requires a central electron and a muon, both with P_T above a 15 GeV/c threshold (signal region). Each event has been triggered by at least one of the central electron and muon triggers, which are highly efficient above 15 GeV/c. The high transverse momentum threshold separates the $t\bar{t}$ signal from $b\bar{b}$ and particle misidentification backgrounds, which concentrate at low P_T . Figure 3 shows CDF electron-muon data selected with $E_T^e > 15$ GeV and $P_T^\mu > 5$ GeV/c. There is one event in the top quark signal region. This high- P_T $e\mu$ event has a dilepton azimuthal opening angle of 137 degrees. There is also a second muon candidate in the event in the forward region, and some jet activity (see Table 1). With one candidate event, a limit of $M_{top} > 72$ GeV/c 2 at the 95% CL was obtained from the $e\mu$ analysis [7].

A final limit of $M_{top} > 91$ GeV/c 2 has been obtained by CDF in a later analysis that com-

	Charge	P_T GeV/c	η	ϕ deg.
Central e	+	31.7	-0.81	132
Central μ	-	42.5	-0.80	269
Forward μ	+	9.9	-2.0	98
Jet 1		14	1.1	341
Jet 2		5	-2.8	88

Table 1: Characteristics of the top candidate event. Observed calorimeter \cancel{E}_T is used in the P_T column for the electron and jet clusters.

bines the results from two searches [8].

i) Dilepton analysis : an extension of the previous $e\mu$ analysis including the channels ee and $\mu\mu$. The search has also been extended to include electrons in the plug calorimeter. ii) b tag analysis : a search in $lepton+jets$ events for a low transverse momentum muon as a tag of a bottom quark in $t\bar{t} \rightarrow \ell\nu b\bar{q}\bar{q}$ decays.

In the dilepton analysis we require ² each lepton to have $P_T > 15$ GeV/c. After the P_T and lepton identification cuts, there are 4 $e\mu$, 271 ee , and 112 $\mu\mu$ events. Kinematic and event topology cuts are then applied to reject the remaining backgrounds. A back-to-back cut, requiring $\Delta\phi_{\ell\ell} < 160$ degrees, where $\Delta\phi_{\ell\ell}$ is the dilepton azimuthal opening angle, is placed to suppress a small expected $Z^0 \rightarrow \tau\tau$ background. For dielectron and dimuon channels, the $\Delta\phi_{\ell\ell}$ cut also reduces large backgrounds from Z^0 and Drell-Yan events. These backgrounds are reduced further by a dilepton invariant mass ($M_{\ell\ell}$) cut around the Z^0 peak and a cut on missing transverse energy. We remove ee and $\mu\mu$ events with $75 < M_{\ell\ell} < 105$ GeV/c 2 or with $\cancel{E}_T < 20$ GeV. In $t\bar{t}$ events, there would be two undetected high transverse energy neutrinos, and the two leptons are not expected to be back-to-back. Therefore, with these cuts, most of the $t\bar{t}$ acceptance is preserved.

Of the 271 ee and 112 $\mu\mu$ events, 50 ee and 15 $\mu\mu$ events survive the invariant mass cut. The

²For the subset of $e\mu$ events with electron in the plug calorimeter and muon detected outside the muon chambers, the electron threshold has been raised to 30 GeV to ensure that the trigger is efficient.

distribution of $\Delta\phi_{\ell\ell}$ versus E_T for these events is shown in Figure 4 along with Monte Carlo predictions for $M_{top} = 90 \text{ GeV}/c^2$. After imposing the $\Delta\phi_{\ell\ell}$ and E_T cuts, no dielectron or dimuon events remain in the data. A total of 1.5 ± 0.8 background events, mostly from Drell-Yan and particle misidentification, are expected in the ee and $\mu\mu$ channels after all cuts.

Three of the four $e\mu$ events are rejected by the $\Delta\phi_{\ell\ell}$ cut. The three events have an electron in the plug calorimeter and therefore had not been found in the previous $e\mu$ analysis. They also have small E_T , and are consistent with being background events. The remaining event is the same candidate found in the previous analysis [7]. A total of 1.2 ± 0.5 background events, mostly from $b\bar{b}$ and particle misidentification, are expected in the $e\mu$ channel after all cuts. We note that these backgrounds concentrate at low P_T , far from the candidate event.

In the b tag analysis, we search for additional low P_T muons in the $e + jets$ and $\mu + jets$ samples. The low P_T muon in the event is employed as a tag of the bottom quark in the chain $t \rightarrow b \rightarrow \mu$. It is expected to have a soft transverse momentum spectrum, with an average of $3 \text{ GeV}/c$ for $M_{top} = 90 \text{ GeV}/c^2$. Muons with $P_T < 1.6 \text{ GeV}/c$ are stopped in the calorimeter and do not reach the muon chambers. We require $P_T > 2 \text{ GeV}/c$ to avoid uncertainties in the detection efficiency of the lowest momentum muons. To prevent overlap with the dilepton analysis, muons with $P_T > 15 \text{ GeV}/c$ are excluded.

For top quark masses near the W mass, muons from b decays in $t\bar{t}$ events are usually well separated from the leading jets. The two highest E_T jets in such events tend to come from hadronic W decay or from gluon radiation, rather than from the hadronization of the b -quarks. For backgrounds from $W + jets$ events, on the other hand, fake soft muons (from decays in flight and hadronic punch through) are normally associated to the most energetic jets. These backgrounds are reduced by rejecting events where the muon is within $\Delta R < 0.5$ ⁴ of either of the two leading jets. Fig-

M_{top} GeV/c^2	ϵ_{top} dilep.	ϵ_{top} b tag	$\sigma_{t\bar{t}}$ pb.	N_{ev}
80	0.68%	0.20%	291	10.5
90	0.80%	0.26%	150	6.5
100	0.83%	0.29%	94	4.3

Table 2: Detection efficiencies, ϵ_{top} , for the high P_T dilepton and b tag analyses, the predicted central value of $t\bar{t}$ production cross section from Ref. [4] and the total number of events expected.

ure 5 shows the distribution of the distance ΔR between the soft muon and the nearest of the two leading jets for the CDF data and for $t\bar{t}$ Monte Carlo. No candidates are found. The expected number of background events from $W + jets$ with a fake soft muon is 0.9 ± 0.5 .

The detection efficiencies for the dilepton and b tag analyses are summarized in Table 1. Also shown is the total number of events expected, $N_{ev} = \epsilon_{top} \times \sigma_{t\bar{t}} \times \int L dt$, where ϵ_{top} is the sum of the detection efficiencies of the two analyses, and $\int L dt$ is the integrated luminosity of the data sample. The total uncertainty in ϵ_{top} , taking into account correlations in the uncertainties in the two analyses, is 11%. The uncertainty in the integrated luminosity is 7%.

Given one candidate event, and without subtracting backgrounds, we derive an upper limit on the $t\bar{t}$ production cross section as a function of M_{top} (113 pb at the 95% CL for $M_{top} = 90 \text{ GeV}/c^2$). This upper limit cross section is compared to theoretical lower estimates of $\sigma_{t\bar{t}}$ [4] to obtain a lower limit on the top quark mass of $91 \text{ GeV}/c^2$ at the 95% CL for the dilepton and b tag analyses combined [8] (see Figure 6). From the dilepton analysis alone, the limit would be $85 \text{ GeV}/c^2$.

A lot has been learned about the mass of the top quark since 1988. Now we are looking forward to the next 1992-1993 collider run, during which about 100 pb^{-1} of data are planned to be collected by CDF. With such a data sample we expect to find the top quark if it is as heavy as

$150 \text{ GeV}/c^2$.

³The $\mu + jets$ sample consists of 91 events with $P_T^\mu > 20 \text{ GeV}/c$ and $|\eta| < 0.6$, with the same jet and missing energy requirements of the $e + jets$ sample.

⁴ ΔR is a distance measured in pseudorapidity-azimuth space (radians). $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

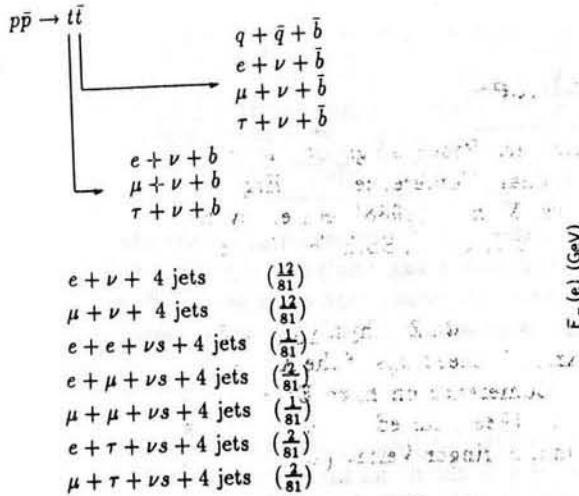


Figure 1: Parton final states and event topologies for top pair production. Only final states containing at least one electron or muon from the top decay are shown. Branching ratios are indicated in parentheses.

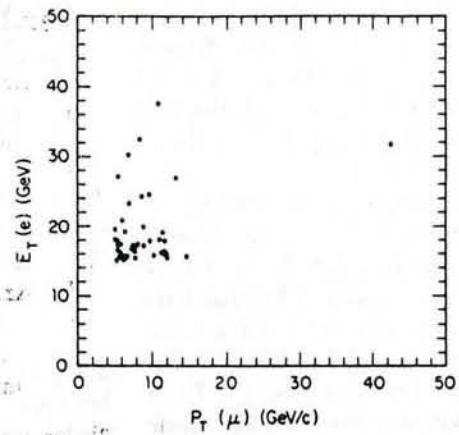


Figure 3: Electron transverse energy vs muon transverse momentum for CDF data with integrated luminosity of 4.1 pb^{-1} .

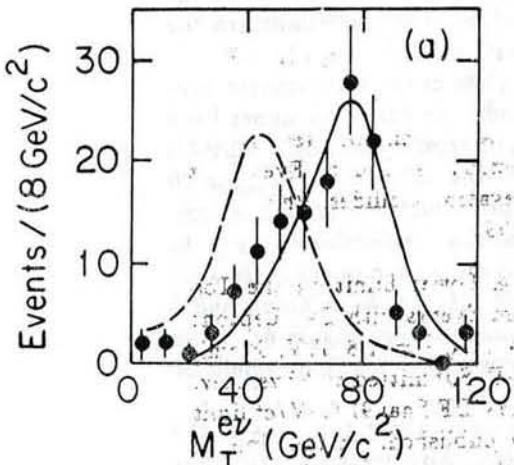


Figure 2: Transverse mass distribution for the $e + \text{jets}$ sample (points). The solid line corresponds to expectations from W boson decays alone. The dashed line is for Monte Carlo top events for $M_{top} = 60 \text{ GeV}/c^2$ normalized to the total number of events predicted.

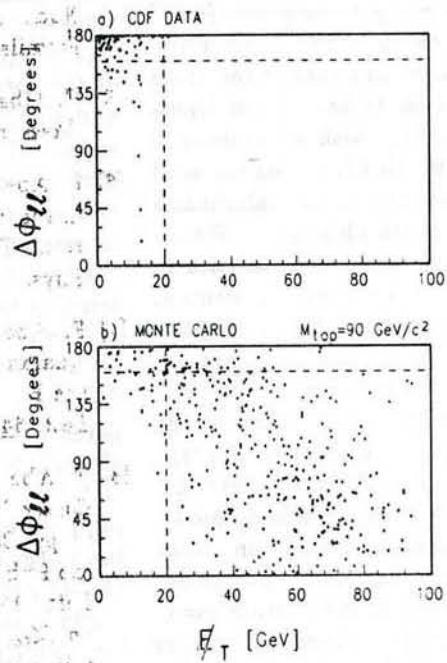


Figure 4: Distributions of E_T vs $\Delta\phi_{\ell\ell}$. (a) CDF dielectron and dimuon data with integrated luminosity of 4.1 pb^{-1} . (b) Monte Carlo $t\bar{t} \rightarrow \ell\ell + X$ events for $M_{top} = 90 \text{ GeV}/c^2$ (unnormalized). Events with dilepton mass in the range $75 < M_{\ell\ell} < 105$ are not included in the figure.

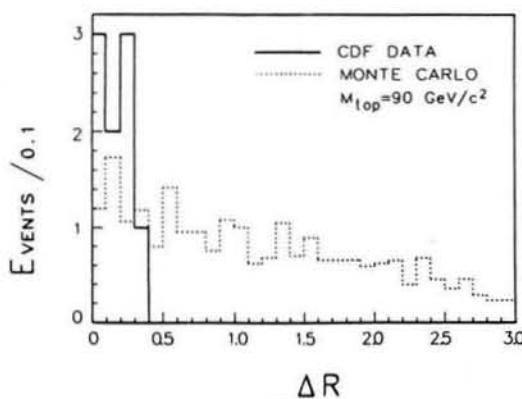


Figure 5: The η - ϕ distance ΔR to the nearest of the two most energetic jets for low P_T muon candidates in the *lepton + jets* sample. Also shown is the $90 \text{ GeV}/c^2$ $t\bar{t}$ Monte Carlo prediction (arbitrary normalization).

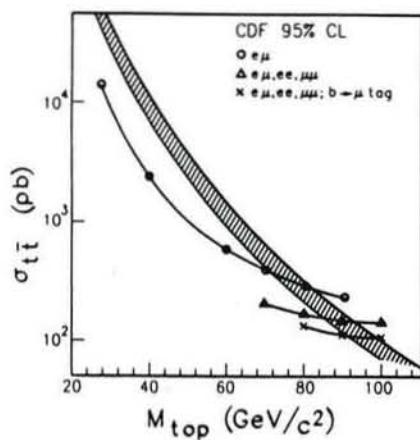


Figure 6: The 95% CL limits on $\sigma_{t\bar{t}}$ compared with a band of theoretical predictions from Ref. [3]. The three sets of experimental limits are: (1) from the $e\mu$ analysis alone; (2) from the dilepton modes ee , $e\mu$ and $\mu\mu$; (3) from the combination of the dilepton analysis with the b tag analysis.

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