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Search for the Top Quark with CDF *

The CDF Collaboration

presented by

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ABSTRACT

During the 1988-89 Tevatron Collider run the CDF detector has collected data for an integrated luminosity of 4.4 pb^{-1}. The sample has been used to search for the top quark in several topologies. Preliminary results show that a top mass below 89 GeV is excluded at the 95% confidence level, thus extending the limit of 77 GeV previously published by CDF.

1 Introduction

The Standard Model includes three lepton and three quark doublets as confirmed by recent measurements at SLC and LEP, which find [1] the number of neutrinoes to be 3.1 ± 0.1. Apart from a lack of direct observation of the ν_τ, the top quark is the last missing block of the model. Experiments at Hadron Colliders have reported lower mass limits (95% C.L.) of 60 and 66 GeV at CERN (UA1 [2] and UA2 [3] collaborations respectively) and of 77 GeV at Fermilab by the CDF collaboration [4]. Recent fits to the Standard Model parameters, including radiative corrections to the W and Z mass, provide an upper limit of $m_t < 200$ GeV [5].

2 Top Signature

Top production at a hadron collider can take place through the electroweak process $p\bar{p} \to W \to t\bar{b}$ or the hard scattering process $p\bar{p} \to t\bar{t}$. For the first process to occur the top mass has to be below the W mass. Figure 1 shows the total cross sections for the two processes [6] at $\sqrt{s} = 0.63$ and 1.8 TeV. At the Tevatron Collider the top production rate through the electroweak process is always lower than that from hard scattering, therefore it is not considered here. The hard scattering cross sections of Figure 1 are obtained by combining the higher order calculations of Nason et al [7], with the structure functions of Diemoz et al.[8], using the method of Altarelli et al. [9]. Uncertainties due to choice of Q^2 scale and Λ_{QCD} are shown by the bands.

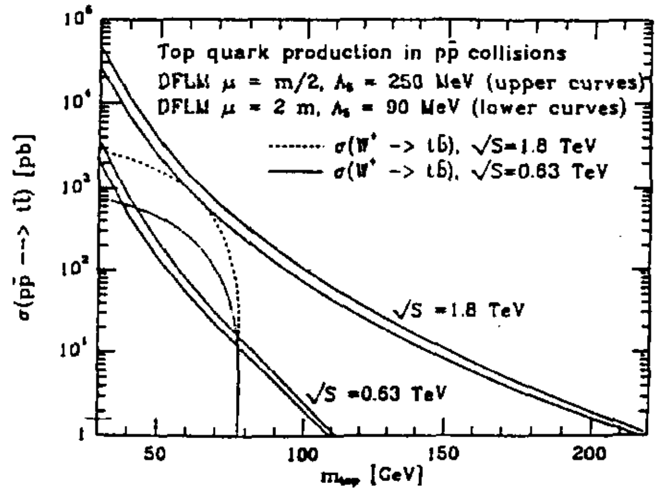

Figure 1: Top pair production cross section versus top mass [6-9]. The bands represent the uncertainty due to μ scale and range in Λ_5. The $W \to t\bar{b}$ cross section is also included. Both Tevatron and CERN energies are shown.

The $t \to Wb$ decay of the top via the weak charged current into a bottom quark and a virtual (real for $m_{top} > m_W + m_b$) W , provides the signatures to be exploited for a top search. In the naive parton model the relative rates for the different top decay modes are

$t\bar{t} \to b\bar{b}$	$+4$ jets	(44.2%)	
$\to b\bar{b}$	$+2$ jets $+ \ell + \nu$	3(14.8%)	
$\to b\bar{b}$	$+\ell_1\nu_1 + \ell_2\nu_2$	3(2.5%)	$\ell_1 \neq \ell_2$
$\to b\bar{b}$	$+\ell_1\nu_1 + \ell_2\nu_2$	3(1.25%)	$\ell_1 = \ell_2$

[1]CDF is a collaboration of the following Institutions: Argonne National Laboratory; Brandeis University; University of Chicago; Fermi National Laboratory; INFN, Laboratory Nazionali di Frascati; Harvard University; University of Illinois; KEK, Japan; Lawrence Berkeley Laboratory; University of Pennsylvania; INFN, University and Scuola Normale Superiore of Pisa; Purdue University; Rockefeller University; Rutgers University; Texas A&M University; University of Tsukuba, Japan; Tufts University; University of Wisconsin.

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The most copious channel is given by the multijet decay mode, but it suffers from severe backgrounds since the QCD multijet production is several orders of magnitude larger. A much cleaner signature consists of high P_T leptons in the event. Leptons from top have large transverse momenta due to the large mass of the top and tend to be isolated, because of the large transverse momentum to the top line of flight. The number of jets in the event is determined by the kinematics and depends on the top mass, i.e., the b jet can have very low momentum and be hardly detected especially for top masses close to m_W, where there is a change from three-body to two-body kinematics.

Backgrounds to leptonic decays of top come from other physics processes and from lepton misidentification. Assuming that misindentification is reduced by proper requirement on the data (see later), there remain the physics backgrounds to take into account. The Drell-Yan process, W, Z production and $b\bar{b}$ pair production are sources of high P_T leptons. These processes have to be understood in order to assess their contribution to the signals. For the lepton+jets final state the major background comes from $b\bar{b}$ and W+jets production. For the dilepton channels it comes from $b\bar{b}$ production and Drell-Yan: for $e\mu$ from $Z^0 \rightarrow \tau\bar{\tau}$, for the ee and $\mu\mu$ final states the Z mass region has to be removed altogether.

3 The CDF detector

The CDF detector [10] is a solenoidal detector with tracking and calorimetry covering almost the full solid angle, and with muon coverage over the central and forward region. We describe here briefly the parts relevant to this analysis.

Charged particle tracking is provided by the Vertex Time Projection Chamber (VTPC) and the Central Tracking Chamber (CTC). The VTPC is located just outside the beam pipe extending to a pseudorapity η = 3.25. Outside the VTPC is a large drift chamber (CTC) that extends to η =1.2 and to a radius of 1.38 m. Both tracking chambers are inside a 1.41 T solenoid which is 5 m. long. The CTC momentum resolution is $\delta(P_T)/P_T = .0017 P_T$ where P_T is in GeV/c.

The calorimetry used for the electron and muon analyses consists of the central electromagnetic (CEM), the central hadron(CHA) and the wall hadron (WHA) calorimeters. These calorimeters are segmented in a projective geometry consisting of towers of 15^0 in azimuth by 0.1 unit of rapidity. The CEM is a lead-scintillator sampling calorimeter with a single layer strip chamber (CES) with cathode and wire readout, located at shower maximum. The hadron calorimeters are steel-scintillator sampling calorimeters. The rest of the calorimeters, plug and forward regions down to η=4.2, consist of many layers of MWPC sandwiched with lead for the EM compartment and steel for the HAD compartment. Their segmentation is of 5^0 by 0.1 units of rapidity. Finally, outside the central calorimeters, are four layers of streamer chambers for muon identification in the region $|\eta| < 0.65$. For this analysis the muon coverage has been extended to $|\eta|$=1.2 by using CTC tracks that appear as minimum ionizing and that are isolated in the calorimeters.

The CDF trigger system has two levels of hardware triggers followed by a software (Level-3) trigger that utilizes a farm of processors running offline-like algorithms. Two of the many triggers are used for this analysis, a. the central "inclusive electron" trigger with P_T > 12 GeV/c and b. the central "inclusive muon" trigger with a 9 GeV/c P_T threshold.

The identification of electrons in the central region uses information from the tracking chambers, the central calorimeters and the strip chambers (CES). The electron/pion separation has been studied in the test beam and verified with data taken at the collider [11] using an unbiased sample of electrons. The efficiency was obtained from a $Z \rightarrow e^+e^-$ and a W sample obtained from the missing E_T trigger, it was found to be $(78 \pm 3)\%$.

Muon identification uses calorimeters, muon chambers as well as tracking chamber (CTC) information. Matching cuts in $r\phi$ are applied to the CTC track and the track segment found in the muon chambers. The calorimeter response in the tower where the muon track points to, must be consistent with minimum ionizing with the additional requirement of isolation for the region beyond the muon chambers coverage. The efficiency for the μ selection was evaluated by using a sample of Z events and found to be $(96 \pm 3)\%$.

4 Searches in the lepton+jets channels

These channels have the largest branching ratios, but also have large backgrounds from $b\bar{b}$ and W+jets events.

The inclusive electron spectrum measured by CDF is shown in Figure 2. The hadronic background is estimated to be $(15 \pm 15)\%$. Most electrons from photon conversion have been removed, the remaining contribution to the background is estimated to be $(12 \pm 7)\%$. Top candidates are obtained by requiring an electron and two or more jets in the event. To remove bottom and W+jets background the following cuts are applied: a. $E_T^e > 20\ GeV$ in the $|\eta| < 1.$ region; b. missing

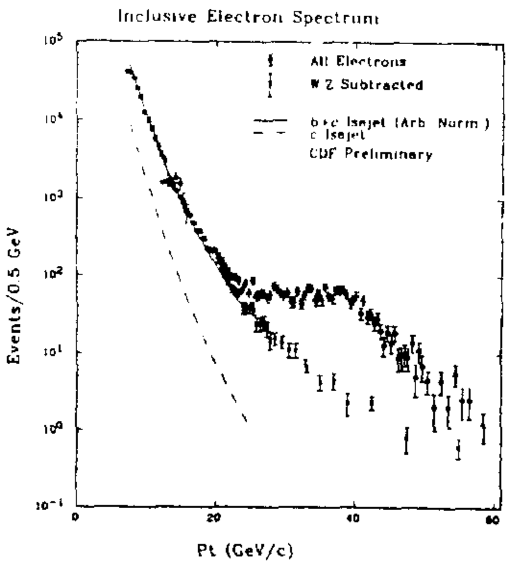

Figure 2: The inclusive electron spectrum for both the 7 and the 12 GeV triggers. The lower set of points represents the spectrum obtained after W and Z subtraction.

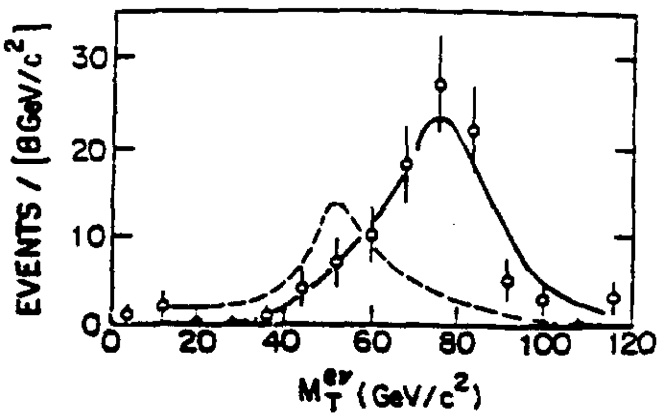

Figure 3: The $e\nu$ transverse mass distributions for the $e + \geq$ 2jets data (points), W +2jets Monte Carlo (solid) and $t\bar{t}$ production with m_t =70 GeV (dashed)[4].

E_T >20 GeV where the energy was added in the $|\eta| <$ 3.6 region; c. two or more jets with uncorrected energy $E_T^{jet} > 10$ GeV. After these selection criteria 104 events remain. The transverse mass distribution $M_T^{e\nu}$ for these events is shown in Figure 3. A top signal would appear as a deviation from the distribution expected for W production. The requirement of $\geq$ 2 jets reduces the W+jets rate considerably, retaining only the high P_T W's. From these data CDF published an upper limit $m_t > 77$ GeV [4].

For $m_t \geq m_W + m_b$ the transverse mass study method is no longer valid as top events become indistinguishable from W events. The second W decays into two jets, but a W peak in the two jet mass is difficult to detect because of large W+jets production as seen in Figure 4. At this time, this is due to lack of statistics more then to jet resolution. For $m_t = 90$ GeV the expected number of events is 20, with a signal/background ratio of about 1/2. In this mass region it is not possible to improve the s/b ratio by requiring more jets. Infact, close to the real W threshold, the kinematics is such that the b jets are very soft and are not measurable. Very few of the 104 events have more than two jets.

To extend the sensititivity to higher top mass, this analysis has been applied to the μ sample where 87 additional events are found. The strategy for separating W+jets from top production is then to search for a low P_T μ from the b quarks. There is no minimum P_T re-

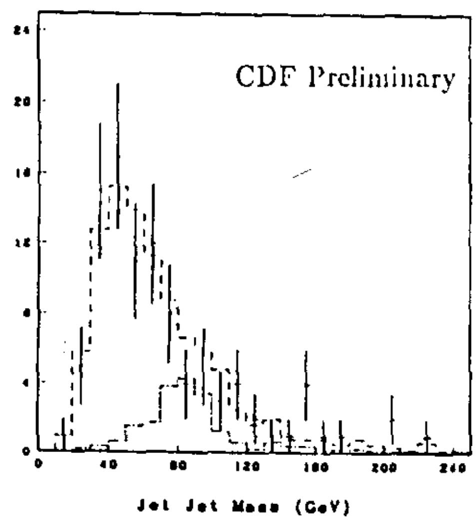

Figure 4: The invariant mass (in GeV) of the two jets in W+$\geq$ 2 jets events as measured by CDF (data points) and as calculated (dashes) by the PAPAGENO Monte Carlo [12]. The dot-dashed histogram represents the expected signal for a 90 GeV top, using the production cross section of Figure 1.

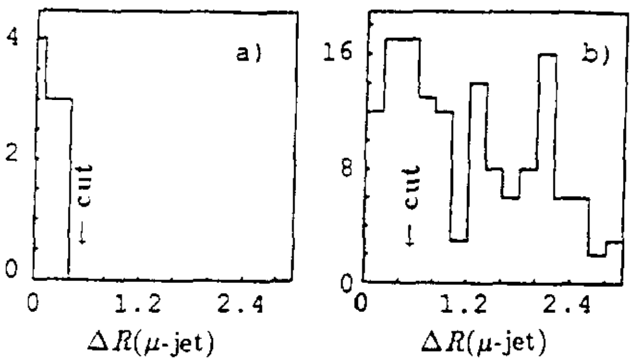

Figure 5: The ΔR between the low energy μ and the closest of the two jets, for (a) the CDF data (preliminary), and (b) a top Monte Carlo with m_t =80 GeV[13].

quirement for the μ, i.e., it is sufficient that it reaches the muon detector ($P_T > 1.6$ GeV/c); a loose ϕ match between the track measured in the central tracking chamber and the μ chambers is required. Preliminary results of this analysis have been reported previously [13].

A total of 13 low P_T μ candidates are found in the 104+87 event sample. Figure 5a shows the distance $\Delta R=\sqrt{\Delta\phi^2+\Delta\eta^2}$ between the μ candidate and the direction of the closest of the two highest energy jets in the event. The μ's are all very close to a jet indicating that they are very likely to be punch-through or decay in flight from pions. A comparison with the expected distribution (Figure 5b) for real decays of b from top, confirms this assessment. The number of events expected for m_t= 80 GeV is 2.3. Requiring a minimum separation $\Delta R > 0.5$, there are no events left. This allows to compute an upper limit on the observed top cross section, once the uncertainties on the acceptance, efficiency of detection, μ spectrum, $b \to \mu$ branching ratio and luminosity are combined with the 95% C.L. limit from Poisson statistics. A limit on the top mass is then obtained by comparing this measured upper limit to the lower bound of the theoretical cross section of Figure 1 (see Sec. 6).

5 Searches in the di-lepton channels

The CDF analysis of the $e\mu$ channel has already been published [14], it gave $m_t > 72$ GeV with 95% C.L. The signature for second W (real or virtual) is provided here by the W decay into a μ or e. To remove bottom background the following cuts are applied: a. $E_T^e > 15$ GeV in the $|\eta| < 1.0$ region, b. $P_T^\mu > 15$ GeV/c in the $|\eta| < 1.2$ region. Figure 6 shows the E_T^e

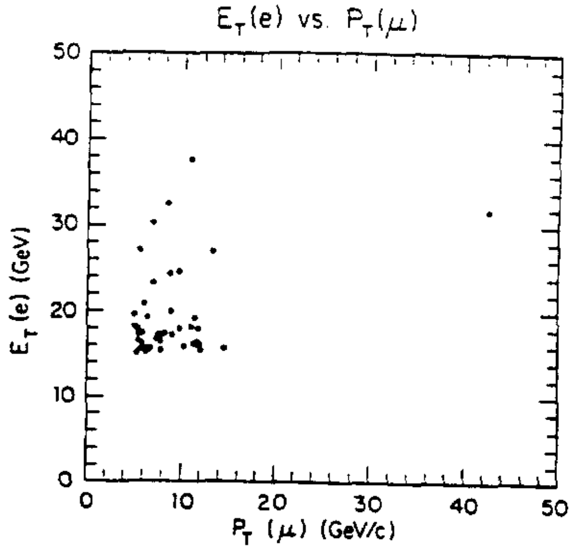

Figure 6: Electron transverse energy vs muon transverse momentum for the CDF $e\mu$ events [14].

vs P_T^μ scatter plot for the $e\mu$ sample. There is one top candidate in the signal region. The calculated background contributions are as follows: one event from $Z^0 \to \tau\bar{\tau}$ and 0.2 events from $Z^0 \to b\bar{b}$. The expected number of events for WW production is 0.15 and for WZ is 0.05. For leptons of such high momenta ($E_T(e) > 30$ GeV and $P_T(\mu) > 40$ GeV/c) the probality of $Z^0 \to \tau\bar{\tau}$ is $\leq 1\%$. The one observed event is thus consistent with background.

In order to increase statistics the ee and $\mu\mu$ channels have been added to the analysis. Preliminary results have been presented [13]. For the channels with two leptons of the same flavor Drell-Yan production contributes considerably to the background. To eliminate Z production additional requirements are imposed: a. events with $M(ll)$ between 75 and 115 GeV are removed, b. missing $E_T > 20$ GeV and c. azimuthal separation of the leptons is in the interval $20^0 < \Delta\phi < 160^0$. This last requirement, in addition to removing Drell-Yan and low P_T Z's, rejects fake muons in which both μ candidates belong to the same jet. Figure 7 shows the $\Delta\phi$ vs missing E_T for the ee candidates after the mass cut requirement has been met. It shows no top candidates in the signal region. There are no top candidates in the $\mu\mu$ channel either, leaving just the one candidate in the $e\mu$ channel. Convoluting the Poisson probability for observing the one event with all the other uncertainties (which are gaussian distributed) on the cross section determination, the curve of Figure 8 is obtained as a function of the top mass. The upper limit is set by the top mass

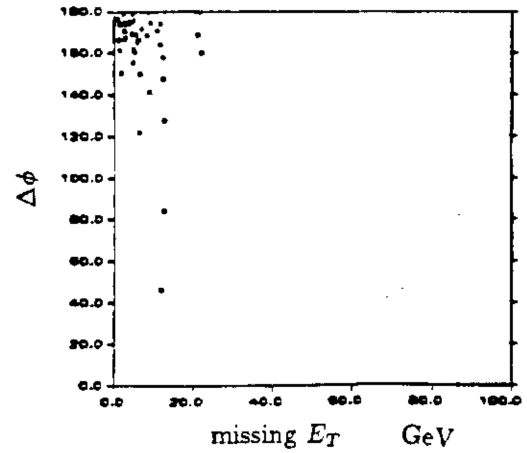

Figure 7: Angle between the two electrons, $\Delta\phi$ vs missing E_T for the di-electron sample.

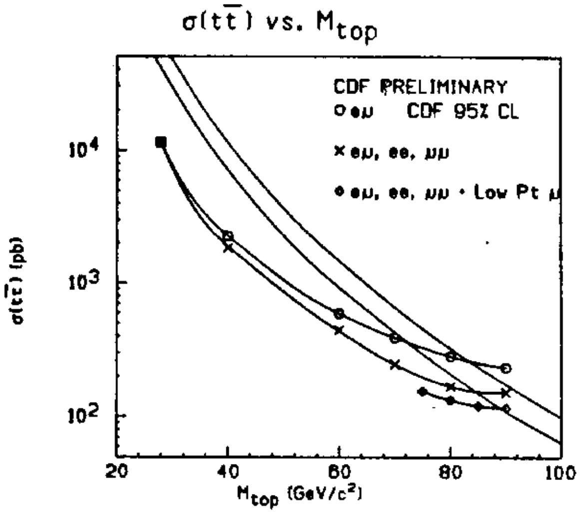

Figure 8: The 95% C.L. upper limit of the top cross section as a function of the top mass, for several sets of CDF data: the published $e\mu$ data[14], the combination of all di-lepton channels and the combination of the di-lepton channels, and the lepton+2jets+low energy μ channnels.

at which the measured upper limit crosses the lowest calculated value of the cross section. The di-lepton channel sets a limit $m_t > 84$ GeV.

6 Summary and Conclusions

Combining the results from the di-lepton channels and the $\ell+$ jets + low P_T muon channels the lowest curve shown in Figure 8 is obtained. Assuming that top decays exclusively via the charged current mode ($t \rightarrow Wb$) the preliminary CDF result [13] thus is:

$$m_t > 89\ GeV \text{ with } 95\% \text{ C.L.}$$

7 References

[1] Average of many experiments. See minireview in Review of Particle Properties, Phys. Lett. B239, 1(1990), for references.

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