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Search for the Top Quark in Dilepton Decay Modes at DØ

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For the DØ Collaboration

Abstract

We present preliminary results on the search for the top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV by the DØ collaboration at the Fermilab Tevatron. The results are based on an integrated luminosity of 13.5 pb^{-1} of data collected by the DØ detector during the 1992-3 Tevatron collider run. We have searched for Standard Model $t\bar{t}$ decays into the dilepton decay modes $ee + X$, $e\mu + X$ and $\mu\mu + X$. No significant signal is observed for top quark production in these channels. We find one candidate event in the $e\mu + X$ channel and no events in the other two channels with an estimated non-top background of 0.76 ± 0.16 events.

1. Introduction

The top quark (t) is one of the few remaining pieces of the Standard Model yet to be experimentally verified. Measurements of the isospin of the b quark [1] and the hadronic width of the Z [2] require the b quark to be the lower mass component of a weak isospin doublet. In the Standard Model its partner the t quark is known, through studies of the decay width of the W boson, to have a mass in excess of $62 \text{ GeV}/c^2$ at 95 % CL [3]. Additional evidence for the large mass of the top quark comes from the analysis of precision electroweak data from LEP and SLC which imply a mass of $m_t = 178 \pm 14_{-19}^{+18} \text{ GeV}/c^2$ [2].

Prior to this conference the most stringent results from direct top quark searches come the two $p\bar{p}$ experiments at the Fermilab Tevatron where strong $t\bar{t}$ pair production is believed to be the dominant production mechanism. Each t quark decays via the semiweak transition $t \rightarrow W + b$ and the experimental searches key on the decays of the W bosons. From such studies the DØ collaboration has published an experimental lower bound on the top quark mass of $m_t > 131 \text{ GeV}/c^2$ at 95 % CL [4] and the CDF collaboration

has shown possible evidence for top quark production at a mass of $174 \pm 10_{-12}^{+13} \text{ GeV}/c^2$ [5, 6]. In this and the two following papers [7, 8], we present the results of a new analysis from the DØ collaboration which focuses on the search for the top quark in the mass region $m_t > 130 \text{ GeV}/c^2$.

This paper concentrates on searches in the three 'dilepton' decay modes: $t\bar{t} \rightarrow ee + \cancel{E}_T + \text{jets}$, $t\bar{t} \rightarrow e\mu + \cancel{E}_T + \text{jets}$ and $t\bar{t} \rightarrow \mu\mu + \cancel{E}_T + \text{jets}$. The following paper [7] describes results of searches in the 'lepton+jet' decay modes: $t\bar{t} \rightarrow e\nu + \text{jets}$ and $t\bar{t} \rightarrow \mu\nu + \text{jets}$ and the third paper [8] describes the result of a search in the decay mode $t\bar{t} \rightarrow e\nu + \text{jets}$ in which a soft muon is used to tag possible b quark jets. The third paper also contains the overall analysis summary and a combined estimate of the top quark production cross-section.

2. The DØ Detector

DØ is a second generation multipurpose detector for the study of $p\bar{p}$ interactions at high luminosity. Its hermetic 4π coverage emphasizes good jet, charged lepton and missing energy measurement which are essential for the search for the decay of high mass top quarks. The detector consists of three subsystems:

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a central tracking system for charged track detection; three large uranium liquid argon calorimeters for electromagnetic and hadronic energy measurement; and a muon spectrometer for muon momentum analysis. A detailed description of the detector and data collection systems is given in reference [9]. Here we summarize the features relevant to the top search.

The calorimeter is a uranium liquid argon sampling detector, contained within three cryostats (one central, two forward) which provide coverage out to pseudorapidity $|\eta| = 4.2$. Its fine lateral and longitudinal granularity ($\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ and 0.05×0.05 at shower maximum) are important for electron, muon and jet identification and isolation measurement. The energy resolution, $\sigma/E \approx 15\%/\sqrt{E}$ for electrons, $\approx 50\%/\sqrt{E}$ for single hadrons, and $\approx 80\%/\sqrt{E}$ for jets (where E is in GeV) [9]. For minimum bias events the resolution for either component of the missing transverse energy, \cancel{E}_T , is $1.1 \text{ GeV} + 0.02 \times (\Sigma E_T)$, where ΣE_T is the scalar sum of all the transverse energy in the calorimeter.

The muon system consists of three layers of chambers, with magnetized iron toroids located between the first and second layers. The innermost layer has 4 planes of proportional wire drift tubes and the second and third layers each have 3 planes. The magnetic field in the iron toroid is 1.9 T, providing momentum measurement with a resolution of $\delta(1/p)/(1/p) = 0.20 \oplus 0.01p$ (where p is in GeV/c). The thickness of the calorimeter plus the iron toroids varies from 14-19 λ and minimizes the background from hadronic punchthrough. In-flight π and K decay background is also negligible because of the compact calorimetry and central tracking volume.

DØ was proposed, reviewed, and approved in 1984. The detector was commissioned with $p\bar{p}$ collisions during the summer of 1992 and began its first physics run in August, 1992. This first run was completed in May, 1993 with a total data sample of 13.5 pb^{-1} written to tape. A second collider run began in January 1994 and the total data sample from this second run is expected to be in excess of 100 pb^{-1} .

3. Particle Identification

The experiment triggers on events with combinations of electron, muon and jet candidates and \cancel{E}_T . The trigger efficiencies are determined from full detector and trigger simulations and vary from 85% to 90% as m_t increases from 140 to 180 GeV/c².

Electron candidates are identified as energy clusters in the calorimeter for which more than 90% of the total energy is contained in the electromagnetic section and which have a matching track in the central tracking system. The clusters are also required to have longitudinal and transverse shower profiles consistent

with Monte Carlo calculations and test beam electron measurements [10]. These are further required to be isolated by requiring that the energy deposited in the annular cone $0.2 < \Delta R < 0.4$ about the electron track be less than 10% of the electromagnetic energy contained in the inner cone of radius $\Delta R < 0.2$.

Muons are identified by tracks in the muon spectrometer and are required to be consistent with the reconstructed vertex position. Additional requirements include a matching minimum ionizing energy deposition in the calorimeter and an isolation cut on calorimeter activity near the muon track. Muons which pass through the transition region between the central and end toroids (and thus through an insufficient amount of magnetic field for good momentum measurement) are rejected by requiring a minimum path length in the magnetized iron toroid of $\int B dl > 1.83 \text{ Tm}$ which corresponds to a p_T kick of 0.55 GeV/c.

Jets are reconstructed using a fixed cone algorithm with cone radius, $\Delta R = 0.5$, where $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$. The reconstructed jet energies are corrected for non-uniformity of the calorimeter response, out-of-cone leakage, noise, and for the underlying event. The missing transverse energy, as determined from the energy deposited in the calorimeter after all corrections, is denoted by $\cancel{E}_T^{\text{cal}}$ and same quantity, after correction for muon momentum is denoted \cancel{E}_T .

4. Dilepton Search

4.1. $t\bar{t} \rightarrow ee + \cancel{E}_T + \text{jets}$

For the ee channel the initial data sample is obtained by requiring two isolated electromagnetic clusters with $E_T > 20 \text{ GeV}$ in the region $|\eta| < 2.5$. After requiring that both clusters match to tracks in the central tracking chamber and that at least one track be consistent with a single minimum ionizing particle, an initial sample of 739 events is obtained. To reduce backgrounds from $Z \rightarrow ee$, a cut is made on the dielectron mass: $|M_{ee} - M_Z| > 12 \text{ GeV}/c^2$ if $\cancel{E}_T < 40 \text{ GeV}$; 111 events remain after this cut. To eliminate background from QCD and the Drell-Yan continuum, an additional cut of $\cancel{E}_T > 25 \text{ GeV}$ is imposed, leaving 4 events. Finally, to reduce backgrounds from diboson (WW, WZ) events and $Z \rightarrow \tau\tau$ decays, we require two hadronic jets with $E_T > 15 \text{ GeV}$ in the region $|\eta| < 2.5$. No events survive after this cut. To illustrate the basic features of the data, Fig. 1 shows the distribution of \cancel{E}_T vs. M_{ee} for data and $t\bar{t}$ Monte Carlo ($m_t = 160 \text{ GeV}/c^2$ after making the initial electron E_T and the final jet cuts).

The acceptance for $t\bar{t} \rightarrow ee$ decays is studied using samples of $m_t = 140, 160$ and $180 \text{ GeV}/c^2$ Monte Carlo events which were generated using ISAJET [11] and put through the full DØ detector simulation and

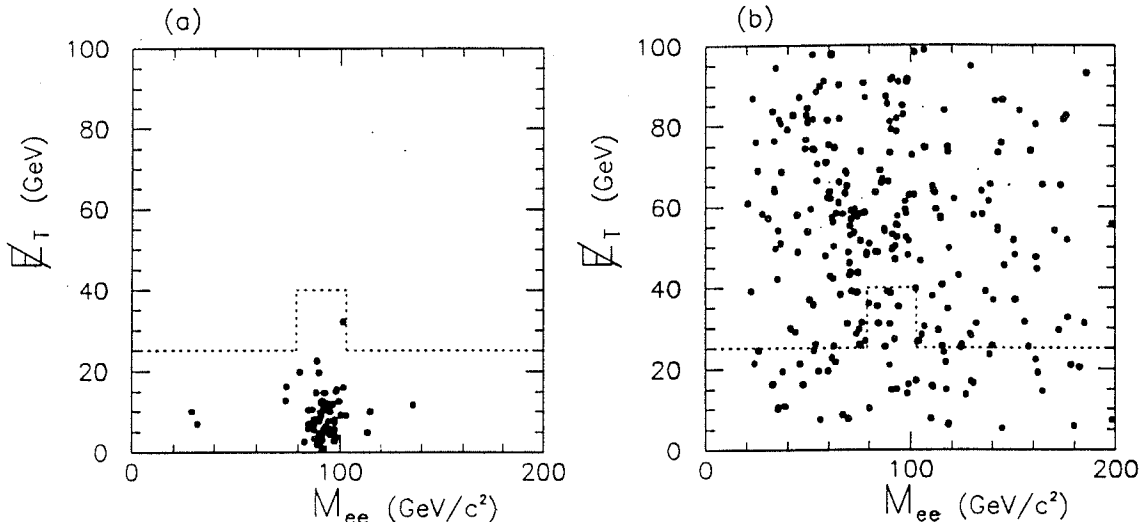


Figure 1. Scatter plots of E_T^{miss} vs M_{ee} after all but the E_T^{miss} cuts for ee events from (a) data, and (b) $t\bar{t} \rightarrow ee$ MC ($m_t = 160 \text{ GeV}/c^2$ and $\int \mathcal{L} dt \approx 19 \text{ fb}^{-1}$).

reconstruction. After making small corrections to the electron efficiencies to account for the differences between simulation and data, the expected top event yields vary from 0.41 ± 0.07 to 0.12 ± 0.02 events as m_t is changed from $140 \text{ GeV}/c^2$ to $180 \text{ GeV}/c^2$ for an integrated luminosity of 13.5 pb^{-1} . This is based on the central QCD cross sections of Laenen *et al* to NLO with soft gluon summation [12].

Estimation of non-top background is based on Monte Carlo and data studies. The sources considered include the Drell-Yan continuum, $Z \rightarrow ee$, $Z \rightarrow \tau\tau$, $Z \rightarrow b\bar{b}$ and $c\bar{c}$, strong production of $b\bar{b}$ and $c\bar{c}$, WW , WZ , W + jets, Z + jets, and fake leptons. The dominant contributions come from $Z \rightarrow \tau\tau$ (0.05 events), misidentified electrons (0.05 events) and $Z \rightarrow ee$ (0.03 events). Combining all sources gives a total expected background of 0.16 ± 0.07 events.

4.2. $t\bar{t} \rightarrow e\mu + E_T^{\text{miss}} + \text{jets}$

The initial $e\mu$ data set is selected by requiring an isolated electron with $E_T > 15 \text{ GeV}$ in the region $|\eta| < 2.5$ and an isolated muon with $p_T > 12 \text{ GeV}/c$ and $|\eta| < 1.7$. For the electron we impose all of the cuts used in the ee analysis except for the single minimum ionizing particle requirement. 12 events satisfy these criteria. Backgrounds from $Z \rightarrow \tau\tau$ and QCD/ $Z \rightarrow b\bar{b}$ and $c\bar{c}$ are suppressed by making a cut on the missing transverse energy: $E_T^{\text{miss}} > 10 \text{ GeV}$; 8 events remain after this cut. To eliminate misidentification background from W + jets $\rightarrow \mu$ + jets events in which one of the jets fakes an electron, a cut is made on the vector energy

imbalance in the calorimeters, $E_T^{\text{cal}} > 20 \text{ GeV}$. This cut is particularly useful since for $W \rightarrow \mu\nu$ events, E_T^{cal} is a direct measure of the W transverse momentum. To reject backgrounds due to muon bremsstrahlung (where the outgoing muon radiates a photon which is matched to the muon track in the central tracking chamber), a cut is made on the opening angle, ΔR , between the muon and “electron”: $\Delta R^{e\mu} > 0.25$. This leaves 7 events. Lastly, to reduce backgrounds from WW , WZ , and $Z \rightarrow \tau\tau$ we imposed the same two jet requirements as were used for the ee channel. One event survives this final cut. Figures 2a and 2b show the distribution of $1/p_T^\mu$ vs E_T^e for the data and $t\bar{t}$ Monte Carlo ($m_t = 170 \text{ GeV}/c^2$) prior to the final jet cuts. The surviving $e\mu$ candidate is marked by a \star in Fig. 2a.

The high mass $t\bar{t} \rightarrow e\mu$ acceptance is studied using Monte Carlo event samples generated using ISAJET [11] and put through a full simulation of the DØ detector and trigger system. After folding the resulting acceptances with the Laenen *et al.* production cross section [12] we obtain predicted event yields which vary from 0.72 ± 0.16 to 0.23 ± 0.05 as m_t is varied from $140 \text{ GeV}/c^2$ to $180 \text{ GeV}/c^2$.

The corresponding non-top background has been estimated using a combination of Monte Carlo calculations and data measurements. Among the sources investigated are $Z \rightarrow \tau\tau$, $b\bar{b}$ and $c\bar{c}$ production in Z decays and QCD multijet events, WW , WZ , and W (or Z) + jet events in which one of the jets fakes a lepton. The dominant contributions come from $Z \rightarrow \tau\tau$ (0.18 events), and W + jets $\rightarrow \mu$ + jet (fake e) + jets (0.05 events).

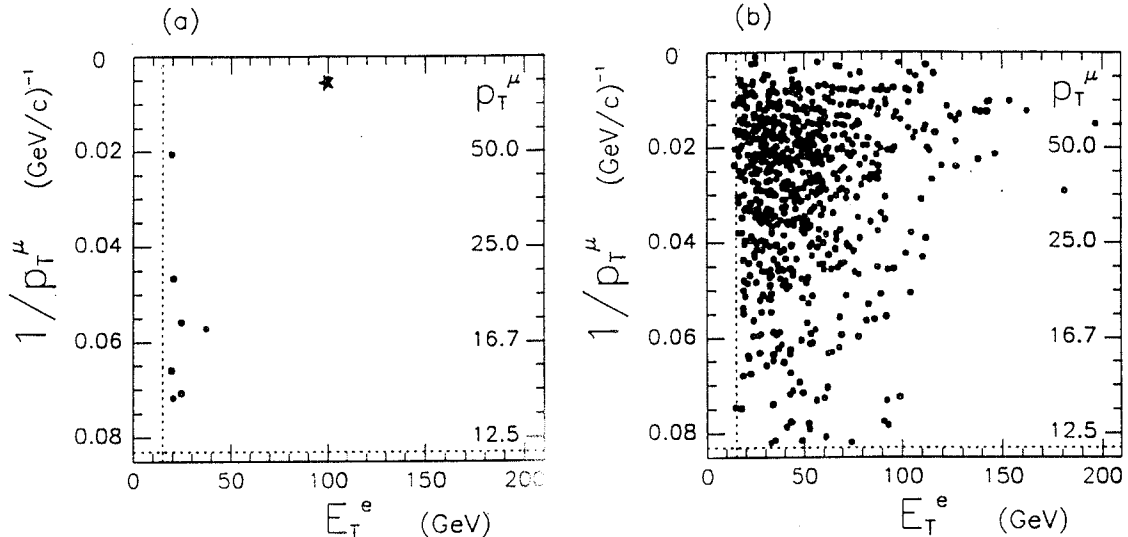


Figure 2. Scatter plots of $1/p_T^\mu$ vs E_T^e prior to final (jet) cut for $e\mu$ events from (a) data, and (b) $t\bar{t} \rightarrow e\mu$ MC ($m_t = 170$ GeV/c² and $\int \mathcal{L} dt \approx 21$ fb⁻¹).

Combining these with other smaller sources gives a total background of 0.27 ± 0.09 events.

4.3. $t\bar{t} \rightarrow \mu\mu + \cancel{E}_T + \text{jets}$

The $\mu\mu$ analysis uses the 9.8 pb⁻¹ subset of the full dataset for which the $t\bar{t} \rightarrow \mu\mu$ trigger was optimized. The initial event sample was selected by requiring two isolated muons with $p_T > 15$ GeV/c in the region $|\eta| < 1.1$. To remove background from $J/\psi \rightarrow \mu\mu$ decays an additional cut on dimuon invariant mass: $M_{\mu\mu} > 10$ GeV/c² is imposed, giving an initial sample of 13 events. Similar cuts in the region of the Z mass to exclude $Z \rightarrow \mu\mu$ decays are not possible because of the poor momentum resolution at large values of p_T . To exclude these backgrounds we exploit the topological differences between $t\bar{t} \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ decays. Events in which the leading muon is mismeasured leading to fake \cancel{E}_T are removed by requiring the azimuthal opening angle between the \cancel{E}_T and leading muon p_T to be $< 170^\circ$. 10 events survive this cut. Next we exclude events in which one or both muons are significantly mismeasured by requiring that the azimuthal opening angle between the calorimeter energy imbalance ($\cancel{E}_T^{\text{cal}}$) and dimuon transverse momentum vectors be at least 30° . This strongly suppresses mismeasured $Z \rightarrow \mu\mu$ decays for which these quantities both measure the p_T of the Z ; 5 events remain after this cut. Further background rejection is achieved by requiring a minimum of 40 GeV \cancel{E}_T for those events in which the azimuthal opening angle between the two muons is $> 140^\circ$; 2 events remain after this cut. Lastly to reduce backgrounds

from WW , WZ , and ZZ decays we imposed the same two jet requirement as is used for the other two channels. No events survive after this cut. To illustrate the basic features of the data Figs. 3a, 3b and 3c show the distribution of $\Delta\phi^{\mu\mu}$ vs. \cancel{E}_T for the data and samples of $Z \rightarrow \mu\mu$ and $t\bar{t}$ Monte Carlo, respectively.

The acceptance for $t\bar{t} \rightarrow \mu\mu$ decays is studied using Monte Carlo event samples generated using ISAJET [11] and put through a full simulation of the DØ detector and trigger system. After folding the resulting acceptances with the Laenen *et al.* production cross section [12] we obtain predicted event yields which vary from 0.24 ± 0.05 to 0.06 ± 0.01 as m_t is varied from 140 GeV/c² to 180 GeV/c².

The corresponding non-top background has been estimated using a combination of Monte Carlo calculations and data measurements. This is dominated by background from $Z \rightarrow \mu\mu$ decays (0.32 events). The contributions from other processes such as WW , WZ , ZZ , and Drell-Yan continuum production are very small. Combining these and other small contributions gives a total background of 0.36 ± 0.06 events.

4.4. Combined Results

Taking the three channels together, we observe one event candidate ($e\mu$ channel) with an estimated non-top background of 0.76 ± 0.16 events. We therefore observe no significant signal for top quark production in the present data. If we interpret the small excess over background to a possible $t\bar{t}$ signal the event yield is consistent with the expectations for a top quark

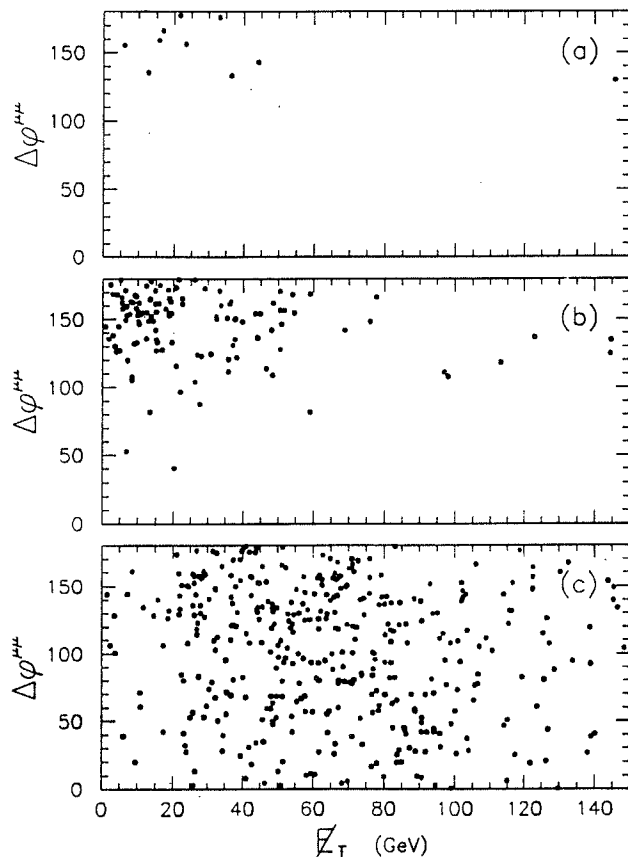


Figure 3. Scatter plots of $\Delta\phi^{\mu\mu}$ vs. p_T^Z after the initial selection cuts for $\mu\mu$ events from (a) data, (b) $Z \rightarrow \mu\mu$ MC ($\int \mathcal{L} dt \approx 110 \text{ pb}^{-1}$) and (c) $t\bar{t} \rightarrow \mu\mu$ MC ($m_t = 160 \text{ GeV}/c^2$ and $\int \mathcal{L} dt \approx 21 \text{ fb}^{-1}$).

with mass above the present DØ mass limit of $131 \text{ GeV}/c^2$. It is also consistent with the QCD cross section calculations of Laenen *et al.* [12] which give yields of between 1.37 ± 0.24 and 0.41 ± 0.07 events as the m_t is varied between $140 \text{ GeV}/c^2$ and $180 \text{ GeV}/c^2$. The data are also consistent with the yield corresponding to the measured CDF cross section of 13.9 pb [5] which gives a prediction of 1.13 ± 0.49 events.

Further study of the surviving $e\mu$ event shows that it is difficult to explain in terms of the expected non-top backgrounds. Both leptons have transverse momentum well above the selection cuts ($E_T^e \approx 100 \text{ GeV}$ and $p_T^\mu \approx 200 \text{ GeV}/c$). In addition it has two jets of $E_T = 25$ and 22 GeV , respectively and $p_T^Z \approx 120 \text{ GeV}$. The $Z \rightarrow \tau\tau$ hypothesis (dominant background) is kinematically excluded and although the lepton transverse momenta are large, the overall likelihood for this event agrees well with expectations for SM top production with a mass of $\approx 150 \text{ GeV}/c^2$ [4, 13, 14].

5. Conclusions

Using the full data sample of the 1992/3 collider run DØ has performed a search dilepton events consistent with the decay of a Standard Model top quark with large mass ($m_t \geq 130 \text{ GeV}/c^2$). We observe one event in the $e\mu$ channel and no events in either the ee or $\mu\mu$ channels. This is the same $e\mu$ event as was found in the previous top search [4].

For a preliminary analysis of the non-top background and the expectations for $t\bar{t}$ production we observe no significant signal for top quark production. The observed event rate is consistent with a null signal and both the expected event yield for a high mass top quark [12] and the production cross section reported by the CDF collaboration [5].

6. References

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