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# Results on Top Quark Production from DØ

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# Results on Top Quark Production from DØ*

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## Abstract

The DØ Collaboration reports on a search for the Standard Model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron, with an integrated luminosity of approximately 50 $pb^{-1}$. We have searched for $t\bar{t}$ production in the dilepton and single lepton channels with and without tagging of *b* quark jets. We observe 17 events with an expected background of $3.8 \pm 0.6$ events. The probability for an upward fluctuation of the background to produce the observed signal is $2 \times 10^{-6}$ (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measure its mass to be $199^{+19}_{-21}$(stat.)$\pm$ 22 (syst.) GeV/$c^2$ and its production cross section to be $6.4 \pm 2.2$ pb.

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## 1 Introduction

The Standard Model requires the $b$ quark to have a weak isospin partner, the hitherto unobserved top quark. The search for the top quark and measurement of its properties are important tests of the Standard Model. Parameters such as $m_W$ $m_Z$, $sin^2\theta_W$ and the $Z$ boson decay asymmetry depend on the mass of the top quark, and to a lesser extent the Higgs boson mass, through radiative corrections involving top quark loops. Precision measurements of these parameters permit an indirect measurement of the top quark mass, $m_t$ which can be compared to that obtained by direct measurement. These measurements currently suggest a top quark mass in the range 150-210 GeV/$c^2$ [1].

The most sensitive direct searches for the Standard Model top quark have been carried out at the Fermilab Tevatron by the DØ and CDF experiments. Recent results from these experiments, based on data from the 1992-1993 Tevatron run include a lower limit of 131 GeV/$c^2$ on $m_t$ by DØ [2], and 1.9$\sigma$ and 2.8$\sigma$ positive results by the DØ [3] and CDF [4] Collaborations, respectively.

In this paper we assume that the top quark is pair-produced and decays 100% of the time into a $W$ boson and a $b$ quark. The search is divided into seven distinct channels depending on how the two $W$ bosons decay and on whether or not a non-isolated muon from a $b$ or $c$ quark semileptonic decay is observed. The so-called "dilepton channels" occur when both $W$ bosons decay leptonically ($e\mu + jets$, $ee + jets$ and $\mu\mu + jets$). The "single lepton channels" occur when just one $W$ boson decays leptonically ($e + jets$ and $\mu + jets$). These are subdivided into ":$b$-tagged" and "untagged" channels according to whether or not a muon is observed consistent with $b \rightarrow \mu + X$. The tagged channels are denoted $e$ + jets/$\mu$ and $\mu$ + jets/$\mu$ for the electronic and muonic $W$ decay modes, respectively. The data set for this analysis includes the data from Ref.3 and additional data from the current Tevatron run, giving an integrated luminosity of about 50 $pb^{-1}$ with slight differences among the seven channels. The new results from DØ reported here increase the significance of the top quark signal to > 4$\sigma$ [5]. Similar results from CDF have also been presented at this meeting [6].

## 2 Particle Identification

The DØ detector and data collection systems are described elsewhere [7]. Here we summarize the features of the particle detection and identification relevant to this analysis.

Muons are detected and their momentum is measured using an iron toroid spectrometer located outside of a uranium-liquid argon calorimeter and a non magnetic central tracking system inside the calorimeter. Muons are identified by their ability to penetrate the calorimeter and the spectrometer magnet yoke. Two distinct types of muons are defined. "High-$p_T$" muons, which are predominantly from gauge boson decay, are required to be isolated from jet axes by a distance $\Delta R > 0.5$ in $\eta$-$\phi$ space ($\eta$ = pseudorapidity, $\phi$ = azimuthal angle), and to have transverse momentum $p_T > 12$ GeV/c. "Non-isolated" muons, which are primarily from $b$, $c$ or $\pi/K$ decay, are required to be within a distance $\Delta R < 0.5$ of any jet axis. The minimum $p_T$ for soft muons is 4 GeV/c. The maximum $\eta$ for both kinds of muons is 1.7 for the data from Ref. [5] and 1.0 for the data from the current run, where a tighter cut is imposed to exclude data, sensitive to the effects of forward muon chamber aging.

Electrons are identified by their longitudinal and transverse shower profiles in the calorimeter and are required to have a matching track in the central or forward tracking chambers. The background from photon conversions is suppressed by an ionization ($dE/dx$) criterion on the chamber track. A transition radiation detector is used to confirm the identity of electrons for $|\eta| < 1$. Electrons are required to have $|\eta| < 2.5$ and a transverse energy $E_T > 15$ GeV.

Jets are reconstructed using a cone algorithm with a radius R = 0.5 and are required to have $|\eta| < 2.5$ and transverse energy $E_T > 15$ GeV.

The presence of neutrinos in the final state is inferred from the missing transverse energy ($\not{E}_T$). The calorimeter-only $\not{E}_T$ ($\not{E}_T^{cal}$) is determined from the energy deposition in the calorimeter for $|\eta| < 4.5$. The total $\not{E}_T$ is determined by correcting $\not{E}_T^{cal}$ for the measured $p_T$ of the detected muons.

## 3 Measurement of the Production Cross Section

The event selection has been chosen to give the maximum expected significance for top quarks with mass 180-200 GeV/c$^2$, using the ISAJET event generator [8] to model the top quark signal, the top quark pair production cross section of Ref. [9] and the background estimates described below. In this analysis we achieve a signal-to-background ratio of better than 1:1 for a top quark mass of 200 GeV/c$^2$. This is a better ratio, but with smaller acceptance than our previous analyses [2,4]. The improved rejection arises primarily from the introduction of a requirement on the minimum transverse energy by means of a cut on the quantity $H_T$. We define $H_T$ to be the scalar sum of the jet $E_T$'s (for the single lepton and dimuon channels) or the scalar sum of the $E_T$'s of the leading electron and the jets (for the $e\mu$ and $ee$ channels). This variable is a powerful discriminator between the backgrounds and high mass top quark production. We have verified our understanding of $H_T$ distributions using comparisons of measurements and calculations of background-dominated event samples such as $e$ + $\not{E}_T$ + *two or three jets* [5]. For the predicted $H_T$ spectra we use a combination of calculations of $W+jets$ production using the VECBOS Monte Carlo [10] and measurements of QCD multijet production taken from data. As a further cross check to our "standard" event selection we also retain a "loose" selection in which the cuts on $H_T$ have been removed.

The signature for the dilepton channels is defined as two isolated leptons in association with two or more jets and large $\not{E}_T$. The signature for the single lepton channels is defined as one isolated lepton, a large $\not{E}_T$, and three or more jets (with muon tag) or four or more jets (without muon tag). The single lepton signature also requires either a soft muon $b$-tag or a "topological" tag based on the values of $H_T$ and the aplanarity, A of the jets. "Double-tagged" events are counted only once, as part of the muon tagged channels. The selection cuts are summarized in Table 1.

Additional cuts are used in the $ee$, $\mu\mu$ and $\mu+jets/\mu$ channels to remove backgrounds from events containing large $p_T$ $Z$ boson decays. For the $ee$ channel we require that $|m_{ee}-m_Z| > 12$ GeV/c$^2$ or $\not{E}_T^{cal} > 40$ GeV to remove $Z \rightarrow ee$ decays. For the $\mu\mu$ channel the event as a whole is required to be inconsistent with $Z+jets$ based on a global kinematic fit. The loose event selection cuts differ from those listed in Table 1 by the removal of the $H_T$ requirement and by the relaxation of the aplanarity cut on the $e+jets$ and $\mu+jets$ channels to A > 0.03. This has the effect of increasing the predicted background by approximately a factor of five.

| Channel | High $p_T$ $e/\mu$ | | Jets | | Missing $E_T$ | | Tag $\mu$ | Topological | |
|---|---|---|---|---|---|---|---|---|---|
| | $E_T^e$ | $p_T^\mu$ | $N_{jet}$ | $E_T^{jet}$ | $E_T^{cal}$ | $E_T$ | $p_T^\mu$ | $H_T$ | A |
| $e\mu+jets$ | 15 | 12 | 2 | 15 | 20 | 10 | - | 120 | - |
| $ee+jets$ | 20 | | 2 | 15 | 25 | - | - | 120 | - |
| $\mu\mu+jets$ | | 15 | 2 | 15 | - | - | - | 100 | - |
| $e+jets$ | 20 | | 4 | 15 | 25 | - | - | 200 | 0.05 |
| $\mu+jets$ | | 15 | 4 | 15 | 20 | 20 | - | 200 | 0.05 |
| $e+jets/\mu$ | 20 | | 3 | 20 | 20 | - | 4 | 140 | - |
| $\mu+jets/\mu$ | | 15 | 3 | 20 | 20 | 20 | 4 | 140 | - |

Table 1: Minimum kinematic requirements for the standard event selection ( energy in GeV ).

The acceptance for $t\bar{t}$ events has been calculated using the ISAJET generator [8] and a detector simulation based on the GEANT program [11]. As a check, the acceptance was also calculated using the HERWIG event generator [12]. The difference between ISAJET and HERWIG is included in the systematic error.

For the dilepton channels, the main backgrounds were from $Z$ and continuum Drell-Yan production ($Z$, $\gamma^* \to ee$, $\mu\mu, \tau\tau$), vector boson pairs ($WW$, $WZ$), heavy flavor ($b\bar{b}$ and $c\bar{c}$) production, and backgrounds with jets misidentified as leptons. For the single lepton channels, the main backgrounds were from $W+jets$, $Z+jets$, and multijet production with a jet misidentified as a lepton. The methods for estimating these backgrounds are the same as in Ref.'s [4,5] and use a combination of data and Monte Carlo calculations.

| | Standard Cuts | Loose Cuts |
|---|---|---|
| Dileptons | 3 | 4 |
| Lepton + Jets (Shape) | 8 | 23 |
| Lepton + Jets ($\mu$ tag) | 6 | 6 |
| All Channels | 17 | 33 |
| Background | $3.8 \pm 0.6$ | $20.6 \pm 3.2$ |
| Probability | $2 \times 10^{-6}$ (4.5 $\sigma$) | 0.023 (2.0 $\sigma$) |
| $\sigma_{t\bar{t}}$ ($m_t$ = 200 GeV/c$^2$) | $6.4 \pm 2.2$ pb | $4.5 \pm 2.5$ pb |

Table 2 : Summary of observed event yields, the predicted backgrounds and the top quark production cross section for the standard and loose cut data samples.

Using our standard cuts we observe a total of 17 events with an expected background of 3.8 ± 0.6 events (see Table 2). The corresponding cross section as a function of $m_t$ is shown in Fig. 1. Assuming a top quark mass of 200 GeV/c$^2$ the corresponding production cross section is 6.3 ± 2.2 pb where the error includes an overall 12 % uncertainty in the luminosity. The probability for a background fluctuation to 17 events is $2 \times 10^{-6}$, which corresponds to 4.6$\sigma$ in the case of Gaussian probability distribution. We have calculated the probability for our observed distribution of excess events among the seven channels and find that the results are consistent with the predicted top quark branching fractions at the 53 % CL. As a check of the background estimation, the cross section was recalculated using the 33 event loose cut sample and we obtained essentially the same result. We therefore conclude that we have observed a statistically significant signal which is consistent with top quark production. Additional analysis of the kinematic properties of the data also supports the conclusion that we have observed the top quark [5].

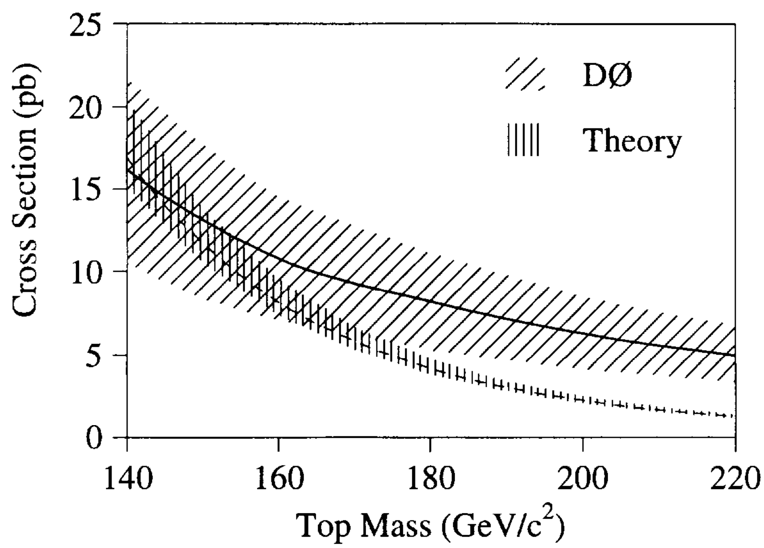


Figure 1: DØ measured $t\bar{t}$ production cross section (solid line with one standard deviation error band) as a function of assumed top quark mass. Also shown is the theoretical cross section curve (dashed line) [9].

## 4 Determination of the Top Quark Mass

To measure the top quark mass, single lepton + four jet events were subjected to 2-constraint kinematic fits to the hypothesis $t\bar{t} \to W^+W^-b\bar{b} \to l\nu q\bar{q}b\bar{b}$. The fits were performed on all permutations of the jet assignments of the four highest $E_T$ jets, with the provision that muon-tagged jets were always assigned to a $b$ quark in the fit. Up to three permutations with $\chi^2 < 7$ (two degrees of freedom) were retained, and a single $\chi^2$-probability-weighted average mass ("fitted mass") was calculated for each event. Monte Carlo studies using ISAJET and HERWIG have shown that the fitted mass is strongly correlated with the true top quark mass. The effects of gluon radiation, jet assignment combinatorics, and the event selection procedure result in a mass-dependent shift between $m_t$ and the fitted mass which is taken into account in the final mass determination [13].

Eleven of the 14 single lepton + jet events selected using the standard cuts and 24 of the 27 events selected with the loose cuts were fitted successfully. The fit may fail because there are fewer than four reconstructed jets (in the case of b-tagged events), or because there are no solutions with a good $\chi^2$. The resulting fitted mass and likelihood distributions for these events are shown in Fig. 2. An unbinned likelihood fit, incorporating top quark and background contributions, with the value of $m_t$ allowed to vary, was performed on the fitted mass distributions. This gives a top quark mass of $199^{+31}_{-25}$(stat.) GeV/c$^2$ for the standard cuts and $199^{+19}_{-21}$(stat.) GeV/c$^2$ for the loose cuts. The result of the likelihood fits do not change significantly if the background normalization is left free or constrained in the fit. Because of its smaller error, we use the loose cuts fit for our final result.

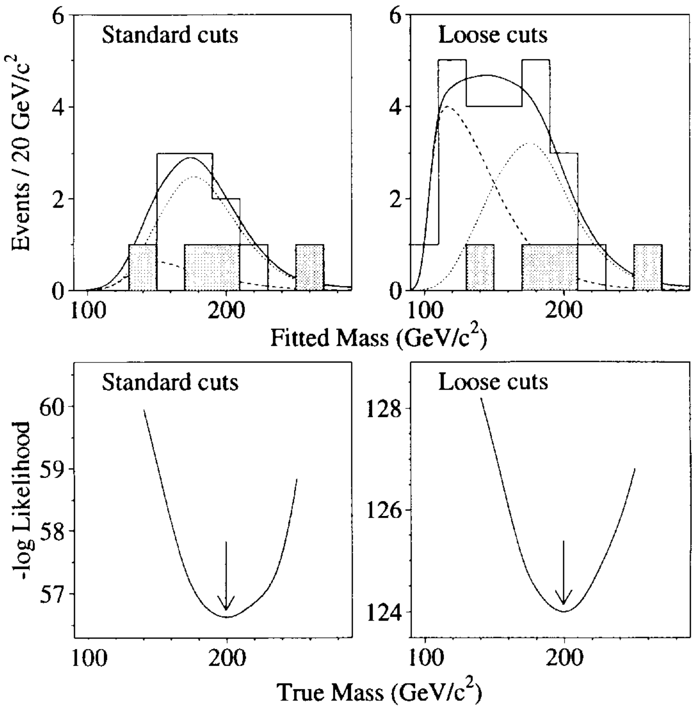


Figure 2: Fitted mass and likelihood distributions for the standard and loose cut event samples. The shaded events have a non-isolated muon tag.

The systematic error on the mass determination is dominated by the jet energy scale uncertainty. We estimate this to be 10 % or less and determine the corresponding error in $m_t$ by varying the jet energies by ± 10 % and observing the shift in $m_t$. The top mass measurement also depends on having an event generator which realistically models effects such as gluon radiation and jet shapes. We estimate this uncertainty by comparing results obtained using ISAJET and HERWIG. Repeating all of the corrections using HERWIG results in a decrease of 4 GeV/c$^2$ in the value of $m_t$. We include this difference in the total systematic error on $m_t$ but it has little effect when combined in quadrature with the 11 % from the jet energy scale. The total systematic error on $m_t$ is 22 GeV/c$^2$.

## 5 Conclusions

We have searched for top quark signals in seven channels in a data sample having an integrated luminosity of 50 $pb^{-1}$. We observe 17 candidate events with an expected background of $3.8 \pm 0.6$ events. The probability for the background to fluctuate up to 17 events is $2 \times 10^{-6}$, which corresponds to $4.6\sigma$ in the case of Gaussian errors. From these events we measure the top quark mass to be $199^{+19}_{-21}$(stat.) $\pm$ 22(syst.) GeV/$c^2$. Using the acceptance calculated for our central top quark mass, we measure the top quark pair production cross section to be $\sigma_{t\bar{t}} = 6.4 \pm 2.2$ pb.

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