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DØ Note 2527

TOP QUARK RESULTS FROM D-ZERO

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We report 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 decay channels, with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. 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.) ± 22 (syst.) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb. We discuss a multivariate analysis of $t\bar{t} \to e + \text{jets}$ events.

1. Introduction

In the Standard Model (SM), the top quark is the weak isospin partner of the b quark. Precision electroweak measurements predict a top quark mass of approximately 150–210 GeV/c^2, depending on the mass of the Higgs boson.[1] Recently both the DØ Collaboration and the CDF Collaboration have reported the observation of the top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron.[2,3] In this paper, we present results on the top quark from the DØ experiment, obtained with both conventional and multivariate analysis techniques.

We assume that the top quark is produced in pairs and decays according to the minimal SM, *i.e.* $t\bar{t} \to W^+W^-b\bar{b}$. We have searched for the top quark in the dilepton channels where both W bosons decay leptonically ($e\mu + \text{jets}$, $ee + \text{jets}$, and $\mu\mu + \text{jets}$) and in the single-lepton channels where just one W boson decays leptonically (e+jets and μ+jets). The SM branching fractions are 2/81 for the $e\mu$ channel, 1/81 each for the ee and $\mu\mu$ channels, and 12/81 for each of the two single-lepton channels. The single-lepton channels were further subdivided into b-tagged and untagged channels according to whether or not a muon was observed consistent with the decay $b \to \mu + X$. The muon-tagged channels are denoted as $e + \text{jets}/\mu$ and $\mu + \text{jets}/\mu$.

The present analysis is based on data collected at the Fermilab Tevatron at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of approximately 50 pb^{-1}. The DØ detector and data collection system are described in Ref. 4. The triggers and reconstruction algorithms for jets, electrons, muons, and neutrinos were the same as those used in our previous top quark searches.[5,6]

2. Conventional Analysis

2.1. *Dilepton events*

The signature for the dilepton channels is a final state containing two isolated high p_T leptons ($e\mu$, ee, or $\mu\mu$), at least two jets, and large missing transverse energy $\not\!\!E_T$ due to undetected neutrinos. The main physics backgrounds arise from Z and continuum Drell-Yan production ($Z, \gamma^* \to ee, \mu\mu$, and $\tau\tau$), vector boson pairs ($WW \to e\mu\nu\nu, ee\nu\nu$, and $\mu\mu\nu\nu$, and $WZ \to e\mu X, eeX$, and $\mu\mu X$), and heavy flavor production ($b\bar{b}$ and $c\bar{c} \to e\mu X, eeX$, and $\mu\mu X$). These backgrounds were estimated by Monte Carlo simulation or from a combination of Monte Carlo and data. Instrumental backgrounds arising from highly electromagnetic jets misidentified as electrons were estimated entirely from the data. The expected number of $t\bar{t}$ events was calculated using the ISAJET event generator[7] and a detector simulation based on the GEANT program.[8]

The kinematic requirements for our standard event selection are summarized in Table 1. The variable H_T is defined as the scalar sum of the transverse energies E_T of the leading electron and the jets (for the ee and $e\mu$ channels) or as the scalar sum of the jet E_T's (for the $\mu\mu$ channel). H_T is a powerful discriminator between background and high-mass top quark production, as shown in Fig. 1.

In the dilepton channels, we observe 2 $e\mu$ events, 0 ee events, and 1 $\mu\mu$ event passing our selection criteria. The estimated backgrounds are 0.12 ± 0.03, 0.28 ± 0.14, and 0.25 ± 0.04, respectively.

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

Channel	Leptons $E_T(e)$	$p_T(\mu)$	Jets $N_{\rm jet}$	E_T	$\not\!\!E_T$	H_T	$\mathcal{A}$
$e\mu$ + jets	15	12	2	15	20	120	-
ee + jets	20		2	15	25	120	-
$\mu\mu$ + jets		15	2	15	-	100	-
e + jets	20		4	15	25	200	0.05
μ + jets		15	4	15	20	200	0.05
e + jets/μ	20		3	20	20	140	-
μ + jets/μ		15	3	20	20	140	-

2.2. *Lepton + jets events*

The signature for the single-lepton channels is a final state with one isolated high pt lepton (e or μ), large $\not\!\!E_T$, and at least four jets. The important backgrounds are W + jets and QCD multijet production with a jet misidentified as an isolated lepton. The latter events do not normally have large $\not\!\!E_T$. We estimated the multijet background directly from data, based on the joint

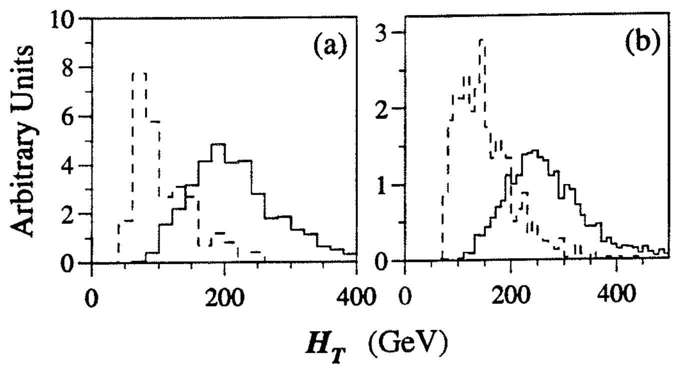

Fig. 1. H_T distributions expected for the principal backgrounds (dashed line) and 200 GeV/c^2 top quarks (solid line) for (a) $e\mu$ + jets and (b) untagged single-lepton + jets.

probability of multijet events having large $\not\!\!E_T$ and a jet being misidentified as a lepton. The W + jets background was calculated using the VECBOS Monte Carlo program.[9] The absolute normalization of this background was determined directly from the data.

The criteria for selecting the single-lepton events are shown in Table 1. The event shape variable $\mathcal{A}$, aplanarity of the jets, is proportional to the lowest eigenvalue of the 3-momentum tensor for observed jets. A cut on $\mathcal{A}$ helps separate top quark events from less spherical background events.

In the data, we observe 5 e + jets events with a background of 1.22 ± 0.42 and 3 μ + jets events with a background of 0.71 ± 0.28. The smaller background for μ + jets is due to the reduced QCD multijet contribution in this channel.

2.3. *Lepton + jets events with μ tagging*

The signature for the single-lepton channels with a μ-tag is defined as a final state with one isolated high p_T lepton (e or μ), large $\not\!\!E_T$, at least three jets, and a tagging muon. The tagging muons were required to have a transverse momentum $p_T > 4$ GeV/c, and they were required to be within distance $\mathcal{R} = 0.5$ of a jet axis in η-ϕ space (pseudorapidity $\eta = \tanh^{-1}(\cos\theta)$, and θ,ϕ = polar, azimuthal angles). The important backgrounds arise from W +jets, QCD multijet production, and Z + jets in case of the μ + jets/μ channel.

The criteria for selecting the single-lepton events with a μ-tag are shown in Table 1. The μ + jets/μ candidate events were required to be inconsistent with the Z + jets hypothesis, based on a global kinematic fit.

In the data we observe 3 e+jets/μ events with a background of 0.85 ± 0.14 and 3 μ + jets/μ events with a background of 0.36 ± 0.08.

2.4. *Summary of all channels*

Table 2 summarizes our results for all seven channels. We observe a total of 17 events with an expected background of 3.8 ± 0.6 events. The $t\bar{t}$ cross section is obtained from the equation

$$\sigma_{t\bar{t}} = \frac{\sum_{i=1}^{7} (N_i - B_i)}{\sum_{i=1}^{7} \varepsilon_i \mathcal{B}_i L_i}, \tag{1}$$

where N_i is the number of observed events in decay channel i, B_i is the expected background, ε_i is the detection efficiency for a particular top quark mass, $\mathcal{B}_i$ is the branching fraction, and L_i is the integrated luminosity. Our measured cross section as a function of the top quark mass hypothesis is shown in Fig. 2. Assuming a top quark mass of 200 GeV/c^2, the production cross section is 6.3 ± 2.2 pb. The probability of an upward fluctuation of the background to 17 or more events is 2×10^{-6}, which corresponds to 4.6 standard deviations for a Gaussian probability distribution.

Table 2. Number of observed events, the expected background, and the expected number of top quark events in the seven channels, based on the central theoretical $t\bar{t}$ production cross section of Ref. 10, with m_t = 200 GeV/c^2.

Channel	Data	Background	Top
$e\mu$ + jets	2	0.12 ± 0.03	0.34 ± 0.04
ee + jets	0	0.28 ± 0.14	0.25 ± 0.05
$\mu\mu$ + jets	1	0.25 ± 0.04	0.11 ± 0.02
e + jets	5	1.22 ± 0.42	1.84 ± 0.31
μ + jets	3	0.71 ± 0.28	0.95 ± 0.24
e + jets/μ	3	0.85 ± 0.14	0.81 ± 0.16
μ + jets/μ	3	0.36 ± 0.08	0.41 ± 0.10
ALL	17	3.79 ± 0.55	4.71 ± 0.66

2.5. *Mass analysis*

Additional support for the top quark interpretation of the observed excess comes from an invariant mass analysis of lepton + jets events. For this analysis, we selected 27 four-jet events with $\mathcal{A} > 0.03$ and with no H_T requirement. An invariant mass analysis was performed, based on the hypothesis $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu q\bar{q}b\bar{b}$. A jet assignment algorithm minimizing the $t - \bar{t}$ mass difference assigned one jet to t and the remaining three jets to $\bar{t}$. The $\bar{t}$ invariant mass is denoted by m_{3j} and the smallest two-jet invariant mass arising from $\bar{t}$ decay is denoted by m_{2j}. Fig. 3 shows the distribution of m_{3j} vs. m_{2j} for: a) background from W + jets and QCD multijet production, b) top quark of mass 200 GeV/c^2, and c) data. The data are peaked at higher invariant mass than the background in both dimensions, supporting

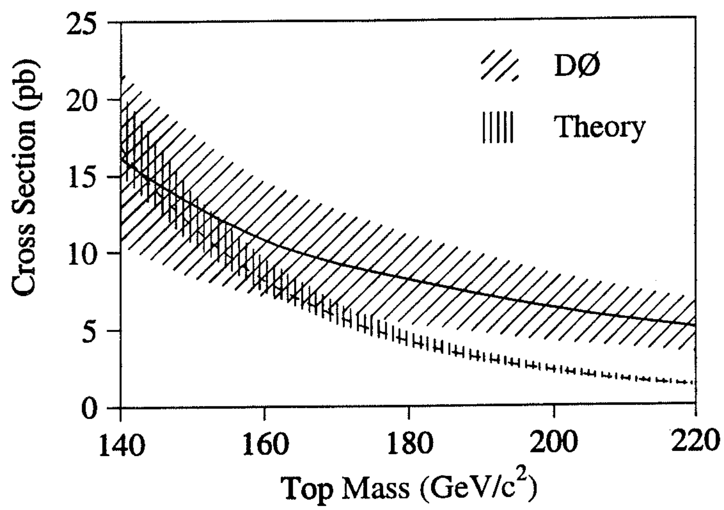

Fig. 2. DØ measured $t\bar{t}$ production cross section (solid line with one standard deviation error band) as a function of assumed top quark mass. Also shown is the theoretical cross section curve (dashed line).[10]

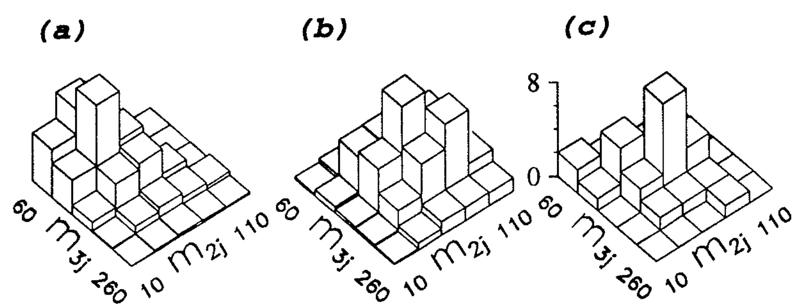

Fig. 3. Single-lepton + jets two-jet *vs.* three-jet invariant mass distribution for (a) background, (b) 200 GeV/c^2 top Monte Carlo, and (c) data.

the hypothesis that the data are a combination of top quark and background events.

The top quark mass was determined from 2-constraint kinematic fits to the hypothesis $t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu q\bar{q}b\bar{b}$, using the 14 lepton + jets events in Table 2, and also using the 27 events selected with looser requirements. Fig. 4 shows the distributions of "fitted mass" for the successfully fitted events. An unbinned likelihood fit, with the top quark mass allowed to vary, was performed on the fitted mass distributions, and yielded a top quark mass of 199^{+31}_{-25} GeV/c^2 (199^{+19}_{-21} GeV/c^2) with the standard (loose) event selection. The systematic error in the mass is 22 GeV/c^2, dominated by the uncertainty in the jet energy scale. The production cross section at our central mass is 6.4 ± 2.2 pb.

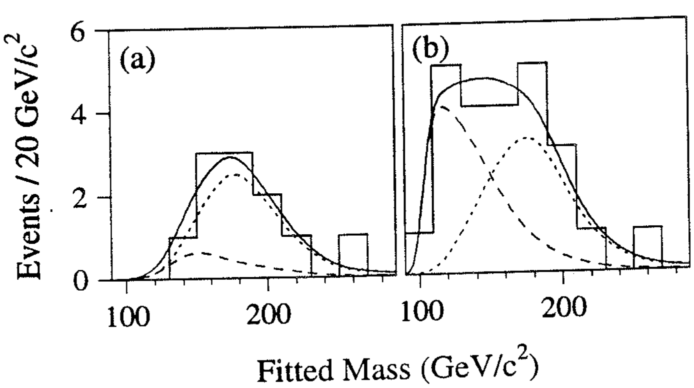

Fig. 4. Fitted mass distribution for candidate events (histogram) with the expected mass distribution for 199 GeV/c^2 top quark events (dotted curve), background (dashed curve), and the sum of top and background (solid curve) for (a) standard and (b) loose event selection.

3. Multivariate Analysis

We have carried out an analysis of the e + jets events using the PDE method[11], a new multivariate technique based on Probability Density Estimation. Our Monte Carlo studies indicate that the performance of this method is similar to that of a neural network, and that both methods show promise of outperforming conventional analysis.

3.1. *PDE method*

The PDE method classifies events as signal or background candidates by means of a discriminant function

$$D(\mathbf{x}) = \frac{f_s(\mathbf{x})}{f_s(\mathbf{x}) + f_b(\mathbf{x})}, \tag{2}$$

where f_s and f_b are the probability density functions (pdf) for the signal and background events, and $\mathbf{x}$ is a vector of d physical variables representing each event. The pdf's are constructed from data (real and/or Monte Carlo) by smoothing out the d-dimensional scatter plots for signal and background events. This is accomplished by summing up multivariate kernel functions placed at each data point. The kernel functions are taken to be d-dimensional Gaussians such that in each dimension the width of the Gaussians is proportional to the standard deviation of the pertinent variable. The original variables are first transformed linearly into uncorrelated variables so that the covariance matrices are diagonal within the signal and background classes and hence the covariance structure of the kernel matches the covariance of the density being estimated. The PDE method has only one free parameter, the global smoothing parameter h, which sets the overall scale for the widths of the Gaussians. Its value is set by maximizing the signal-to-background ratio at a fixed signal efficiency, which we have taken to be 70%.

Once the discriminant function $D(\mathbf{x})$ has been constructed from training data, the method is applied to real data by plotting the distribution of $D(\mathbf{x})$ for a "parent sample" of events selected with loose kinematic cuts. A cut $D(\mathbf{x}) > \alpha$ (typically $\alpha = 0.8$) is then applied to select the candidate events from the parent sample. Such a cut is simply a graphical cut in d dimensions.

3.2. *Results on e + jets*

For the PDE analysis we selected a sample of 190 $e +$ jets events, with or without μ-tagging, and with $E_T(e) > 20$ GeV, $\not{E}_T > 20$ GeV, and at least three jets of $E_T > 15$ GeV. These five transverse energies were used as input variables in the analysis. The discriminant function $D(\mathbf{x})$ was constructed from a training sample of 1050 $t\bar{t}$ events (top quark mass of 180 GeV/c^2) and 1050 background events ($W+$jets and QCD multijets). The background sample reproduced well the observed distributions for the 190 data events. Figs. 5(a) and 5(b) show the distribution of $D(\mathbf{x})$ for an independent testing sample of 2100 background and signal events, respectively.

Fig. 5(c) shows the distribution of $D(\mathbf{x})$ for the 190 data events. We impose a cut $D(\mathbf{x}) > 0.8$ to select the candidate events. This selection yields 21 $e +$jets events with a background of 14.0 ± 1.6 events. Two of the events have a μ-tag. The expected top quark yield is 6.3 ± 0.3 events for m_t = 180 GeV/c^2. The resulting $t\bar{t}$ cross section is 4.7 ± 3.3 (stat.) pb, in good agreement with our result from conventional analysis. Similar results have been obtained with other sets of 2-5 variables.

A neural net (NN) analysis of these data is in progress. Preliminary results suggest good agreement between the NN and PDE techniques.

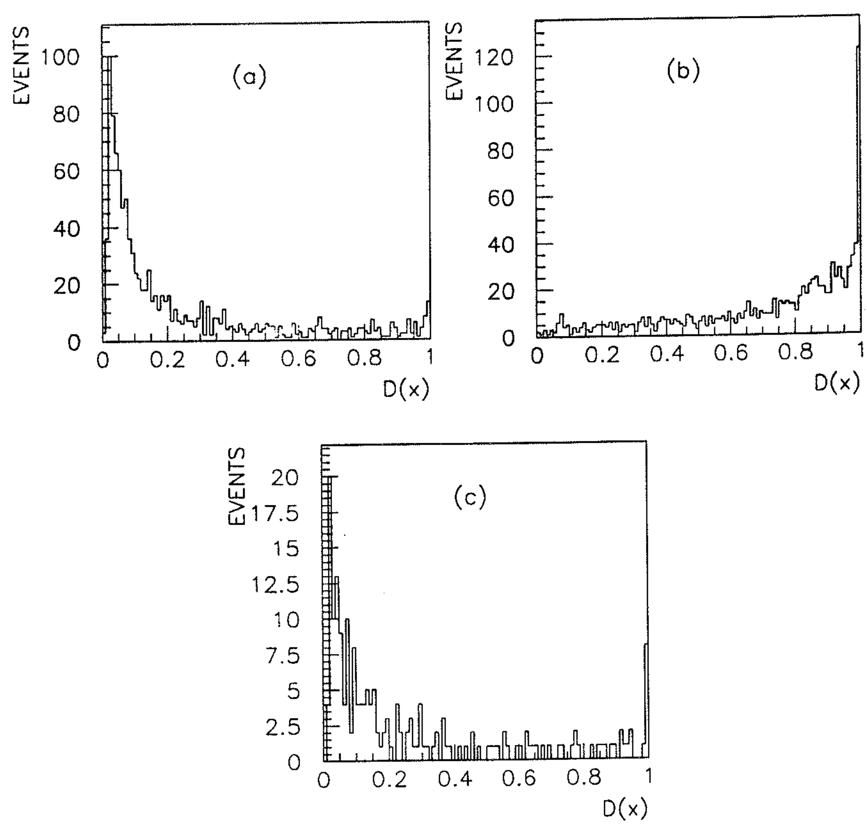

Fig. 5. Distribution of $D(\mathbf{x})$ for (a) background events, (b) 180 GeV/c^2 top quark events, and (c) data (190 $e+$jets events).

4. Conclusions

We have observed the top quark in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. We measure the top quark mass to be 199^{+19}_{-21} (stat.) ± 22 (syst.) GeV/c^2 and measure a production cross section of 6.4 ± 2.2 pb at our central mass. A multivariate analysis of e + jets events yields a cross section in agreement with that from conventional analysis.

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