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D0 Papers on Top Quark Physics Submitted to DPF '96

R.L. Kehoe, E. Won and E.W. Varnes
For the D0 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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DØ PAPERS ON TOP QUARK PHYSICS SUBMITTED TO DPF '96

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MEASUREMENT OF THE $t\bar{t}$ CROSS SECTION AT DØ

R. L. Kehoe
(for the DØ Collaboration)
Department of Physics, University of Notre Dame
South Bend, IN 46656, USA

We have measured the $t\bar{t}$ cross-section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using dilepton and single lepton final states. This analysis uses approximately 106 pb^{-1} of data collected with the DØ detector at Fermilab during the 1992-1996 run. We observe 37 events with an expected background of 13.4 ± 3.4 events, giving $\sigma_{t\bar{t}}$ of 5.3 ± 1.8 pb for $m_t = 169$ GeV.

1 Introduction

Top is expected to be dominantly produced in $t\bar{t}$ pairs at the Tevatron and, in the standard model, each top quark decays rapidly to a $W + b$ quark. As a result, the final states we consider are determined by the subsequent hadronic or leptonic decays of the $W's$. To contain backgrounds, we utilize dilepton channels $(ee, e\mu, \mu\mu)$, single lepton channels $(e + jets, \mu + jets)$ topologically like top, and single lepton channels possessing a soft, non-isolated μ from the decay of a b quark $(e + jets/tag, \mu + jets/tag)$. We have also investigated the dilepton channel in which one W decays to a leading electron and the other decays to a leading neutrino ('$e\nu$'), although this is not yet included in our final $\sigma_{t\bar{t}}$ measurement. We have analyzed 105.9 ± 5.7 pb^{-1} for the $ee, e + jets$, and $\mu + jets$ channels, while the other channels use about 90 pb^{-1}.

2 Dilepton Channels

For the dilepton analyses, we require two isolated high p_T leptons, large missing E_T ($\not\!\!E_T$) since the neutrinos do not deposit energy in the calorimeter, and at least two jets from the b quarks. Additionally, we require large $H_T \equiv \Sigma_{e1,jets} E_T$. For the dimuon channel, the $\not\!\!E_T$ requirement is replaced by a cut on the probability χ^2 from a kinematic fit to the postulate of a Z event. The $e\nu$ analysis does not require a second lepton (e or μ), and instead of an H_T cut a requirement of large transverse mass ('m_T') is used. The cuts are given in Table 1. The physics backgrounds are $Z \rightarrow ll, WW \rightarrow ll$, and $b\bar{b}$, $c\bar{c}$ production. The instrumental background arises when one electron is fake. It is determined by first measuring the rate at which a jet fluctuates to a good 'electron' and then folding this into a sample with quality cuts on the other

Table 1: Cuts for indiviual channels.

cuts	ee	$e\mu$	$\mu\mu$	$e\nu$	topological	b-tag
lepton p_T (GeV)	20/20	15/15	15/15	20	20	20
$\not{E}_T$(GeV)	25	20	-	50	20	20
jets E_T (GeV)	20/20	20/20	20/20	30/30	4×15	3×20
E_T^l (GeV)	-	-	-	-	60	-
H_T (GeV)	120	120	100	-	180	110
A_W	-	-	-	-	0.065	0.04
m_T (GeV)	-	-	-	115	-	-

lepton. Systematics in the background estimates arise from variations due to different Monte Carlo generators, uncertainty in the background cross sections, and the effect of multiple interactions.

3 Single Lepton Channels

For the single lepton channels, we require one isolated high p_T e or μ, large $\not{E}_T$, and $\geq$ 3 jets. We then either apply 'topological' cuts or we require a muon tagged jet to reduce the otherwise large W + jets background. In the topological analysis, we require a fourth jet, large leptonic activity ($E_T^l \equiv p_T^l + \not{E}_T$), H_T, and significant aplanarity ($A_W \equiv 3/2$ of the smallest eigenvalue of the normalized momentum tensor). We have selected cuts on A_W and H_T which simultaneously maximize S/B and minimize the error on $\sigma_{t\bar{t}}$. Because there are two b quarks per $t\bar{t}$ event and, since the soft muon detection efficiency is about 50%, we expect 20% of top events to have a tagged jet. This contrasts with 2% for the background. For events possessing a b-tag we relax the topological cuts, and instead the tagging μ is required to have $p_T \geq 4$ GeV and $\Delta R(\mu, jet) < 0.5$. For the $\mu + jets/tag$ analysis, we further cut on the probability χ^2 from the Z-fit mentioned above. The final cuts for the single lepton analyses are given in Table 1. Systematics in the background arise from uncertainties in kinematic modelling, tagging rate, and the effect of multiple interactions.

4 Measured Cross Section

We observe a total of 37 events (5 dilepton, 32 lepton + jets) with an expected background of 13.4±3.0 events (1.6 dilepton, 11.7 lepton + jets). The estimate of $\sigma_{t\bar{t}}$ for the dilepton, topological, and b-tag analyses is 4.9 ± 3.3 pb, 4.5 ± 2.2 pb, and 7.2 ± 3.4 pb, respectively. The resulting combined cross section

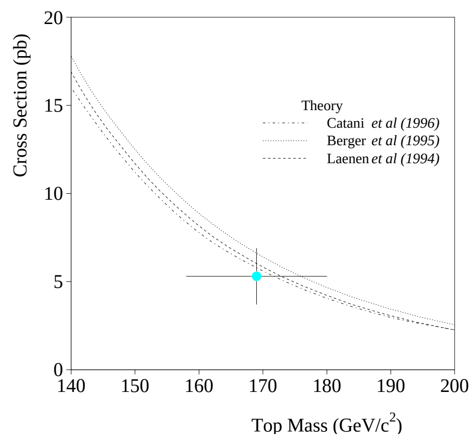

Figure 1: Measured $\sigma_{t\bar{t}}$ *vs.* m_t. Recent theoretical calculations are shown.

is plotted in Figure 4 along with three theoretical calculations for comparison [2,3,4]. For our measured top mass (169 GeV [1]), we determine $\sigma_{t\bar{t}}$ to be 5.3 $\pm$ 1.8 pb. As an independent excersize, we observe 2 events in the $e\nu$ channel with an expected background of 1.4 $\pm$ 0.5 events. The expected top yield (m_t= 170 GeV) is 1.4 $\pm$ 0.1 events.

5 Summary

Our top cross section analysis has been tuned to give the best error on $\sigma_{t\bar{t}}$. In 106 pb^{-1} we observe 37 events with a background of 13.4 $\pm$ 3.0 events, which gives us a $\sigma_{t\bar{t}}$ of 5.3 $\pm$ 1.8 pb if m_t= 169 GeV.

We acknowledge the support of the US Department of Energy and the collaborating institutions and their funding agencies in this work.

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TOP QUARK STUDY IN ALL-JETS CHANNEL AT DØ

Eunil Won
Department of Physics, University of Rochester
Rochester NY 14627, USA

for the DØ Collaboration

We report on the search for top quark decaying into all-jets at the Tevatron collider. We measure preliminary cross sections of 4.4 ± 4.9 pb and 3.9 ± 9.8 pb for $t\bar{t}$ production, using singly and doubly b-tagged all-jets channels, respectively.

6 Introduction

At the Tevatron collider, $t\bar{t}$ pairs are produced primarily through $q\bar{q}$ annihilation. Each top decays via the reaction $t \rightarrow W + b$. The W bosons subsequently decay either leptonically or hadronically. In the all-jets mode, both Ws decay hadronically. Although this represents the largest branching fraction of any decay channel (44%), extracting a signal is difficult due to the QCD multijet background.

7 Selection and Analysis of All-Jets Channel

The DØ detector has been described elsewhere.[1] The data used in these analyses are from the '92-'96 data runs at the Tevatron collider (Run 1), and include 13 events/pb from Run 1a and 70 events/pb from Run 1b.

The multijet trigger required the presence of calorimeter energy, five or more jets (reconstructed using the $\mathcal{R}$=0.3 cone algorithm) with $E_T > 10$ GeV, and the scalar sum of E_T of all jets (H_T) greater than 115 GeV. The efficiency for this trigger is greater than 90% for m_t = 180 GeV/c^2. A total of 550,000 events were collected, with an expected top yield of approximately 200. Thus, the signal to background ratio is of order 10^{-4} at this stage.

7.1 Kinematic Variables

Variables were chosen to discriminate between $t\bar{t}$ events and QCD multijet background. QCD multijet events are dominated by $2 \rightarrow 2$ processes with additional gluon radiation. The additional jets are typically lower in E_Ts, and tend to lie in the plane consisting of the beam and the two leading jets. Conversely, $t\bar{t}$ events have jets which are more central, have higher E_T, and are less planar.

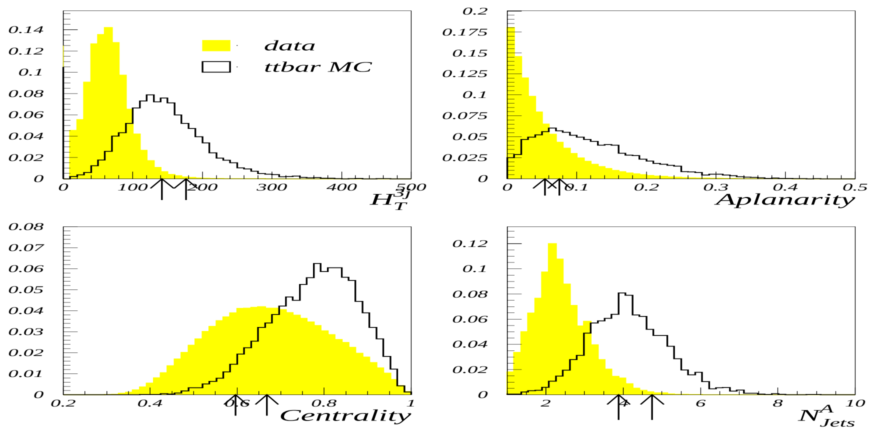

Figure 2: Distributions (normalized to the same area) in kinematic parameters: (a) H_T^{3j}, (b) $\mathcal{A}$, (c) C, and (d) average jet count N^A_{Jets}, are shown for data from Run Ib (shaded) and ISAJET $t\bar{t}$ Monte Carlo for $m_t = 180$ GeV/c^2 (normal histograms). Arrows show threshold points (looser for double tag, tighter value for single tag analysis)

These properties are used to define the following four kinematic variables which parameterize the event: H_T^{3j}, the scalar sum of the E_T of the jets, excluding the leading two; *aplanarity* ($\mathcal{A}$), 3/2 of the smallest eigenvalue of the normalized jet-momentum tensor; *centrality* (C), the ratio of the sums of transverse and total energies of all the jets; *average jet count* (N^A_{Jets}), the number of jets with E_T above a threshold, weighted by the threshold and averaged over a range of thresholds.[2] Distributions of these variables for data, and the expected (Monte Carlo) distributions for $t\bar{t}$, are shown in Fig. 2. These variables provide effective discrimination between $t\bar{t}$ signal and background.

7.2 Optimizing Selection Criteria

Threshold requirements on the kinematic variables were chosen to optimize the signal to background ratio at a given acceptance for signal. We used the Random Grid Search technique[3] to choose optimal values of these thresholds. These were chosen on the basis of the distribution of values in the data (for background) and in the $t\bar{t}$ ISAJET sample.

7.3 Soft-muon Tagging

The presence of a soft muon in a jet indicates that the jet was likely to have originated from a heavy (b or c) quark. Requiring that at least one jet in each event have a b-tag, significantly improves our signal to background ratio. The $t\bar{t}$ events are tagged roughly 20% of the time, while only 3% of the QCD background is tagged.

A tagging muon must have $p_T \geq 4$ GeV/c, and pass the standard DØ muon requirements.[4] In addition, the separation ($\Delta\mathcal{R}$) between the muon and the reconstructed jet must be less than 0.5 units. In addition to improving the signal to background ratio, tagging also provides a means of estimating the background for events passing the kinematic criteria.

As a second method of estimating background, the tagging probability is extracted in a simultaneous fit to Eqns 1-2.

$$N_i^{tagged} = \epsilon e^{-\epsilon}\ N_i^{QCD} + 0.2\ N_i^{TOP} \tag{1}$$

$$N_i^{untagged} = (1 - \epsilon e^{-\epsilon})\ N_i^{QCD} + 0.8\ N_i^{TOP} \tag{2}$$

where $N_i^{TOP} = \mathcal{L}\ \sigma_{TOP}\ \varepsilon_i^{MC}$, N_i^{QCD} and N_i^{TOP} are the number of background and signal events passing some set of thresholds labeled i, $\mathcal{L}$ is the integrated luminosity, σ_{TOP} is the $t\bar{t}$ cross section, ε_i^{MC} is the Monte Carlo acceptance times branching fraction for the chosen set of thresholds and 20 % is assumed for the signal tag-rate. Equations 1-2 were fitted to data for six statistically independent sets of event samples that passed different kinematic criteria, and as a result, we obtained $\epsilon = 0.034 \pm 0.005$, $\sigma_{TOP} = 4.0 \pm 4.8$ pb (consistency check), and $\chi^2/\mathrm{dof} = 6.2\ /\ 4$.

7.4 Results

We observe 15 candidate events in the singly-tagged channel, with an expected background of 10.9 ± 2.3. This gives a cross section of 4.4 ± 4.9 pb. In the doubly-tagged channel, we observe 2 events with an expected background of 1.4 ± 0.4, giving a cross section of 3.9 ± 9.8 pb.

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MEASUREMENT OF THE TOP QUARK MASS AT DØ

E.W. VARNES
Fermilab P.O. Box 500, MS 352
Batavia, IL 60510, USA

DØ has measured the top quark mass using a sample of 32 single-lepton events selected from approximately 115 pb^{-1} of $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions collected from 1992 - 1996. The result is $m_t = 169 \pm 8(stat) \pm 8(syst)$ GeV/c^2. Using a sample of 3 $e\mu$ events, DØ measures $m_t = 158 \pm 24(stat) \pm 10(syst)$ GeV/c^2.

8 Event Selection

It is assumed that top quarks are pair-produced and decay via $t \rightarrow Wb$, so that every candidate event includes two top quarks and two on-shell W bosons. In the subset of events where one of the Ws decays to $e\nu$ or $\mu\nu$ and the other hadronically, the final state consists of a high-p_T lepton, four high-p_T jets, and significant missing E_T ($\not\!\!E_T$) due to the fact that the neutrino does not interact in the detector. Hence the initial selection requires four jets with $E_T > 15$ GeV and $|\eta| < 2.0$, $\not\!\!E_T > 25$ GeV, and a central electron (or muon) with $E_T > 20$ GeV. Additionally, a soft muon tag in a jet or a leptonic W with $|\eta^W| < 2.0$ and $E_T^W \equiv E_T(\ell) + E_T(\nu) > 60$ GeV was required. Ninety-three events survive these cuts from ≈ 115 pb^{-1} collected between 1992 and 1996 and form the *base sample* for the mass analysis.

9 Kinematic Fitting

Each event in the base sample is kinematically fit for the top quark mass. The presence of a final-state neutrino means that three quantities are unmeasured. Four-momentum conservation provides five constraints (total $\vec{p_T} = 0$, $m_{\ell\nu} = m_{jj} = m_W$, $m_t = m_{\bar{t}}$), so a 2C fit is possible. In performing this fit, there are 12 possible assignments of jets to parent partons. All combinations are attempted, and the solution with lowest χ^2 is used to give the *reconstructed mass.* If no solution has $\chi^2 < 7$ the event is rejected, leaving 73 events in the base sample. As this sample is dominated by QCD W + multijet events, a procedure is required to assign the relative probability that each event is top. This is done by forming a *top likelihood discriminant* based on four variables which are nearly uncorrelated with the reconstructed mass: $\not\!\!E_T$, aplanarity, $H'_{T2} \equiv \left(\sum_{\text{jets}} E_T - E_T(\text{jet1})\right) / \sum_{\text{jets}} |E_z|$, and $K_{T\min} \equiv \left(\min \Delta R_{jj} \times E_T(\text{lesser jet})\right) / E_T^W$.

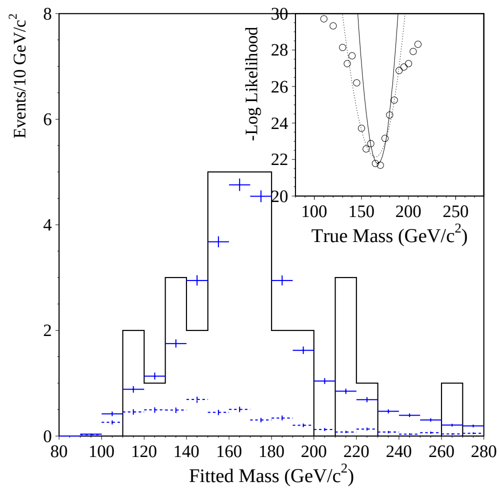

Figure 3: Result of maximum likelihood fit to mass sample, projected onto the reconstructed top mass axis.

10 Maximum Likelihood Fit

In order to extract the top quark mass, a maximum likelihood fit is performed. First, the base sample is binned in two dimensions (reconstructed mass vs. top discriminant), and a binned likelihood fit is made with m_t and the number of signal and background events as unconstrained output parameters. The result is $m_t = 168 \pm 10$ GeV/c^2, $n_s = 27 \pm 7$, and $n_b = 46 \pm 10$, where the errors are statistical. Tests using ensembles of Monte Carlo events show that one expects better resolution on m_t when fitting only those events in the half of the two-dimensional plane which are most likely to be top, with a constraint on the number of signal events provided by the fit to the full base sample. Thirty-two events are in this *mass sample*, and a binned likelihood fit yields $m_t = 168 \pm 8$ (*stat*) GeV/c^2 (see Fig. 1). To account for small differences observed between the input m_t and mean maximum likelihood mass from ensemble tests, the central value is increased by 1 GeV/c^2.

11 Systematic Errors

The dominant error is due to uncertainty in the jet energy scale. Jets are corrected both for calorimeter effects and for gluon radiation that falls outside of the jet cone. Studying the E_T balance in $Z+$ multijet events gives a scale uncertainty of 4% with a 1 GeV constant term, giving an uncertainty in m_t of ± 7.3 GeV/c^2. Differences in models of top quark production (between ISAJET and HERWIG) and in the W + multijet background add ± 3.3 GeV/c^2 and the limits of the Monte Carlo statistics another ± 2.0 GeV/c^2. Summing these in quadrature gives a systematic uncertainty of ± 8.3 GeV/c^2.

12 Mass Fitting Using Topological Variables

As a cross-check to the kinematic fitting result, mass analyses are also performed using topological variables which are highly correlated with the top quark mass as mass estimators for each event. Three such variables are $H_{T\ell} \equiv \sum_{\text{jets},\ell} E_T$, $M_T \equiv$ transverse mass of ℓ + jets system, and M, the mass of the ℓ + jets system. The event sample fit consists of 34 events with an expected background of 19.6 $\pm$ 2.6 events, and an unbinned maximum likelihood fit is performed with background unconstrained. The result for the $H_{T\ell}$ fit is $m_t = 170 \pm 18(stat) \pm 10(syst)$ GeV/c^2, while the M_T and M fits have central values of 171 and 163 GeV/c^2, with similar errors.

13 Dilepton Analysis

DØ has also measured the top quark mass using the sample of three events in the $e\mu$ channel, for which the background is low. The second ν in the final state renders a kinematic fit impossible, so one must consider a range of top quark masses consistent with the event kinematics and assign a probability for each solution. Two methods of assigning this probability are employed. Method 1, which follows the ideas of Dalitz, Goldstein, and Kondo [1], finds $m_t = 158 \pm 24(stat) \pm 10(syst)$ GeV/c^2. Method 2, which integrates over the ν phase space, gives a similar result: $m_t = 157 \pm 23(stat) \pm 9(syst)$ GeV/c^2.

14 Conclusions

DØ has measured the top quark mass using 32 events in the ℓ + jets decay channel, and finds $m_t = 169 \pm 8(stat) \pm 8(syst)$ GeV/c^2. Cross-checks using topological variables rather than constrained kinematic fitting to estimate the mass give consistent results, as do fits using the smaller sample of $e\mu$ events.

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