Search for the Top Quark: Results from the DØ Experiment

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Abstract

We review the search for the top quark conducted by the DØ collaboration using data from the Fermilab $\overline{p}p$ collider. Based upon a preliminary analysis of an integrated luminosity of about 13.5 pb^{-1}, we have searched for $t\overline{t}$ production and decay in the experimental channels involving a pair of dileptons (e or μ) plus jets, or single leptons plus jets. Summed over all channels, we observe 7 events in our data, to be compared with an expectation from background processes of 3.2 ± 1.1 events. The $t\overline{t}$ cross-section deduced from the small excess of events is presented as a function of the top quark mass. The statistics are sufficiently limited that no clear evidence for the existence of the top quark can be obtained.

We also comment upon contributions to the Parallel session devoted to the top quark at this conference.

1. Introduction

We have a firm expectation that the top quark should exist; the Standard Model (SM) requires it as the weak isospin partner for the b-quark, completing the roster of three isodoublet quark and leptonic fundamental fermions. Extensions of the SM almost uniformly demand the existence of the top as well.

We now strongly believe that the top is heavy. The present experimental limit [1] assuming SM production and decays is 131 GeV/c^2. The CDF collaboration [2] has presented results which suggest the possibility of top quark production with masses in the range $160 \leq \mathrm{m}_t < 190$ GeV/c^2. Under the assumption that the top is so massive, certain simplifying features result. The production of the top quarks proceeds primarily through the pair production of $t\overline{t}$, initiated primarily by $\overline{q}q$ annihilation (and to some extent by gluon-gluon fusion processes) [3]. Production of single top quarks through W-gluon fusion [4] is expected to be small in comparison. The decays of t are simple in the SM: the $t(\overline{t})$ decays to W^+b $(W^-\overline{b})$ 100% of the time, though new particles outside the SM framework, such as a charged Higgs boson with mass below top mass m_t, could perturb the decay scheme.

At the partonic level, the final state reached after $t\overline{t}$ decay is controlled simply by the nature of the W decays. With both W's decaying leptonically, we expect two leptons, two jets due to the b's, and missing transverse energy ($\not{E}_T$) due to the two neutrinos. With one W decaying leptonically and the other hadronically, we expect a single lepton, four jets and $\not{E}_T$. The channels in which both W's decay hadronically result in six jets, but are experimentally difficult owing to the large multijet production cross-sections. In real life the simple partonic content in the $t\overline{t}$ decays can be modified by inefficiencies in jet reconstruction and by the radiative emission of gluons from initial and final state partons. The decay branching ratios are controlled by the branching ratio's $W \rightarrow \ell\nu = 1/9$ for each lepton type, and $W \rightarrow q\overline{q} = 2/3$ for the hadronic modes. In the experiments only e and μ decays of the W are sought.

It is expected that for a top quark with mass above 130 GeV/c^2, the top will decay so rapidly that the fragmentation of the top into hadrons does not have time to occur [5]. Thus the future study of top quarks will afford a unique opportunity for investigation of bare quark states.

It has long been known that there remains a possibility for $m_t < m_W$ in the case that some unobserved particle exists into which the top can decay [6]. The total W decay width is sensitive to a contribution from $W \rightarrow t\bar{b}$; present data from CDF and DØ on Γ_W [7] limit possible top masses to about 63 GeV/c$^2 \leq m_t \leq m_W$.

A large body of very precise data on electroweak processes has been assembled over the past years which give rather stringent constraints upon the possible values for m_t – *assuming the validity of the SM.* The measurements of the mass, width, and line shape of the Z at LEP; asymmetries in the decay distributions of fermions from the Z at LEP and production asymmetries using polarized electrons at SLC; the W mass measurements from the Tevatron collider and CERN S$\bar{p}p$S; and neutrino scattering experiments are summarized elsewhere in these Proceedings [8]. With the assumption that these phenomena are correlated within the SM, one may infer the range of possible top masses [8]: $m_t^{SM} = 178 \pm 11 \, ^{+18}_{-19}$ GeV/c^2, where the last error derives from the variation of the SM Higgs boson mass between 60 and 1000 GeV/c^2.

Despite the indirect evidence for top it is necessary to pursue the direct search with as little model prejudice as possible, since non-SM effects could affect either the production or decay properties. Indeed, with the expectation that the top is heavy, the phase space available for new phenomena to alter either production or decay schemes in enhanced. In any case, the large Yukawa coupling expected for a heavy top suggests that the top quark may play a special role in the mass generation mechanism and therefore that its properties may be special.

2. DØ Search for the Top Quark

The DØ detector [9] is well suited for the search for the top quark. The detector employs a finely segmented uranium-liquid argon calorimeter, with uniform response to electromagnetic particles and hadrons for $|\eta| < 4.2$. The calorimeter permits good multijet discrimination with relatively small corrections to the observed jet energies. Discrimination of electrons and pions is given by the pattern of energy deposits in the calorimeter. Muon candidates are confirmed by their ionization in the calorimeter. Good $\not{E}_T$ resolution is achieved for signalling the presence of neutrinos, due to the good energy resolution and hermetic calorimeter coverage. The sagitta of muon trajectories is measured using proportional drift tube chambers before and after five magnetized iron toroids surrounding the calorimeters. The muon detector is sensitive over the interval $|\eta| < 3.3$. The large amount of material in the calorimeters and toroids (between 13 and 18 absorption lengths) suppresses backgrounds due to the leakage of hadronic showers. The compact non-magnetic tracking volume within the inner calorimeter boundary is filled with drift chambers and a transition radiation detector (TRD). Its small outer radius helps to reduce the backgrounds to muons from π and K decays. The tracking chambers serve to establish the primary event vertex and confirm candidate lepton tracks. The dE/dx measurements in the drift chambers and the signals from the TRD allow extra rejection of background to electrons.

The search for the top quark reported here is based upon preliminary analyses of data taken during the 1992-93 collider run. We have optimized the selection criteria for this search for top masses above 130 GeV/c^2 in view of the existing limit [1]. The integral luminosity for these searches is 13.5 ± 1.6 pb^{-1} for the channels involving a W decay to electrons, and 9.8 ± 1.2 pb^{-1} for those with $W \rightarrow \mu$. The normalization of the luminosity scale has been set on the basis of a weighted average of the available total cross-section measurements at 1.8 TeV [10][11]. This average $\sigma_{\rm tot}$ is less than the CDF measurement [11] by about 6%. In calculating our $t\bar{t}$ cross-sections we include a systematic error on luminosity of ±12%; the effects of this luminosity error are small compared with our statistical and other systematic errors.

We report preliminary measurements from three independent searches: the dilepton (all combinations of e and μ) [12]; the single lepton channel (both e and μ) with topological cuts to suppress the background [13]; and the single electron channel with b-jet tagging through the semi-muonic decay of the b [14].

2.1. Dilepton searches

The dilepton mode analyses [12] require the presence of high p_T leptons, large $\not{E}_T$, and at least two jets with E_T^{jet} >15 GeV. Additional cuts are employed to suppress specific backgrounds arising from Z decays, cosmic rays and QED radiative processes. Table 1 summarizes the dilepton search results.

The data for the $e\mu$ mode before the final cut on ≥ 2 jets, and the expectation for m_t = 170 GeV/c^2 taken from the ISAJET Monte Carlo [15], are displayed in Figure 1 as a function of muon p_T and electron E_T. The scale for the muon p_T is linear in $(1/p_T)$ since the measurement errors are approximately constant and symmetric in this quantity. Only the data event far from both electron and muon p_T cuts survives the jet cut. This event is quite striking; its kinematic

Mode	*ee*	$\mu\mu$	$e\mu$	All
Branching Ratio	1/81	1/81	2/81	4/81
Acceptance	15%	9%	13%	13%
No. $t\bar{t}$(m_t=160)	$0.22 \pm .04$	$0.12 \pm .02$	$0.40 \pm .05$	$0.74 \pm .10$
Main Bknds	$Z \rightarrow \tau\tau$ Multijet fakes	$Z \rightarrow \mu\mu$	$Z \rightarrow \tau\tau$ W^+W^-	
$\mathbf{N}_{Bknd}$	$0.16 \pm .07$	$0.33 \pm .06$	$0.27 \pm .09$	$0.76 \pm .13$
DATA	**0**	**0**	**1**	**1**

Table 1. Expected top signal, backgrounds and observed events in the data for the dilepton searches.

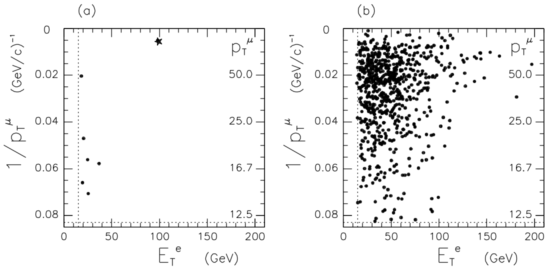

Figure 1. Distribution of events in E_T^e and p_T^μ for the data (before application of the final cut requiring two jets) and for Monte Carlo ($m_t = 170\ GeV/c^2$). The Monte Carlo corresponds to about 1600 times the luminosity for the data.

parameters are $E_T^e \approx 100$ GeV, $p_T^\mu \approx 200$ GeV/c, $\not{E}_T \approx$ 120 GeV, and two jets with $E_T = 25$ and 22 GeV. Although the lepton transverse momenta for this event are quite large, the overall likelihood for this event agrees well with the expectations for SM top production, considering the values of all 14 kinematic variables [1]. The backgrounds from $Z \rightarrow \tau\tau$ are ruled out for this event due to the large invariant mass of the $e\mu$ pair. Over the full kinematic range for the selection of events in this mode, we calculate that the ratio of expected number of $t\bar{t}$ (m_t = 160 GeV/c^2) events to the number of backgrounds is 4 ± 2. Doubling the kinematic cuts on electron, muon and missing E_T leaves the candidate event still far from the cuts and yields a top/background ratio of 16 ± 6. Interpreting this event as SM top and performing a likelihood analysis for m_t [1] gives a large central value for the mass (in the vicinity of 150 GeV/c^2) with a relatively broad dispersion.

2.2. Lepton + jets searches

For the modes in which one W decays leptonically and the other hadronically, the branching ratio is greater than for the dilepton modes (12/81 for each lepton type) but the backgrounds are larger. There are two primary background sources. The first is due to the QCD (Drell-Yan) production of a W in association with the requisite ($\sim$ 4) number of jets. This process gives exactly the same final state objects as the $t\bar{t}$ signal, though the heavy quark content and topology may be different. The second is due to QCD production of multijets ($N_{jet} \sim 5$) in which one of the jets is misidentified as a lepton and instrumental effects simulate sufficient $\not{E}_T$ to satisfy the neutrino requirement. The latter background afflicts primarily the searches in the electron final states. DØ has performed two independent searches in the lepton + jets mode. The first employs the differences in event topology to suppress backgrounds and tag the top signal events. The second uses tagging of b-quark jets through their semileptonic decays into muons to reject the QCD backgrounds, which are expected to be less rich in heavy quark content.

2.2.1. Topological tagging for lepton + jets.

The topological tag search [13] selects $W+$ jets final state (both e and μ decays) with the following criteria: *(a)* large lepton momenta ($E_T^e > 20$ GeV and $|\eta_e| < 2.0$ or $p_T^\mu > 15$ GeV/c and $|\eta_\mu| < 1.7$); *(b)* large $\not{E}_T$($>$ 25 GeV for the electronic mode and $>$ 20 GeV for the muonic mode); and *(c)* at least 4 jets with $E_T > 15$ GeV and $|\eta_{jet}| < 2.0$. The *absence* of a b-tag is required (see below) to preserve the independence of this search from the b-tag analysis. Finally, two variables describing the topology of the

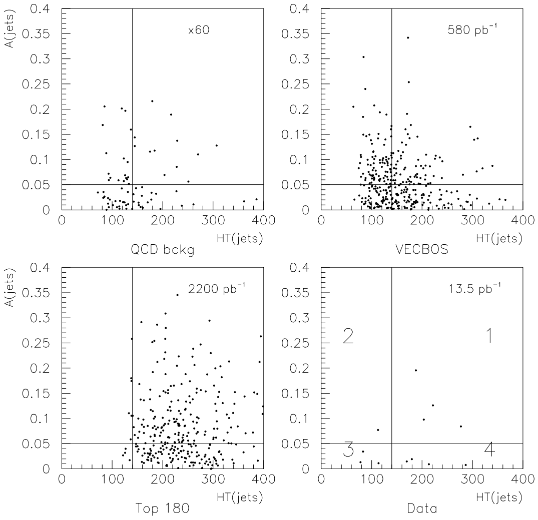

Figure 2. Event distributions *vs.* $\mathcal{A}$ and H_T for QCD multijets (upper left), W+jets (upper right), a $t\bar{t}$ Monte Carlo sample (lower left) and for data (lower right).

event are defined. The aplanarity ($\mathcal{A}$), introduced for the study of event shapes in e^+e^- experiments, is defined as 1.5 times the smallest normalized eigenvalue of the momentum tensor, constructed in the overall $\overline{p}p$ frame from the observed jets with $|\eta| < 2$ in the event. The cut chosen is $\mathcal{A} > 0.05$. The $t\bar{t}$ events tend to be more spherical (larger $\mathcal{A}$) than the backgrounds which derive from QCD radiative processes which show more tendency towards collinearity. The variable H_T is defined as the sum of the scalar transverse momenta of all final state jets observed for $|\eta| < 2$ in the event. Large H_T is indicative of the decay of a high mass state, and thus favors the $t\bar{t}$ process. The cut is chosen at $\mathrm{H}_T > 140$ GeV.

Distributions of events in the $\mathcal{A}$-H_T plane are shown in Figure 2 for Monte Carlo simulation of the QCD multijet background, the W+jets process, and for $t\bar{t}$ ($\mathrm{m}_t = 180$ GeV/c^2) production. The DØ data distribution is also shown. The cuts on $\mathcal{A}$ and H_T are shown; the signal region is above and to the right of the lines.

Two nearly independent methods have been used to estimate the backgrounds for the topological lepton plus jets search. The first proceeds from the observation [16] that for the W+jets processes, the reduction in cross-section upon requiring an additional jet is the same, independent of the number of jets. This is a natural consequence of QCD radiative processes, since qualitatively, the emission of each added jet incurs an additional factor of $\alpha_s(q^2)$ ($q^2 \sim (\mathrm{m}_W)^2$). Although the appropriate q^2 may vary somewhat with N_{jet}, this scaling law is found to be satisfied theoretically to within 20% for up to four jets. We refer to this behavior as 'jet-scaling'.

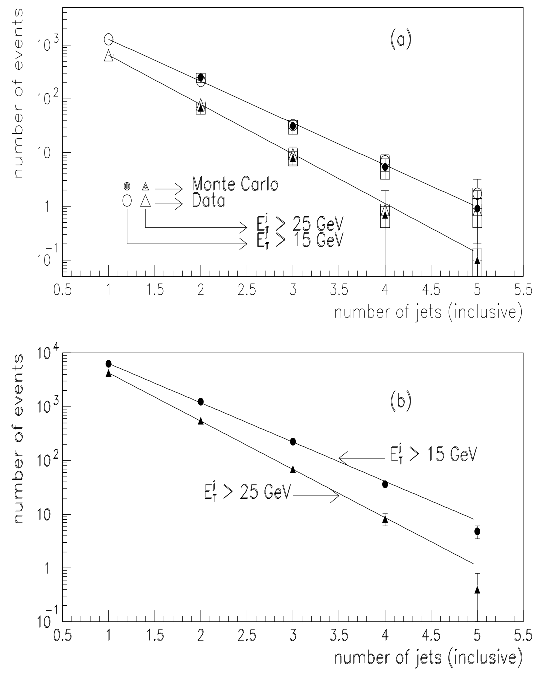

Figure 3. (a) Number of W+jets events (with $W \rightarrow e\nu$) *vs.* the inclusive number of jets for $\mathrm{E}_T > 15$ GeV (upper points) and $\mathrm{E}_T > 25$ GeV (lower points). The open symbols denote data and the filled symbols show the prediction of the Monte Carlo. The lines are fits to the data for the interval $1 < \mathrm{N}_{jet} < 3$. (b) Number of multijet events *vs.* the inclusive number of jets for $\mathrm{E}_T > 15$ GeV (upper points) and $\mathrm{E}_T > 25$ GeV (lower points). The filled symbols denote data and lines are fits to the data for the interval $1 < \mathrm{N}_{jet} < 4$.

In Figure 3(a) we show the W+jets data (for $W \rightarrow e\nu$) before application of the $\mathcal{A}$ and H_T cuts, as a function of the 'inclusive' jet multiplicity (we plot the number of events with $\mathrm{N}_{jet} \geq n$ at abcissa n) for two different jet E_T thresholds. The open symbols represent the data. The filled symbols give the predictions from the Monte Carlo, for which we use the tree-level parton generator VECBOS [17] with subsequent parton showering and fragmentation of the partons in ISAJET and passage of the resulting particles through a GEANT-based [18] simulation of the detector. The lines are fits to the data for ($1 \leq \mathrm{N}_{jet} \leq 3$) and show good agreement with the jet-scaling hypothesis for $\mathrm{N}_{jet} \leq 3$. The extrapolation to $\mathrm{N}_{jet} \geq 4$ shows that the excess of events to be attributed to $t\bar{t}$ in this data selection is not large. It is noteworthy that the data and Monte Carlo predictions agree very well, both in absolute normalization and the slope.

One may expect that similar jet-scaling behavior would arise for the QCD production of multijets. In Figure 3(b) we show the dependence on inclusive jet multiplicity for a sample of multijet events in which one of the jets has fluctuated to resemble (with bad χ^2) an electron and for which $\not\!\!E_T < 25$ GeV. For this process, which should contain no anomalous signals at large N_{jet}, the jet-scaling hypothesis again works well and the slope of the distribution is very similar to that for the W+jets process. Similar behavior is observed with poorer statistics in the jet-scaling of a Z+jets sample where no $t\bar{t}$ production is expected.

The jet-scaling estimate of the background proceeds from the assumption that the W+jets events (and residual QCD multijet contributions) satisfy the jet-scaling hypothesis, while the $t\bar{t}$ events contribute to a given multiplicity N_{jet} according to fractions determined from Monte Carlo calculations. The calculation yields the number of background and $t\bar{t}$ signal events surviving in the lepton + 4 or more jet sample. The resulting background estimate is then corrected for the probability that the background events survive the $\mathcal{A}$ and H_T cuts (taken from Monte Carlo). The resulting background estimated for the topological tagged experiment is $1.8 \pm 0.8 \pm 0.4$; the systematic error includes the uncertainty in the jet-scaling hypothesis.

The second method for estimating the background for the topological tag is independent of the jet-scaling hypothesis. From the Monte Carlo distributions of events from QCD multijets, W+jets and $t\bar{t}$ production shown in Figure 2, we deduce the *fraction* of events in each process which fall into each of the quadrants 1 − 4 of $\mathcal{A}$-H_T space shown in Figure 2. We then fit the data distribution in $\mathcal{A}$-H_T space (also shown in Figure 2) using these fractions with the background and $t\bar{t}$ populations as free parameters. We obtain in this way an estimated background of $1.7 \pm 0.8 \pm 0.4$ events. This second estimate agrees very well with that obtained from jet-scaling above.

We observe a total of four events in our topological tag analysis (two are e+jets+$\not\!\!E_T$ and two are μ+jets+$\not\!\!E_T$).

2.2.2. b-quark tagging for lepton + jets. Since $t\bar{t}$ events are expected to be enriched in b-quarks relative to the backgrounds, effective reduction of the backgrounds can be achieved by tagging the presence of b's in the W+jet sample. The current DØ b-tagging analysis [14] is performed for the $W \rightarrow e$+jets sample using the inclusive semileptonic decay $b \rightarrow \mu$.

The event selection retains the large E_T cut (> 20 GeV) for the electron but relaxes the $\not\!\!E_T$ cut to $\not\!\!E_T > 20$ GeV(> 35 GeV if $\phi_{\mu\nu} < 25°$). Only three jets are required with a threshold $E_T > 20$ GeV. The topological cuts on $\mathcal{A}$ and H_T are not required. A muon consistent with the expectation for $t \rightarrow b \rightarrow \mu$ is required in the event: $p_T^\mu > 4$ GeV/c with $|\eta_\mu| < 1.7$. In the case that $p_T^\mu > 12$ GeV/c, we require a separation between the muon and jet to be less than 0.4 in η–ϕ space to keep this analysis independent of the $e\mu$ dilepton search.

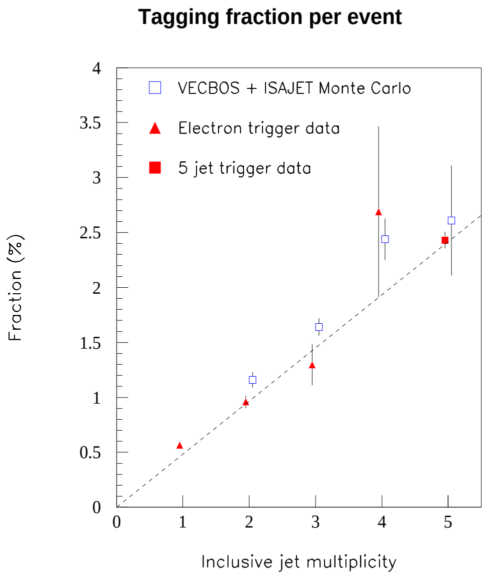

Figure 4. The probability per jet to observe a μ-tag for a sample of fake electron + jets events (due to QCD multijet production) (triangles); QCD multijets from a five jet trigger (closed squares); and from the VECBOS Monte Carlo simulation of the W+jets process.

The b tagging rate is studied for several data sets involving multiple jets. The tag rate is measured using multijet data in our e+jets trigger sample, for which the electron is classified as fake (this sample is almost purely due to multijet background). The probability (per jet) for finding a tagging muon is established from these data; it depends upon the $\not\!\!E_T$ cut imposed, and upon the E_T of the jet. Comparison of this tagging rate for flavor-undifferentiated processes can be made with independent data samples of di-jet triggers, γ+jets and Z+jets. The VECBOS/ISAJET/GEANT Monte Carlo chain can be used to calculate the tagging probabilities for the W+jets process.

These tagging probabilities are shown in Figure 4. The rates observed for the different data samples agree and are also in good agreement with the Monte Carlo expectations. The tagging rates are about 0.5% per jet and are in agreement with the hypothesis that most of the muons come from b decay. There is no discernible difference in the tagging rates for QCD multijets and W+jets.

Using ISAJET and our detector simulation to determine the tagging rates for $t\bar{t}$ production, we find that the tagging rate (per $t\bar{t} \rightarrow e + \not\!\!E_T$ + jets event) is about 20%; it varies somewhat with the mass of the top quark due to the dependence of tagging probabilities with jet E_T. We note that since there are two b's per $t\bar{t}$ event, and each b can decay directly to muons or via the cascade $b \rightarrow c \rightarrow \mu$ chain, the tagging rate before experimental selection cuts and inefficiencies would be expected to be over 40%. A confirmation of our μ-tagging calculation can be found in the determination of the inclusive b-quark production cross-section [19], in which the tagging techniques are similar. In this separate study, the distributions as a function of p_T and p_T^{μ} relative to a nearby jet are shown to conform to the expected mix of subprocesses, and the resulting b cross-section is in good agreement with NLO QCD predictions [20].

The backgrounds from multijets and W+jets in the b-tagging analysis are determined by first separating the two background subprocesses in the data sample, based on their different $\not{E}_T$ distributions, and then applying the relevent μ-tagging probabilities (discussed above) as derived from data. We find that the multijet background contributes 0.12 ± 0.05 events and the W+jets background gives 0.43 ± 0.14 events. The total background of 0.55 ± 0.15 events is to be compared with the two events observed in the DØ data.

A cross check of the background estimates can be made by estimating the background for the $N_{jet} \geq 1$ and $N_{jet} \geq 2$ samples where little $t\bar{t}$ contamination should be present. Within errors, these estimates agree with the data. When these data for $N_{jet} \leq 2$ are extrapolated to $N_{jet} \geq 3$ using the jet-scaling hypothesis, we obtain an estimated background in excellent agreement with that deduced above.

2.3. Cross-section results

The summary of expected $t\bar{t}$ signal events, background estimates, and events observed in the DØ data sample are summarized in Table 2. We observe seven signal events in the three independent analyses and expect a total of 3.2 ± 1.1 background events in this preliminary analysis. The significance of the excess 3.8 events over background can be assessed by calculating the probability that our expected background fluctuates to give at least seven data events, taking into account the Gaussian errors on backgrounds, acceptances and luminosity, and the Poisson errors on the number of events. This probability is 7.2% and corresponds to about 1.5 standard deviations in the Gaussian approximation. We conclude that the DØ experiment does not give significant evidence for an excess of events to be attributed to $t\bar{t}$ production.

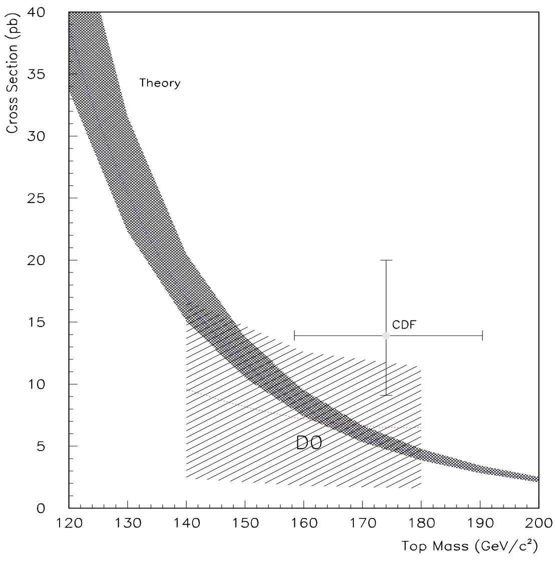

Figure 5. Cross-section *vs.* m_t. The dotted line and cross-hatched area give the DØ preliminary result for a range of possible top quark masses. The shaded band represents the theoretical NLO calculation of Ref [3] with its estimated theoretical errors. The CDF cross-section and mass value [2] are shown as the data point with errors.

We can transform our counting results above into a cross-section for $t\bar{t}$ production by dividing the background-subtracted number of events by the integrated luminosities and acceptances determined from the ISAJET Monte Carlo [21]. The acceptances vary with the assumed top mass, so the cross-sections for the given number of events fall somewhat as m_t increases. The preliminary results are shown in Table 3 and in Figure 5, together with the theoretical expectations [3] and the CDF result [2].

We conclude from Figure 5 that the preliminary DØ data are consistent with the SM expectations for m_t above about 140 GeV/c^2, and can accomodate an arbitrarily heavy top quark. The DØ result does not require the invocation of new physics for $t\bar{t}$ production. The DØ result is also consistent with the CDF counting experiment for $\sigma_{t\bar{t}}$ given the large errors on both experiments.

It is of interest to compare the sensitivity for $t\bar{t}$ production in DØ with that of CDF. To do this, we can compare the expected number of $t\bar{t}$ events in the two experiments for a given choice of $\sigma_{t\bar{t}}$. For this purpose we choose the CDF central value at m_t=174 GeV/c^2 of $\sigma_{t\bar{t}} = 13.9$ pb. This result corresponds to the CDF observation of 12 candidate events. After iterating the background estimate to allow for their excess signal contributions, CDF estimates there are 3.4 background events and 8.6 $t\bar{t}$ signal events. With the same cross-section, DØ would expect 3.2 background events and 8.2 $t\bar{t}$ signal events. Thus the two experiments presently have comparable sensitivity.

Analysis	**Dilepton Search**	**ℓ + jets Topological**	**ℓ + jets b-Tag**	**All Searches**
N($m_t = 140$)	1.4 ± 0.2	4.2 ± 0.9	1.3 ± 0.4	6.7 ± 1.2
N($m_t = 160$)	0.7 ± 0.1	2.8 ± 0.5	1.0 ± 0.2	4.4 ± 0.7
N($m_t = 180$)	0.4 ± 0.1	1.5 ± 0.3	0.6 ± 0.2	2.5 ± 0.4
Background	0.8 ± 0.1	1.8 ± 0.9	0.6 ± 0.2	3.2 ± 1.1
DATA	**1**	**4**	**2**	**7**

Table 2. Expected top signal for m_t = 140, 160, 180 GeV/c^2; expected backgrounds, and observed events for each of the three DØ top search analyses.

Top Mass (GeV/c^2)	**Cross Section (pb)**
140	**9.6 ± 7.2**
160	**7.2 ± 5.4**
180	**6.5 ± 4.9**

Table 3. Preliminary results from DØ for the $t\bar{t}$ cross-section.

From Figure 5 it is apparent that the combined results of DØ and CDF for $\sigma_{t\bar{t}}$ give a result which is more consistent with the SM prediction for $t\bar{t}$ production with m_t in the 140 - 180 GeV/c^2 range than the CDF results alone. Performing an average of the two experiment values is possible, but was not done at the time of the Conference. It will require a full-multichannel likelihood calculation for the several analyses of both experiments, taking into account the effects of positive and negative fluctuations of both signal and backgrounds. It should be done using a proper treatment of the correlated errors between the experiments and common choices for background cross-sections and iteration procedures. For these reasons, and because the DØ results are preliminary at this stage, the average has not been computed. However, it seems likely that the use of the DØ data will lower the significance in the combined analysis compared to that from CDF alone. I conclude that at this time, the experiments seeking the direct observation of the top quark are not sufficiently sensitive to give solid direct evidence for its existence. It is however true that the combined evidence from both experiments is suggestive that the effects of $t\bar{t}$ production are being observed in the Fermilab Tevatron experiments.

3. Comments on theoretical contributions to this Conference

Stimulated by the CDF report [2] that the cross-section for $t\bar{t}$ production could be larger than expected within the SM [3], several suggestions have been made which invoke new physics, either raising $\sigma_{t\bar{t}}$ or adding new processes which could mimic the top signature. As noted above, we believe that in view of the DØ results for $\sigma_{t\bar{t}}$ and the combined errors in the experimental measurements and in the theoretical calculations, it is by no means *necessary* at this time to invoke new physics.

Enhancements to the cross-section due to the production of new states which decay into $t\bar{t}$ pairs were discussed in two contributions to this conference. One [22] notes the possibility of producing the 'technieta' psuedoscalar particle (η_T), required in Technicolor theories. The second invokes the possible existence of color-octet vector mesons (V_8) [23]. Both η_T and V_8 decay dominantly into $t\bar{t}$ pairs, so would add to the experimentally observed cross-section. In both cases, the production of the new objects in standard gluon fusion and $\bar{q}q$ annihilations can be computed; reasonable enhancements (of order of a factor of 2) result for η_T or V_8 masses in the vicinity of 500 GeV/c^2.

The possibility for new weak iso-singlet quarks (present in some string-inspired models) was noted [24]. If these exist, one would expect a full set of all flavors of singlet quarks. The production of singlet quarks would be similar to the "ordinary" iso-doublet top quark when their masses are near m_t. The decays of the iso-singlet quarks involve ordinary vector bosons and quarks. For many flavors of the iso-singlet quarks, the decay patterns would be expected to disagree with known production and decay characteristics, but for the iso-singlet top in particular it is possible to envision enhancement in the signatures expected for the SM top quark.

Enhancement of ordinary top quark pairs would result in the case that anomalous couplings are present between the $t\bar{t}$ and scalar components of the theory. Such anomalous couplings arising from dynamical symmetry breaking considerations were examined [25] and found to be capable of producing up to a factor of two increase in $\sigma_{t\bar{t}}$.

Although we do not find that these mechanisms for signal enhancement are presently warranted by the data, these interesting comments point to the rich opportunities for the study of the top quark in the near future. In addition to increasing the signal cross-section, specific new physics processes make significant modifications to the top quark p_T and angular distributions, to the invariant mass distribution for $t\bar{t}$ pairs, and can give interesting departures from the SM decay patterns. They thus serve to emphasize that the direct searches for the top quark need to remain as free from Standard Model bias as possible. They reinforce the point that a massive top quark, with possible decays into a variety of new objects (*e.g.* the charged Higgs) and its sensitivity to extra non-SM production mechanisms, is a fertile ground for direct observation of new physics. The likely connection between a massive top quark and the mechanisms of symmetry breaking also suggests that crucial new insights could result from precision studies of its production and decay. Finally, the precision measurement of the mass of the top is crucial, since by comparison with the wealth of precision measurements in the electroweak sector one adds powerful constraints on the validity of the SM and on the value of the Higgs boson mass.

Prediction of the value of the top quark mass from general dynamical arguments has by now a long history [26]. Two additional predictions were presented to this conference. The first [27] exploits the likely heaviness of the top quark and its large Yukawa coupling to the Higgs to develop renormalization group constraints yielding a top quark mass prediction of 170 ± 5 GeV. The second is based on a geometrical “spin gauge” model [28] in which no Higgs bosons appear, but sum rules involving fermions and gauge bosons can be derived. In this model the top quark mass is predicted to be 151.7 ± 0.1 GeV. The attempts to calculate the top quark mass using dynamical or theoretical simplicity arguments may ultimately help illuminate fundamental issues concerning symmetry breaking in nature. We hope that in the near future, the experiments will have determined the mass with good precision and that these theoretical issues can come into clearer focus.

Some phenomenological issues for the experimental measurement of the mass of the top quark were discussed in this Conference. As is well known, the simplicity of the $t\bar{t}$ final state at the partonic level (*e.g.* for the lepton + jets mode, a lepton pair from one W, a di-quark from the other W, and a pair of b-quarks to be paired with each of the W's) can be substantially modified in the real experimental environment. In addition to the detector issues resulting from the definition of jets above a certain threshold in p_T with sufficient isolation from other objects in the event, there are complications from the possible presence of recognizable jets arising from QCD radiation. These gluon emissions can be from initial or final state partons, or indeed, as stressed in this conference [29], from interference diagrams which involve both initial and final state radiation. The possible omission of some of the primary parton jets and the possibile addition of radiative gluon jets compounds the combinatorial problems of associating the right jets into W and t states. Indeed Monte Carlo studies by the experimental groups have tended to show that fewer than 50% of the lepton + jets final states are reconstructed correctly. Improved techniques for identifying jets and their combinations into parent objects will be most welcome when the top quark becomes solidly established and attention turns to a precision measurement of its mass.

4. Conclusions

The search for the top quark in the DØ detector has been made in three independent decay modes: dilepton decays of the $t\bar{t}$ system; single lepton decays with topological tags; and a b-tagging analysis for the single electron decays. The sensitivity of the experiment is essentially the same as for the CDF analysis [2]. The DØ analysis finds a total of 7 candidate events, to be compared with an expected background of 3.2 ± 1.1 events. The statistical significance of this result is not sufficient to establish the top quark. The $t\bar{t}$ cross-sections deduced from the analyses are consistent with the Standard Model predictions, and with the CDF measurements. Taking the two experiments together, we find that there is not sufficient evidence to directly establish the existence of the top quark, though the small excess of events are in reasonable agreement with the indirect SM predictions based upon a variety of precision measurements of electroweak parameters.

The DØ results presented at this conference are preliminary. Additional analyses involving the muon + jets with a b-tag are in progress, as are more sophisticated selections based upon multivariate analyses (Neural Networks, Fisher discriminants, probability density estimators, etc.). The analysis of the lepton + jets events to yield mass estimates for a potential top quark are in progress. Most importantly, the Tevatron Collider is working efficiently in the current experimental run expected to continue through mid-1995, and should yield data sets of about four times that of the sample reported upon here.

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