

Top Quark Production at the Tevatron

Erich W. Varnes

for the CDF and DØ Collaborations

(1) *University of Arizona, 1118 E. 4th St., Tucson, AZ, USA 87521,*
[*varnes@physics.arizona.edu*](mailto:varnes@physics.arizona.edu)

Abstract

The Fermilab Tevatron has, until recently, been the only accelerator with sufficient energy to produce top quarks. The CDF and DØ experiments have collected large samples of top quarks. We report on recent top quark production measurements of the single top and $t\bar{t}$ production cross sections, as well as studies of the $t\bar{t}$ invariant mass distribution and a search for highly boosted top quarks.

Introduction

The top quark is unique among fermions in that its large mass implies a Yukawa coupling to the Higgs field of order unity. This may be a hint that the top quark plays a special role in electroweak symmetry breaking, which motivates the detailed study of the production on properties of the top quark.

We report here on recent measurements of top quark production from the CDF and DØ experiments at the Fermilab Tevatron. Both electroweak single top and strong $t\bar{t}$ production are considered, and a search for highly boosted top quarks and studies of the $t\bar{t}$ invariant mass distribution are reported.

Single Top Quark Production

The study of electroweak single top quark production allows direct measurement of the magnitude and nature of the tWb coupling [1]. However, the single top quark production rate is expected to be low, with the dominant s- and t-channel modes having cross sections at the Tevatron of 1.0 and 2.3 pb, respectively, in the SM [2]. In addition, detection of this mode is

experimentally challenging, as it is difficult to distinguish single top quark events from W +jet production, and the latter has a much larger cross section. To overcome this, both CDF and DØ consider only the semileptonic decay channels, make full use of the information from their detectors (including in particular b quark jet identification) and employ multivariate discriminants that combined the several kinematic quantities to estimate the consistency of a given event with single top production. The existence of single top production can then be inferred by comparing the distribution of discriminant values from data events to the expectation from background; single top events would create an excess at high values. To extract the maximum information from the data, both collaborations employ several types of discriminant (likelihood ratio, neural network, boosted decision tree, and matrix element), the outputs from which are combined into a final discriminant.

The results are shown in Fig. 1, where a clear excess above background in the top-like region is observed by both experiments. The excess observed by CDF corresponds to a cross section of $\sigma = 2.3^{+0.6}_{-0.5}$ pb [3] and that observed by DØ corresponds to $\sigma = 3.9 \pm 0.9$ pb [4].

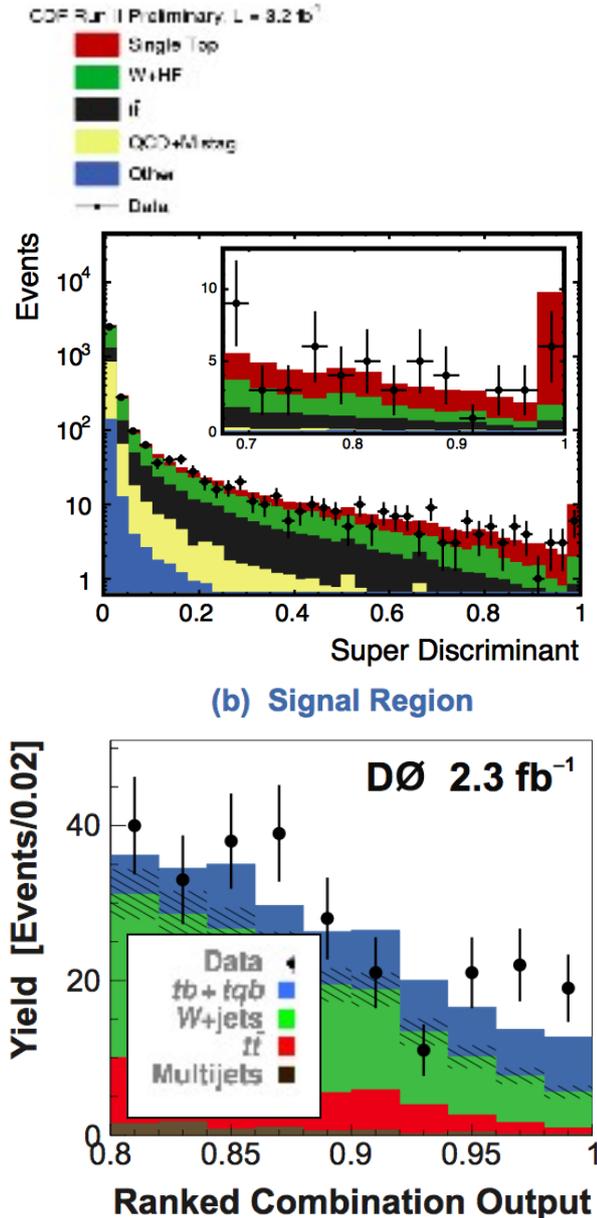


Figure 1. Distributions of combined single-top discriminant values from CDF [3] (top) and DØ [4] (bottom).

(CDF assumes a top quark mass of 170 GeV while DØ assumes a mass of 175 GeV when quoting single top quark results, so the measurements are not exactly comparable.) In both cases the significance of the excess is 5 standard deviations. Combination of the CDF and DØ measurements gives a single top production cross section of $2.76^{+0.58}_{-0.47}$ (stat.+syst.) pb [5].

The above production rates can be translated to measurements of $|V_{tb}|$, with CDF finding

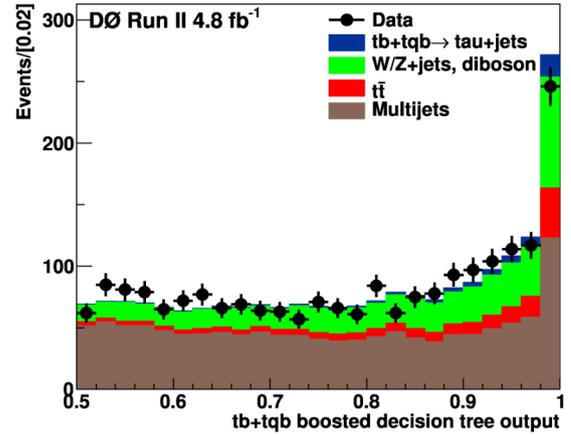


Figure 2. Distribution of the boosted decision tree output for single top quark candidates in the tau+jets final state at DØ [6].

that $|V_{tb}| > 0.71$ while DØ finds that $|V_{tb}| > 0.78$ (all limits in this article are at the 95% C.L.). The combined limit considering both the CDF and DØ measurements is $|V_{tb}| > 0.77$. These measurements are consistent with the assumption that the three-generation CKM matrix is unitary, and therefore that $|V_{tb}|$ must be very close to one.

Further insight into the physics of the tWb vertex is obtained by measuring the cross-sections for s- and t-channel single top production separately, taking advantage of the differences in jet multiplicity and final-state kinematics between the two production mechanisms. CDF measures

$\sigma_s = 1.8^{+0.7}_{-0.5}$ pb and $\sigma_s = 0.8 \pm 0.4$ pb while DØ measures $\sigma_s = 1.05 \pm 0.81$ pb and

$\sigma_s = 3.14^{+0.94}_{-0.80}$ pb. In all cases the results are consistent with the SM prediction. The sensitivity of these measurements to new physics will increase as statistics are accumulated.

A recent result is the measurement of the single top production cross section in the τ +jets channel by DØ. Tau leptons appear as narrow jets (perhaps containing an electromagnetic subcluster) with 1, 2, or 3 charged tracks in the jet cone, depending on the τ decay mode. They are identified using kinematic selections and neural networks that are optimized separately

for each τ signature. A boosted decision tree is then used to distinguish the signal events from background, as shown in Fig. 2. Using 4.8 fb^{-1} of data, DØ finds $\sigma = 3.4^{+2.0}_{-1.8} \text{ pb}$ (stat.+syst.) [6].

Looking to the future, increased statistics from the Tevatron and the advent of the LHC will greatly improve the precision with which the SM can be tested via single top production. This is an area where the Tevatron will remain competitive with the LHC for some time, as the $q\bar{q}$ initial state enhances s-channel production at the Tevatron.

Top Quark Pair Production

Since strong $t\bar{t}$ production gives rise to signatures that are more readily distinguished from background, and has a larger cross section than single top quark production, most top quark measurements are based on $t\bar{t}$ production. These measurements are used to test the SM predictions of many aspects of top quark production.

The most direct of these tests is a comparison of the measured cross section with the prediction from QCD. The full NLO calculation has been done, and there are a variety of calculations that account in part for NNLO effects. Assuming a top quark mass of 175 GeV, the predicted cross sections range from 6.3 to 7.1 pb, with uncertainties of $< 10\%$ [7].

The most sensitive cross section measurements are performed using the $\ell + \text{jets}$ decay channel in which one of the W bosons in the event decays leptonically (where the lepton is an electron or muon) and the other W boson decays to quarks. This channel has the advantage of a relatively large branching ratio ($\sim 30\%$) with manageable backgrounds. One can perform a cross section measurement in this channel by using a multivariate discriminant to separate signal from background, or by requiring that at least one jet in the event be identified as a b quark jet.. The measurement can also be done as a direct rate measurement (as DØ does), or as a ratio of the

rates of $t\bar{t}$ to Z boson production (as CDF does). The latter method is not subject to the uncertainty on the measured integrated luminosity, but does depend on theoretical input for the Z boson production cross section to extract the $t\bar{t}$ cross section.

Without the requirement of an identified b quark jet, CDF measures [8]:

$$\sigma_{t\bar{t}} = 7.8 \pm 0.4 \text{ (stat.)} \pm 0.4 \text{ (syst.)} \pm 0.2 \text{ (theory) pb}$$

and DØ measures [9]:

$$\sigma_{t\bar{t}} = 7.70^{+0.79}_{-0.70} \text{ (stat. + syst. + lumi.) pb.}$$

With an identified b jet required, CDF measures [8]:

$$\sigma_{t\bar{t}} = 7.3 \pm 0.4 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \pm 0.1 \text{ (theory) pb}$$

and DØ measures [9]

$$\sigma_{t\bar{t}} = 7.93^{+1.04}_{-0.91} \text{ (stat. + syst. + lumi.) pb.}$$

Examples of jet multiplicity distributions for $t\bar{t}$ candidates at CDF and DØ are presented in Fig. 3.

DØ has recently extended the measurement by considering the $\tau + \text{jets}$ channel, which is of particular interest since supersymmetry with high $\tan\beta$ and a charged Higgs mass less than the top quark mass would result in a substantial deviation of the top quark branching ratio to tau leptons. Using the same τ identification tools as the single top analysis described above, and a neural network to distinguish signal from background, DØ measures [10]:

$$\sigma_{t\bar{t}} = 6.9 \pm 1.2 \text{ (stat.)}^{+0.8}_{-0.7} \text{ (syst.)} \pm 0.4 \text{ (lumi.) pb.}$$

The neural network output distributions for two classes of τ decays are shown in Fig. 4.

The dilepton decay channel, in which both W bosons decay to leptons, is readily distinguishable from background, but has a small branching ratio, accounting for only $\sim 5\%$ of $t\bar{t}$ decays. CDF has measured the cross section in this mode, both by using kinematic information only and by requiring an identified b quark jet [11]. The former analysis finds:

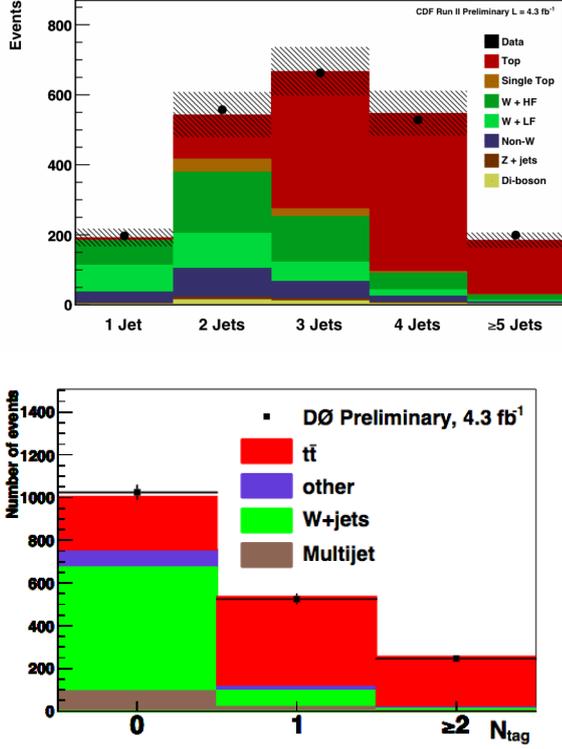


Figure 3. Distribution of the total jet multiplicity observed in top quark pair candidates with at least one identified b quark jet at CDF [8] (top), and the distribution of the number of identified b quark jets in top quark pair candidates from DØ [9] (bottom).

$\sigma_{\bar{t}t} = 7.4 \pm 0.6$ (stat.) ± 0.6 (syst.) ± 0.5 (lumi.) pb while the latter finds:

$$\sigma_{\bar{t}t} = 7.3 \pm 0.7$$
 (stat.) ± 0.5 (syst.) ± 0.4 (lumi.) pb.

DØ's measurement in this mode uses only kinematic information, and finds [12]:

$$\sigma_{\bar{t}t} = 8.2 \pm 0.5$$
 (stat.) $^{+0.9}_{-0.8}$ (syst.) $^{+0.7}_{-0.6}$ (lumi.) pb

Jet multiplicity distributions for dilepton candidates at CDF and DØ are shown in Fig. 5.

The all-hadronic channel, in which both W bosons decay to quark pairs, has the largest branching fraction of any $\bar{t}t$ final state (44%), but is difficult to distinguish from the large multijet background. Nonetheless, both CDF and DØ have measured the cross section in this mode, exploiting both b quark jet identification and multivariate kinematic discriminants to

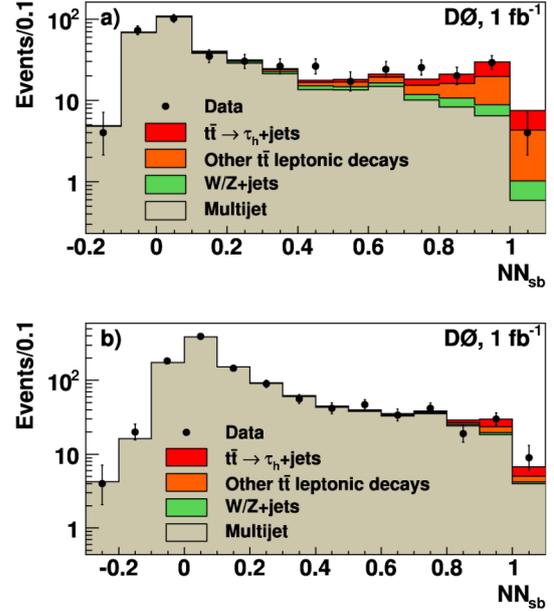


Figure 4. Distribution of neural network output values for top quark pair candidate events in the tau+jets final state at DØ, where the tau candidates have one (a) or two or three (b) associated charged tracks [10].

separate signal from background. Based on a sample of 2.9 fb⁻¹, CDF measures [13]:

$$\sigma_{\bar{t}t} = 7.2 \pm 0.5$$
 (stat.) ± 1.0 (syst.) ± 0.4 (lumi.) pb in his mode, while DØ measures [14]:

$$\sigma_{\bar{t}t} = 6.9 \pm 1.3$$
 (stat.) ± 1.4 (syst.) ± 0.4 (lumi.) pb

A unique decay signature explored by CDF is the missing E_T + jets channel, for which 2-3 jets (at least one of which is identified as a b quark jet) and large missing E_T are required. Events with identified leptons are vetoed. This signature is also of interest in some Higgs boson and beyond SM searches such as $\tilde{b}\tilde{b} \rightarrow b\bar{b}\chi\chi$. Therefore it is important to constrain the contribution to this mode from top quark production. Since backgrounds are still large after the initial selection, the surviving events are passed through two neural networks, the first of which is trained to differentiate QCD multijet events from any other source, and the second of which is trained to distinguish $\bar{t}t$ events from those with W or Z bosons. The output from the final neural network is shown in Fig. 6. Using a 5.7 fb⁻¹ sample, CDF measures $\sigma_{\bar{t}t} = 7.12^{+1.20}_{-1.12}$ pb in this mode [15].

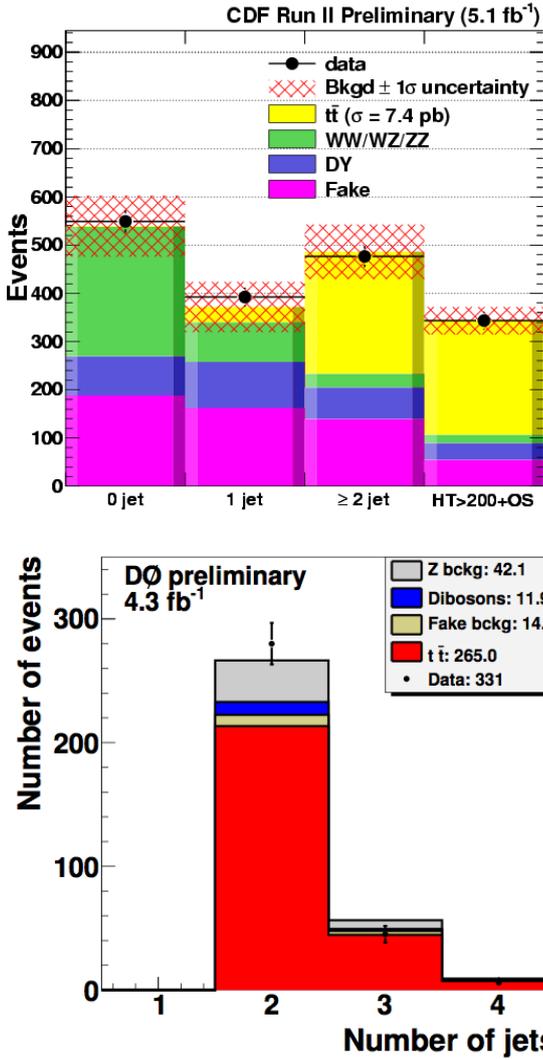


Figure 5. Distribution of jet multiplicity for dilepton top quark pair candidates observed at CDF [11] (top), with the rightmost bin containing only the events that satisfy the final kinematic requirements, and the jet multiplicity distribution of dilepton top quark pair candidates observed at DØ [12] (bottom).

In addition to testing the predicted inclusive production rate, other interesting tests of QCD can also be performed by measuring the cross section in subsets of the final state phase space. CDF has made two such measurements, the first of which focuses on the production of an additional jet along with the $t\bar{t}$ pair. At NLO, it is expected that the cross section for $t\bar{t}$ production associated with an additional jet with p_T of 20 GeV or greater is $1.79^{+0.16}_{-0.31}$ pb. CDF's measurement, which is based upon the jet multiplicity distribution for $t\bar{t}$ candidate

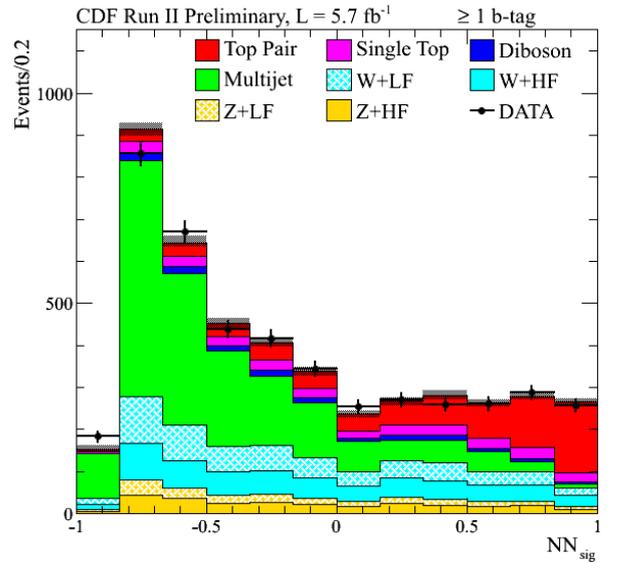


Figure 6. Distributions of values of the final neural network discriminant for events in the missing E_T plus jets channel at CDF [15].

events in which at least one jet is identified as a b quark jet, yields [16]:

$$\sigma_{t\bar{t}+j} = 1.6 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (syst.) pb.}$$

Another measurement from CDF constrains the p_T distribution of the $t\bar{t}$ system by looking for highly boosted top quarks with $p_T > 400$ GeV. In the SM, only a small fraction (5.6×10^{-4}) of top quarks is expected to have such large transverse momentum. Furthermore, since the top decay products will often be contained within a single jet cone for such highly boosted top quarks, the search strategy required is fundamentally different than that used in other top quark measurements, in that it depends upon investigating the structure of individual jets. The search is carried out in two modes, one for the case where both top quarks decay hadronically and one for the case where one top quark decays semileptonically. In the all-hadronic mode, the invariant masses of the two jets in the events are considered. For $t\bar{t}$ events these masses should be close to the top quark mass, while for background events the jet mass distribution peaks at low values. Since the masses of the two jets are uncorrelated in both signal and background, one can use the two one-dimensional jet mass distributions to predict the number of background events in a signal region where both jets are required to be near the top quark

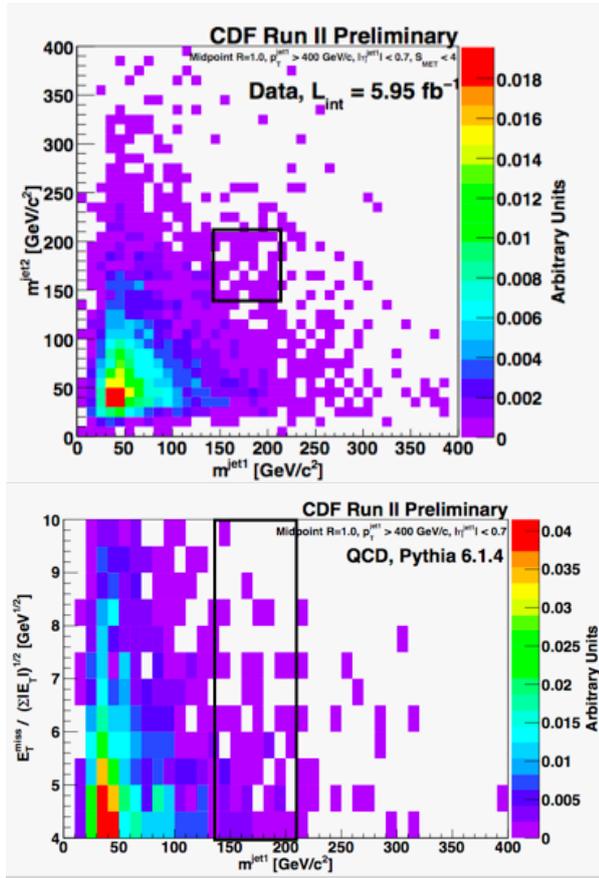


Figure 7. Candidates for highly boosted top quark production observed at CDF [17]. The upper plot shows candidates in the all-hadronic mode with the axes being the invariant mass of each top quark jet. The bottom plot show semileptonic candidates, where the missing E_T significance is plotted against the invariant mass of the hadronic jet. The black boxes bound the signal region in each channel.

mass. The analysis is similar in the semileptonic case, with the exception that the missing E_T significance, rather than the jet mass, is considered for the jet that contains a lepton. The distributions of candidate events in these variables are shown in Fig. 7. A combination of the searches in the two channels yields an upper limit on the production rate for highly boosted top quarks [17]:

$$\sigma_{\bar{p}p \rightarrow t\bar{t} + X; p_T(t) > 400 \text{ GeV}} < 54 \text{ fb @ 95\% C.L.}$$

to be compared to the SM prediction [7] of $4.55^{+0.50}_{-0.41}$ fb.

The final analysis considered here is a study of the invariant mass distribution of the $t\bar{t}$ pairs.

This distribution is sensitive to a variety of non-SM contributions to $t\bar{t}$ production; in

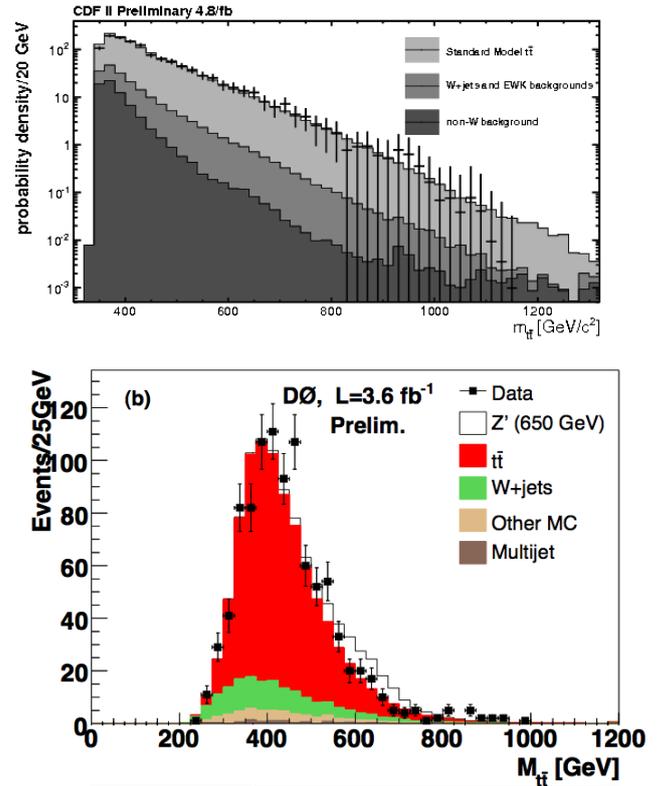


Figure 8. Distributions of the top quark pair invariant mass observed by CDF [18] (top) and DØ [19] (bottom).

particular a contribution from the decay of a heavy resonance to $t\bar{t}$ would appear as a peak in the distribution. For this reason, the results are typically reported as limits on the properties of such resonances, with a fermiophobic Z' resonance taken as a typical model. Both CDF and DØ use the lepton+jets channel to investigate the $m_{t\bar{t}}$ distribution. For both experiments, the distribution (shown in Fig. 8) is found to be consistent with the SM expectation. Translating these findings into mass limits for a Z' boson yields $m_{Z'} > 900$ GeV based on 4.8 fb^{-1} at CDF [18] and $m_{Z'} > 820$ GeV based on 3.6 fb^{-1} at DØ [19].

Conclusions

The CDF and DØ experiments at the Fermilab Tevatron collider have carried out extensive tests of top quark production, both with single top quarks produced by the electroweak

interaction and with top quark pairs produced by the strong interaction. No significant indication of physics beyond the standard model has appeared, which allows constraints to be placed upon several models of new physics. In addition, the observation of single top quark production has provided the first measurement of $|V_{tb}|$ that does not rely on assuming that only three fermion generations exist.

In the coming years the precision of many top quark production measurements will be greatly improved due to the large samples that will be available from the LHC, but there are areas (in particular, single top quark production via the s channel) where the Tevatron will continue to have the best sensitivity for some time.

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