Top Quark Physics at the Tevatron

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Precision studies of the top quark are a prime goal of the Run II physics program at the Fermilab Tevatron. Since the start of Run II in early 2002, the CDF and DØ experiments have analyzed approximately 100 pb^{-1} of data and have re-established the top quark signal. In this article I summarize recent measurements of the top production cross section and mass.

The top quark is the heaviest, rarest, and nearly the most unstable known elementary particle. Its observation by the CDF[1] and DØ[2] collaborations in 1995 marked the start of an extensive program to characterize this most unusual object. Analyses of approximately 110 pb^{-1} of data from the 1992-96 run of the Fermilab Tevatron ("Run I") yielded measurements in several channels of basic top quark properties such as its production cross section[4, 5] and mass[6, 7]. In addition, first results were obtained on the helicity of W bosons in top decays[8], and limits were placed on electroweak production of single top quarks[9, 10], resonant production of $t\bar{t}$[11, 12], FCNC decays[13], and decays to charged higgs[14, 15]. From these studies, a picture emerged of a top quark with a mass of 174.3 ± 5.1 GeV/c^2 and properties generally consistent with Standard Model predictions. However, the precision of these measurements was limited by statistics, as only $\approx$100 analyzable top quark events were recorded in Run I. A major physics goal of Run II, which started in early 2002, is a high-statistics study of the top quark with several inverse femtobarns of data. This program is unique to the Tevatron until the start of LHC running.

The Fermilab accelerator complex underwent extensive upgrades for Run II. These included an increase in the center-of-mass energy from 1.8 to 1.96 TeV, which results in a 30-40% increase in the top pair production cross section. Improvements to the proton linac and booster and to the antiproton accumulator, as well as the commissioning of the Main Injector, promise an eventual factor-of-eight increase in the Tevatron peak luminosity compared with Run I, although to date only factors of two to three have been obtained. Through summer 2003, approximately 250 pb^{-1} of data, more than twice the Run I total, have been collected by each experiment, with a goal of an additional 310-380 pb^{-1} in 2004. By the end of 2005, the delivered luminosity should reach 1 fb^{-1}.

The CDF and DØ detectors have also undergone major upgrades[16]. DØ has added a magnetic tracking system with scintillating fibers and a silicon vertex detector, in addition to a preshower detector and an upgraded muon system. CDF has added a new silicon vertex detector, outer tracker, and endplug calorimeter, and has extended the muon coverage. Both experiments have installed entirely new data acquisition and trigger systems to exploit the new detector elements and deal with the decrease in the Tevatron bunch crossing interval from 3.5 μs to 396 ns. These upgrades have been fully commissioned, and both experiments are now taking data with roughly 90% efficiency.

In this article I present selected results from the first $\approx$100 pb^{-1} of data. Any such compilation is necessarily incomplete, and rapidly becomes obsolete. For the latest results, the reader should consult the public CDF and DØ web pages[17].

TOP QUARK PRODUCTION AND EVENT SELECTION

Top quarks are pair-produced at the Tevatron through $q\bar{q}$ or gg annihilation, with a cross section of roughly 7 pb[18]. In addition, single top quarks can be produced through electroweak interactions, with a cross section of approximately 3 pb. However, single top production yields final states with significantly larger backgrounds than $t\bar{t}$, and consequently this process has not yet been directly observed. The analyses presented here focus on the $t\bar{t}$ process.

In Standard Model $t\bar{t}$ production, each top quark decays promptly to a W boson and a b quark. Each W then decays to either a charged lepton and its neutrino, or to a quark-antiquark pair that appears in the detector as jets. Studies of the top quark focus on two types of these final states: the *dilepton* and *lepton plus jets* modes. The dilepton final state, representing 4/81 of $t\bar{t}$ decays, occurs when both W's decay into an electron or muon and a neutrino. This mode is characterized by two isolated leptons with large transverse momentum P_T, two b jets, and missing transverse energy ($\not\!\!E_T$) from the undetected neutrinos. Although the branching fraction to dileptons is low, this final state is particularly clean. The lepton+jets final state, with a branching fraction of approximately 24/81, occurs when one W decays to an electron or muon plus a neutrino and the other W decays to jets. These final states contain a single high-P_T lepton, significant $\not\!\!E_T$, and (nominally) four jets, two of which are from b's. In practice, jets can be merged or lost, and additional jets can result from initial- or final-state gluon radiation, so analyses of the lepton plus jets channel typically require three or more jets.

Other final states involve $W \rightarrow \tau\nu$ decays or decays of both W's to jets. While top has been observed and studied in both of these channels, the backgrounds are much larger than in the dilepton and lepton plus jets cases. The first Run II analyses therefore emphasise the latter decay modes.

The presence of two b jets in each $t\bar{t}$ event provides a powerful additional handle for selecting and studying top. The finite b lifetime results in secondary decay vertices that can be "tagged" using precision tracking. Such a capability is provided by the CDF and DØ silicon vertex detectors, which allow event-tagging efficiencies on the order of 50%. In addition, b's can be identified through their semileptonic decays to an electron or muon. These "soft" leptons (so-called to distinguish them from the primary "hard" lepton from W decay) are typically found in or near jets from the rest of the b fragmentation and decay. Because most backgrounds to top, such as W+jets events or QCD fakes, contain relatively few b's, b-tagging is very effective at enriching samples of top candidates.

A final selection technique exploits the kinematic differences between top and its various backgrounds. Jets in top events tend to be more energetic, and the event topology more spherical, than in background events. Both experiments sometimes make use of the H_T variable, defined by DØ to be the scalar summed E_T of the jets, and by CDF to be the scaler summed E_T of the jets and lepton(s), plus the magnitude of the $\not\!\!E_T$. Event-shape variables such as sphericity and aplanarity are also sometimes used, either as part of the initial event selection or as subsequent probes of top kinematics.

MEASUREMENTS OF THE TOP PRODUCTION CROSS SECTION

The production cross section for $t\bar{t}$ is interesting in its own right as a test of QCD. In addition, it is a vital engineering measurement, because it assembles all the essential tools of top physics: detailed knowledge of event selection efficiencies, b-tagging techniques, and background normalizations and shapes. The event samples selected for measurements of the $t\bar{t}$ cross section form the starting point for many subsequent analyses, such as the mass and W helicity measurements. CDF and DØ have carried out measurements of the $t\bar{t}$ cross section in both the dilepton and lepton plus jets channels.

The dilepton channel is sufficiently clean that b-tagging is not required to reduce backgrounds, which come primarily from $Z \rightarrow \tau\tau$, Drell-Yan production of e^+e^- and $\mu^+\mu^-$ pairs, WW and WZ production, and QCD fakes. CDF has carried out two complementary analyses using 126 pb^{-1} of data. The first analysis requires two good-quality leptons with $P_T > 20$ GeV/c, $\not\!\!E_T > 25$ GeV, at least two jets with $E_T > 10$ GeV, and a large total transverse energy, $H_T > 200$ GeV. This analysis identifies 10 candidate events (2 ee, 3 $\mu\mu$, 5 $e\mu$), with an expected background of 2.9 ± 0.9 events. The resulting cross section is

$$\sigma_{t\bar{t}} = 7.6 \pm 3.4(\text{stat}) \pm 1.5(\text{sys}) \text{ pb}.$$

Although b-tagging is not required for the event selection, we note that six of the ten candidates are tagged with the secondary-vertex tagger, including one event with a double tag. This tag yield is consistent with the expectation from top of four tagged events. The second CDF analysis imposes similar selection cuts, but allows looser requirements on the second lepton in the event. This increases the acceptance at the price of somewhat larger backgrounds. Thirteen dilepton candidates (five with b-tags) are identified, with a background of 5.1 ± 0.9 events. The resulting cross section is $7.3 \pm 3.4 \pm 1.7$ pb. There is significant event overlap in the two CDF dilepton analyses. Some kinematic properties of the events in the looser analysis

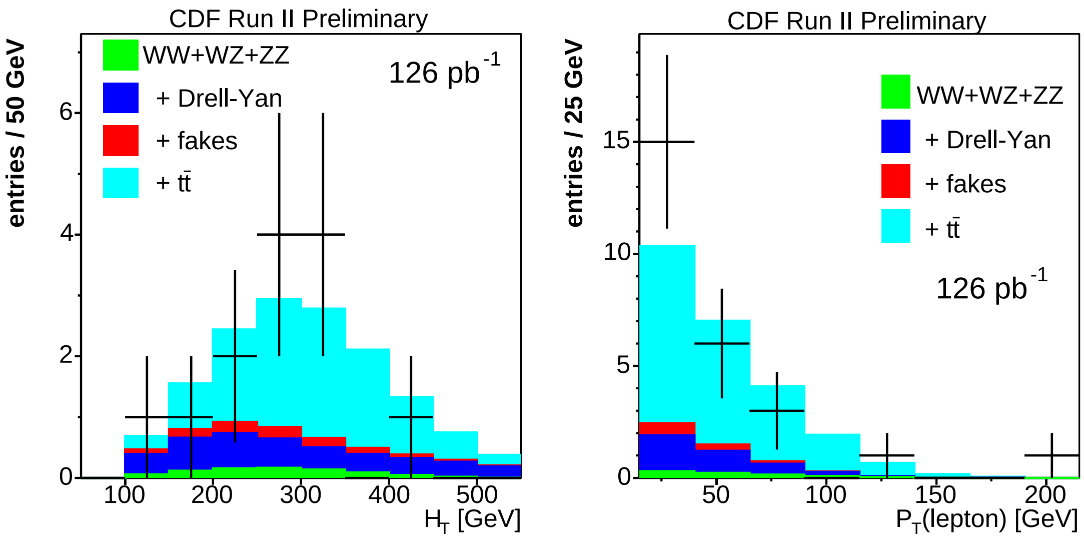

FIG. 1: Total transverse energy H_T (left) and lepton transverse momentum P_T (right) for the CDF dilepton sample.

are illustrated in Figure 1. DØ has also carried out analyses in the ee, $\mu\mu$, and $e\mu$ channels. Five events (2 ee, 0 $\mu\mu$, and 3 $e\mu$) are observed, with a total background of 1.7 ± 0.8 events. The resulting cross section is

$$\sigma_{t\bar{t}} = 8.7^{+6.4}_{-4.7}(\mathrm{stat})^{+2.7}_{-2.0}(\mathrm{sys}) \pm 0.9(\mathrm{lum}).$$

In the lepton plus jets channel, backgrounds are larger, so b-tagging or topological/kinematic cuts must be used to reduce them. DØ has pursued two complementary analyses that rely on each approach. First, a common W sample is selected by requiring an electron or muon with $P_T > 20$ GeV/c and $\not{E}_T > 20$ GeV. In the soft muon tag analysis, at least three jets are required, and loose topological cuts on H_T (> 110 GeV) and aplanarity (> 0.04) are applied. Then soft ($P_T > 4$ GeV/c) muons are searched for near the jet axes. The fake tagging rate is estimated using jet data. Fifteen tagged events are observed, with an expected background of 3.3 ± 1.3 events. The second DØ analysis begins with the same parent W sample. Events containing a soft muon tag are removed, so that the two analyses are orthogonal by construction. Four jets are required, and tighter cuts on H_T and aplanarity are applied. The main remaining backgrounds come from non-W QCD fakes, and W+jets. Backgrounds from the first source are estimated from QCD control samples, while the background from W+jets is estimated from the Berends scaling hypothesis, which states that the ratio of the $W + (n + 1)$ to the $W + n$-jet cross sections is independent of the number of jets. Since there is little top contribution to the $W + 0, 1, 2$ and 3-jet samples, this scaling rule can be used to predict the $W + 4$-jet background in the top signal sample. A total of 26 events with a background of 18.5 ± 2.5 are observed in approximately 90 pb^{-1} of e+jets and μ+jets data. The combined DØ lepton+jets cross section is

$$\sigma_{t\bar{t}} = 8.0^{+2.4}_{-2.1}(\mathrm{stat})^{+1.7}_{-1.5}(\mathrm{sys}) \pm 0.8(\mathrm{lum}).$$

The CDF lepton plus jets analysis emphasizes secondary-vertex b-tagging to reduce backgrounds. An inclusive W sample is selected by requiring an electron or muon with $P_T > 20$ GeV/c and $\not{E}_T > 20$ GeV. Top is expected to appear in the subsample with ≥ 3 jets with $E_T > 15$ GeV and pseudorapidity $|\eta| < 2$. After b-tagging, the dominant backgrounds come from mistags, $Wb\bar{b}$, $Wc\bar{c}$, and non-W events containing a real or fake b. Mistags and non-W backgrounds are estimated from QCD control samples. The W plus heavy flavor backgrounds are estimated by using Monte Carlo to calculate the fraction of W+jets events that contain at least one b or c jet, then normalizing to the total number of W+jets events observed in the data. In 108 pb^{-1} of data, this analysis identifies 35 b-tagged events in the $W+ \geq 3$-jet sample, with an

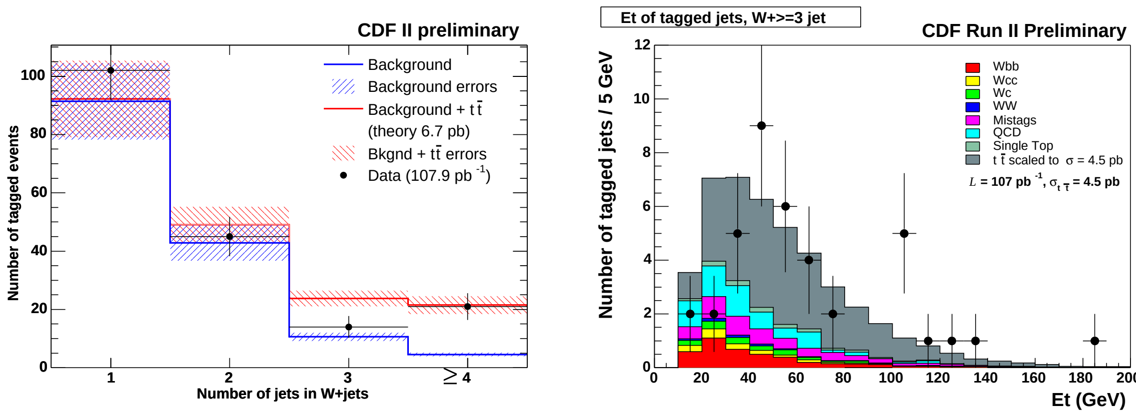

FIG. 2: Left: Jet multiplicity in the CDF lepton plus jets analysis after b-tagging. Right: E_T distribution of the b-tagged jets in the $W+\geq 3$-jet subsample.

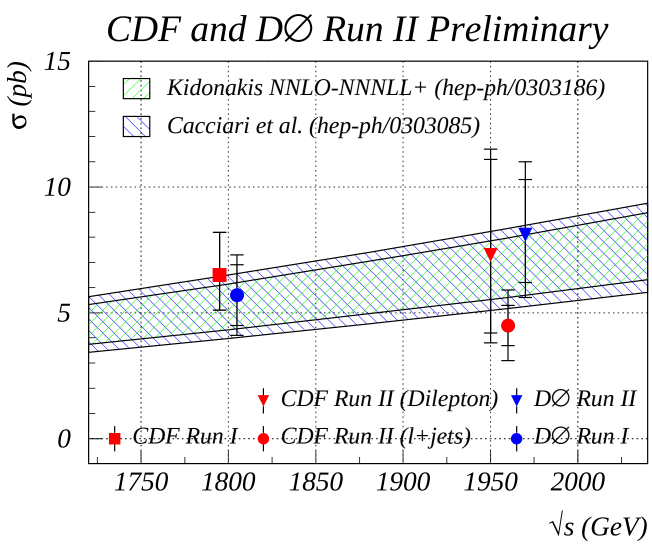

FIG. 3: Summary of CDF and DØ cross section measurements from Run I and Run II.

estimated background of 15.1 ± 2.0 events. Figure 2 shows the jet multiplicity and E_T distributions in this sample. This analysis gives a measured $t\bar{t}$ cross section of

$$\sigma_{t\bar{t}} = 4.5 \pm 1.4 \pm 0.8 \text{ pb}.$$

Figure 3 summarizes the Run I and Run II measurements of the top quark production cross section.

THE TOP QUARK MASS

The top quark mass is a precision electroweak parameter that enters electroweak predictions via radiative corrections. In particular, a precision top mass measurement can be used to constrain the mass of the Higgs. CDF has carried out a measurement of the top mass using the Run II lepton plus jets data. Event selection is identical to that of the lepton plus jets cross section analysis. At least four jets are required with $|\eta| < 2$. Three jets must have $E_T > 15$ GeV, while the fourth must have $E_T > 8$ GeV. At least one of the jets with

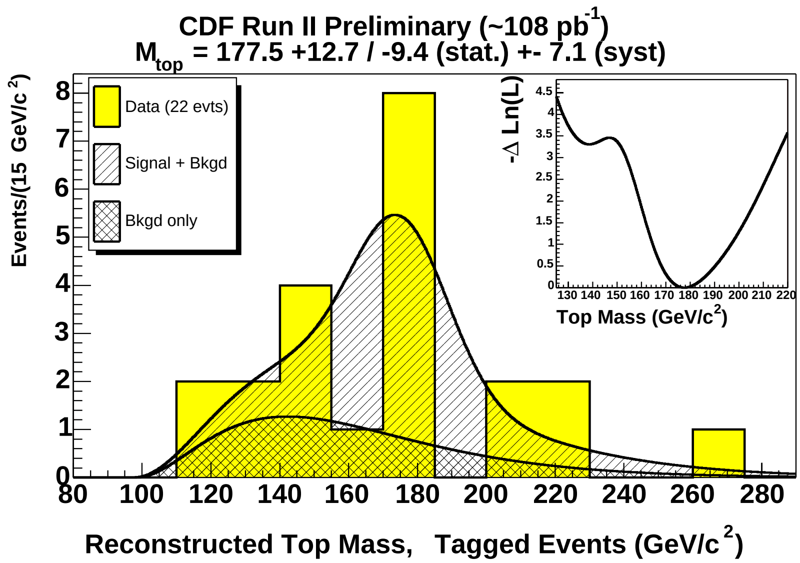

FIG. 4: Reconstructed top mass distribution for events in the CDF mass fit sample.

$E_T > 15$ GeV must be b-tagged by the secondary-vertex algorithm. Jet energies are corrected back to the parton level using a set of corrections developed for generic jets; in addition a set of top-specific corrections are applied (to account, for example, for the presence of neutrinos in b jets). Each event is then passed through a constrained fit to test each of the 24 possible combinations (12 ways to assign the jets to partons from $t\bar{t}$ decay, times two possibilities for the neutrino longitudinal momentum) for consistency with the $t\bar{t}$ hypothesis. The reconstructed combination with the lowest χ^2 from the fit is taken as the best estimator of the top mass from each event. Finally, to extract the top mass, the distribution of these reconstructed top masses is fitted to Monte Carlo background and signal templates generated with different values of $m_{\rm top}$. This distribution, together with the resulting likelihood fit, is shown in Figure 4. The resulting top mass is

$$m_{\rm top} = 177.5^{+12.7}_{-9.4}({\rm stat}) \pm 7.1({\rm sys})\ {\rm GeV}/c^2.$$

The systematic uncertainty is dominated by the jet energy scale, which enters when observed jet energies are corrected back to the parton level. This will improve with better understanding of the calorimeter performance.

DØ has not yet reported a Run II top mass measurement, but has recently released a significantly improved measurement using Run I data. The method uses a matrix element based event-by-event likelihood method, similar to that proposed in Ref. [19]. In contrast to the template method used by both CDF and DØ in previous analyses, all permutations of jet-parton assignments and neutrino solutions contribute with their appropriate weight, as determined by the $t\bar{t}$ matrix element and a transfer function that relates measured to produced quanties. All measured quantities, not just selected variables, are taken into account. Each event contributes its own probability distribution, with well-measured events carrying greater weight. This "optimized" method is described in detail in Ref. [20]. Applied to 125 pb^{-1} of Run I data, this technique yields

$$m_{\rm top} = 180.1 \pm 3.6({\rm stat}) \pm 4.0({\rm syst})\ {\rm GeV}/c^2.$$

The previous DØ measurement in this data set using the template method had a statistical uncertainty of 5.6 GeV/c^2, so this technique represents a significant advance. The matrix element can be generalized to include a dependence on quantities besides $m_{\rm top}$, for example the W helicity.

CONCLUSIONS

The Tevatron experiments have succeeded in re-establishing the top quark signal in the first 100 pb^{-1} of Run II data. Integrated luminosity is increasing rapidly, and within a few years should exceed this total by an order of magnitude. While improved measurements of the top cross section and mass will remain of interest, future analyses will look beyond these baseline quantities to a complete characterization of top quark's properties in all possible final states. Many such analyses are already in progress. Before the end of Run II, these will result either in ever more stringent constraints on new physics or in the surprises that point the way to physics beyond the Standard Model.

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