FERMILAB-Conf-03/384-E December 2003

CDF/PUB/TOP/PUBLIC/6740
Version 1.0

Top Quark Cross-Section Measurements at the Tevatron

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Abstract. Run II of the Tevatron collider at Fermilab is well under way and data samples larger than those of Run I are at hand. In this contribution I summarize the current status of cross-section measurements for top-quark pair ($t\bar{t}$) production at the CDF and DØ experiments.

1 Introduction

The Tevatron accelerator complex at Fermilab underwent a major upgrade to prepare for Run II. Among other measures the beam energy was increased from 800 to 980 GeV, which leads to higher cross-sections for the production of heavy particles. The $t\bar{t}$ cross-section is expected to increase by about 30%. Several other changes allow higher beam currents and thereby lead to a higher instantaneous luminosity. The aim for Run II is to achieve $\mathcal{L} = 5 - 20 \cdot 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The highest luminosity reached to date is $5.2\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Until early September 2003 the Tevatron had delivered 240 pb^{-1}.

In preparation for Run II both collider detectors were upgraded as well. New silicon trackers were installed. DØ added a solenoid in the bore of the detector to facilitate momentum measurements for charged particles. The main tracking chambers were replaced. CDF installed a new drift chamber, DØ a scintillating fiber tracker. CDF replaced its plug calorimeter and extended its muon coverage. Both experiments completely renewed their trigger and data acquisition systems.

The top physics program at the Tevatron comprises an exciting variety of topics. While the $t\bar{t}$ cross-section measurements test perturbative QCD, many other analysis investigate the nature of the top quark: The top mass measurement is an important input to standard model fits and constraining the mass of the Higgs boson. Measurements of the helicity of W bosons from top quark decays test the $V-A$ structure of the charged current. The search for anomalous top quark decays such as $t \to u/c + \gamma/Z/g$ allow to look for flavor-changing neutral currents and new physics. Searches for top decays to a charged Higgs boson, $t \to b + H^+$ allow to test SUSY models. While this article is concerned with the $t\bar{t}$ cross-section measurement, several of these topics are covered by other contributions to these proceedings [1–4].

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2 Top Quark Pair Production

At the Tevatron top quarks are predominantly produced as quark-antiquark pairs via the strong interaction. About 80 to 90% of the $t\bar{t}$ cross-section are due the quark-antiquark annihilation process $q\bar{q} \to t\bar{t}$, the remaining share is due to gluon-gluon fusion. Due to its large width ($\Gamma \simeq$ 1.4 GeV) the top quark does not hadronize, but rather decays as a free quark. In the standard model top quarks decay almost entirely in the mode $t \to W^+ + b$ (BR $\simeq$ 100%). This is an underlying assumption for all cross-section measurements discussed in this article.

Experimentally $t\bar{t}$ events are classified according to the subsequent decays of the two W bosons coming from the top quarks. The W decay modes are: $e\nu$, $\mu\nu$, $\tau\nu$ and $q_1\bar{q}_2$. If both W bosons decay into light leptons ($e\nu$ or $\mu\nu$) the $t\bar{t}$ event is called a *di-lepton* event (4/81 of all $t\bar{t}$ events). If one W decays to $e\nu$ or $\mu\nu$ and the other W decays into two quarks, the event belongs to the category *lepton-plus-jets* (24/81 of $t\bar{t}$ events). The case where both W's decay hadronically is called *all-hadronic* channel (36/81). The remaining events fall into the category where at least one W decays to $\tau\nu$ (17/81).

In Run I ($\sqrt{s}$ = 1.80 TeV) CDF and DØ have measured the $t\bar{t}$ cross-section in the di-lepton, the lepton-plus-jets and the all-hadronic channel. The combined cross-section of all channels is $6.5^{+1.7}_{-1.4}$ pb for CDF and (5.9 ± 1.6) pb for DØ . In the following paragraphs I will discuss preliminary results of cross-section measurements in the di-lepton and the lepton-plus-jets channel for Run II.

3 Di-lepton Channel

The di-lepton $t\bar{t}$ decay mode features a fairly clean signature and a low background level, however it suffers statistically from a small branching ratio. The classical di-lepton analysis at CDF requires two oppositely charged leptons (e or μ). The leptons have to pass standard iden-

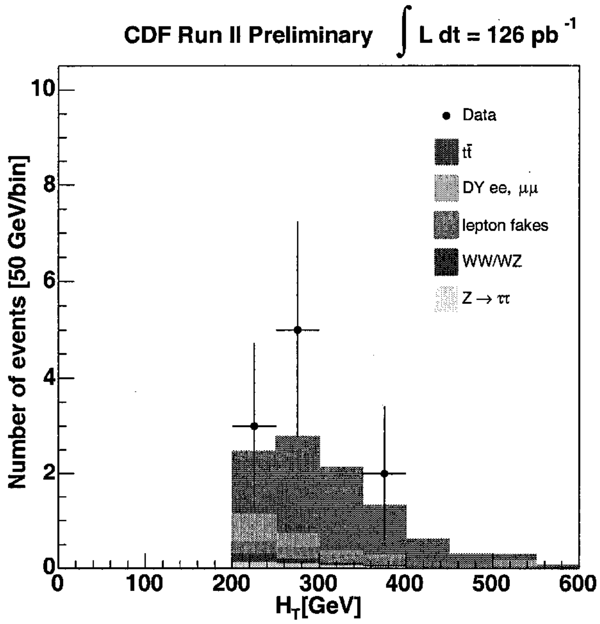

Fig. 1. H_T distribution for CDF data and the standard model expectation. 6.3 ± 0.7 $t\bar{t}$ events are expected.

tification cuts and have a $p_t > 20$ GeV. One of the leptons is required to be isolated. The analysis uses leptons measured in the central and the forward (plug) detectors. If the di-lepton invariant mass falls in the Z window ($76\,\mathrm{GeV} < m_{\ell\ell} < 106\,\mathrm{GeV}$) additional cuts are applied: (1) $\Delta\phi$ between the $\not{E}_T$ vector and nearest jet has to be larger than 10°. (2) The jet-significance

$$jetsig = \frac{|\not{E}_T\,|}{\sum \boldsymbol{E_T}(jet) \cdot \not{E}_T}$$

has to be larger than 8. Neutrinos are detected by asking $|\not{E}_T\,| > 25\,\mathrm{GeV}$. If $|\not{E}_T\,| < 50\,\mathrm{GeV}$, an additional requirement is that the angle $\Delta\phi$ between the $\not{E}_T$ vector and the nearest jet or lepton be larger than 20°. Furthermore, the analysis calls for at least 2 jets ($E_T > 15\,\mathrm{GeV}$, $|\eta| < 2.5$) and $H_T > 200\,\mathrm{GeV}$. H_T is the scalar sum of all transverse energies: $H_T = |\not{E}_T\,| + |E_T(\ell_1)| + |E_T(\ell_2)| + \sum |E_T(jet)|$. A veto to conversions and cosmic rays is applied. CDF finds 10 candidate events (2 e/e, 5 e/μ and 3 μ/μ) passing all cuts in 125 pb^{-1} of data. The expected number of background events is 2.9 ± 0.9. The deduced cross-section is $\sigma(t\bar{t}) = 7.6 \pm 3.4\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})$ pb. Fig. 1 shows the H_T distribution for data in comparison to the standard model expectation.

CDF has performed a second, alternative di-lepton analysis which is based on one tight lepton and one isolated track (without additional lepton identification). This analysis yields a cross-section of $\sigma(t\bar{t}) = 7.4 \pm 3.4\,(\mathrm{stat.}) \pm 1.7\,(\mathrm{syst.})$ pb, which is in good a agreement with the standard analysis described above.

DØ has observed 7 candidate events (4 e/e, 1 e/μ and 2 μ/μ) in the di-lepton channel. The background expectation is 1.7 ± 0.6. The resulting cross-section is $\sigma(t\bar{t}) = 29.9^{+21.0}_{-15.7}(\mathrm{stat})\,^{+14.1}_{-6.1}(\mathrm{syst}) \pm 3.0\,(\mathrm{lum})$ pb.

4 Lepton-plus-Jets Channel

The background in the lepton-plus-jets channel is much more significant than in the di-lepton mode. Dedicated methods to significantly reduce the backgrounds have to be applied. There are three general strategies:

1. Apply *topological cuts (or fits)* to kinematic or event shape variables, such as H_T or aplanarity $\mathcal{A}$.
2. Identification of *b-jets* based on *lifetime information*, either by requiring a secondary vertex from a b-hadron decay or by selecting events that have tracks with large impact parameter significance.
3. Identification of *b-jets* by searching for *non-isolated leptons from semileptonic b-decays* (Soft Muon/Electron Tagger).

In the following paragraph we will discuss the topological $t\bar{t}$ analysis at DØ , the secondary vertex analysis of CDF and the soft-muon-tagger analysis of DØ .

4.1 Topological $t\bar{t}$ analysis at DØ

The preselection of the topological analysis proceeds by asking for an electron or a muon with $p_T > 20$ GeV and $\not{E}_T > 20$ GeV. A veto is applied to soft muons, in order to render a disjoint data sample with the b-tagged analysis (using the soft muon tagger).

The preselected sample is used to estimate the backgrounds: (1) the multi-jet background and (2) the W+jet background. The multi-jet background is determined by applying an additional isolation cut to the lepton. The cut efficiencies for multi-jet (QCD) events and W+jet events are obtained from control samples. Solving the two equations

$$N_{obs} = N_{MJT} + N_{W+J}$$
$$N_{iso} = \epsilon_{MJT} N_{MJT} + \epsilon_{W+J} N_{W+J}$$

gives the number of multi-jet background events N_{MJT} in the sample. Fig. 2 depicts the transverse mass spectrum of reconstructed W bosons for different jet bins in the muon channel. The multi-jet background is indicated as shaded histogram. The W+jets background estimate is based on the empirical Berends scaling law which predicts:

$$\frac{\sigma\,(W + (n+1)\text{ jets})}{\sigma\,(W + n\text{ jets})} = \alpha$$

First the multi-jet background is subtracted from the data, then α is obtained from a fit to the N-jet spectrum (using N=1,2,3). The fit predicts the number of W+4 jets events. The W+4 jets bin is taken as the signal region in this top quark analysis.

The last step is to apply the topological cuts. For electron events the analysis demands: aplanarity $\mathcal{A} > 0.065$ and $\sum E_T\,(\mathrm{jet}) > 180$ GeV. For muon events: $\mathcal{A} > 0.0065$ and $H_T > 220$ GeV. DØ observes 4 electron+jets and 4 muon+jets events. The number of expected background

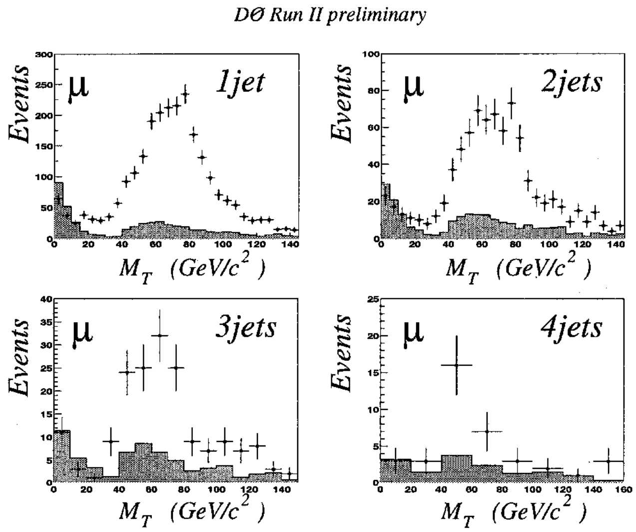

Fig. 2. Transverse mass spectrum of reconstructed W bosons for different jet bins in the muon channel. The multi-jet background is shown as shaded histogram, the data are the dots with error bars.

events is 1.8 ± 0.4 and 2.4 ± 0.4, respectively. The resulting cross-sections are

$$\sigma(t\bar{t}) = 5.2^{+9.4}_{-6.7}(\text{stat})\ ^{+9.1}_{-3.1}(\text{sys}) \pm 0.52(\text{lumi})\ \text{pb}$$

for the electron channel and

$$\sigma(t\bar{t}) = 3.8^{+6.9}_{-4.9}(\text{stat})\ ^{+3.9}_{-5.4}(\text{sys}) \pm 0.38(\text{lumi})\ \text{pb}$$

for the muon channel.

4.2 Secondary vertex based cross-section measurement at CDF

In this analysis one uses the fact that only about 2% of generic W+jets events contain real b-quarks. If b-quarks can be identified with good efficiency and purity, the W + multi-jet background can be considerably suppressed. The preselection of this analysis calls for one tightly identified electron or muon in the central detector. An isolation requirement is applied. Conversion, Z-boson and cosmic ray vetos are imposed. The missing transverse energy has to be larger than 20 GeV. The b-tagger program selects good tracks and tries to form secondary vertices. The 2D decay length in the x-y plane is calculated and taking the vertex resolution into account a vertex significane is formed. The version of the tagger used for the Winter 2003 analysis presented here used the beamline to estimate the position of the primary interaction vertex and yielded an event tagging efficiency for $t\bar{t}$ events of $45\% \pm 1\%(\text{stat}) \pm 5\%(\text{syst})$. At least one b-tagged jet is required in this analysis. The signal region is defined as the W+3 and W+4 jets bin. The jet definition is $E_T > 15$ GeV and $|\eta| < 2.0$. CDF finds 15 candidate events over a background of 4.1 events in 57.5 pb^{-1} of data. The cross-section is found to be:

$$\sigma(t\bar{t}) = 5.3 \pm 1.9(\text{stat}) \pm 0.8(\text{syst}) \pm 0.3(\text{lumi})\ \text{pb}.$$

The W+N jets spectrum is shown in Fig. 3.

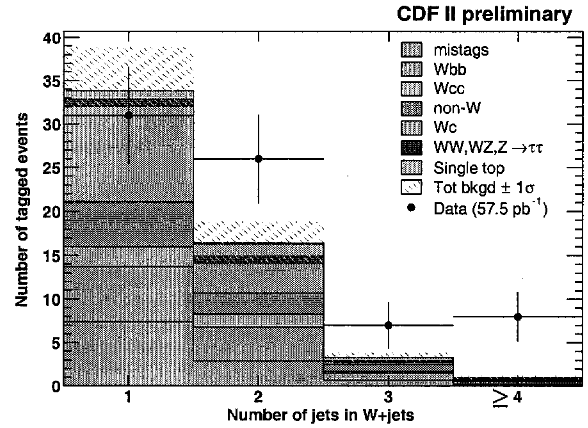

Fig. 3. W+N jets spectrum of the secondary vertex $t\bar{t}$ analysis at CDF. The 15 candidate events are shown as dots. The various backgrounds are shown as shaded areas in different colors. The access of events in the W+3 and 4 jets bin is interpreted as $t\bar{t}$ signal.

4.3 The Soft Muon Tag at DØ

The soft muon tagger searches for muons coming from semileptonic b-decays in jets. The muons must have a minimum $p_T > 4$ GeV and $|\eta| < 2.0$. The distance in the η-ϕ plane must be smaller than $\Delta R(\mu, \text{jet}) < 0.5$. DØ observes 2 events in this analysis over an expected background of 0.9 ± 0.39 events. The cross-section combined with the topological analysis is

$$\sigma(t\bar{t}) = 5.8^{+4.3}_{-3.4}(\text{stat})\ ^{+4.1}_{-2.6}(\text{syst}) \pm 0.6(\text{lumi})\ \text{pb}$$

5 Conclusions

Top quark signals have been reestablished at the Tevatron in the di-lepton and the lepton+jets channels. Various analysis techniques are used and yield results which are in agreement with each other and the theoretical prediction. Data sets larger than those of Run I are at hand and will in the near future allow cross-section measurements well below Run I uncertainties. The final goal for Run IIa (2 fb^{-1} of data) is to achieve a relative uncertainty of 7%.

References

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