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Top: Latest Results From the Tevatron - Cross Section and Mass

Mircea Coca, for the CDF and DØ Collaborations.
University of Rochester
Department of Physics and Astronomy
Rochester, NY, 14627, USA

The Tevatron is presently the world's only source of top quark production. This presentation summarizes the latest Run II results on top physics obtained by the CDF and DØ collaborations, using data taken until mid-January 2003. The first cross section measurements at 1.96 TeV in dilepton and lepton+jets channels agree with the NLO (Next-to-Leading-Order) theoretical predictions. Two top mass measurements, one by CDF using Run II data and another by DØ using an improved technique anticipate the improvements to come in the near future.

1 Introduction

The top quark was discovered at the Tevatron by the Fermilab CDF and DØ collaborations in 1995 [1, 2]. At the current Tevatron energies ($E_{CM} = 1.96$ TeV), top quarks are produced mainly in pairs through the strong force mediated processes $q\overline{q} \rightarrow t\overline{t}$ (85%) and $gg \rightarrow t\overline{t}$ (15%). The single top mechanism involves the electroweak production of a single top via the Wtb vertex, with about half the strong production cross section and much larger backgrounds. The single top mode was not observed in Run I and it is one of the goals of Run II.

Within the Standard Model (SM) framework the top quark decays almost always into a W and b quark. Therefore the decay modes of a $t\overline{t}$ pair are classified based on how the W decays into three distinctive event topologies: a *dilepton* final state when both W bosons decay leptonically, with two high-p_T isolated leptons, two jets and large $\not{E}_T$ [1], due to undetected neutrinos; a *lepton+jets* final state when one W boson decays hadronically, the other leptonically, with a high-p_T lepton, four jets and large $\not{E}_T$; and an *all-jets* state with both W bosons decaying hadronically, consisting of six jets. While the dilepton channel is the cleanest, it amounts to only 5 % of the total $t\overline{t}$ sample [2], whereas the all-jets channel has a branching ratio of 44%, but suffers from large backgrounds. The lepton+jets state, accounting for 30% of events, is the best compromise between purity and statistics.

[1] The missing energy $\not{E}_T$ is energy imbalance in the transverse plane to the beam direction.
[2] By *leptons* we mean electrons or muons, which are directly reconstructed, taus are not considered in this paper.

2 The Tevatron collider and the detectors in Run II

For Run II the Fermilab accelerator complex underwent a major upgrade. As a result the Tevatron operates at a higher energy E_{CM}=1.96 TeV, with a bunch spacing of 396 ns and higher instantaneous luminosities than in Run I. By mid-January 2003, the Tevatron had delivered about 150 pb^{-1} of data, with typical instantaneous initial luminosities of 3-4 x $10^{31}cm^{-2}s^{-1}$. This dataset provides the basis for the results presented here.

The CDF and DØ detectors underwent extensive upgrades for Run II. While the CDF central calorimeter, the solenoid and part of the muon system are inherited from Run I, all the other CDF detectors are entirely new. There is a new tracking system made of three silicon detectors (L00, SVX and ISL) and a central drift chamber (COT). Also the new plug calorimeter and extended muon coverage allow CDF to extend the lepton identification in the forward regions. The DØ detector has a new inner tracking which consists of a silicon microvertex tracker surrounded by a scintillating fiber tracker inside a new 2 T superconducting solenoid. DØ also has an improved muon detector and new preshower detectors. Both CDF and DØ have new DAQ and trigger systems to cope with the shorter interbunch time.

3 Top Production Cross Section Measurements

By measuring the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ with greater precision in many channels we can test the prediction of perturbative QCD in greater detail. Also the cross sections are benchmark measurements and they are sensitive to new physics beyond the SM. It is also crucial to understand top behavior very well given it is an important background in Higgs searches.

3.1 $\sigma_{t\bar{t}}$ measurements in the ***dilepton*** channel

There are two types of background processes that could mimic a top dilepton signature: physical processes such as Drell-Yan ($\gamma^*/Z^0 \rightarrow e^+e^-, \mu^+\mu^-$), $Z^0 \rightarrow \tau^+\tau^-$, $W^+W^-/W^{\pm}Z^0$ and processes with a real lepton and a jet or a track that fakes a second lepton.

Dilepton event selection begins with two oppositely charged high-P_T ($P_T > 20$ GeV/c) leptons (e or μ). Both leptons are required to be well isolated from nearby calorimeter activity, greatly reducing W$b\bar{b}$ and $b\bar{b}$ background contamination. In these processes, the leptons are produced by semileptonic heavy flavors decays. We reject the dielectron and dimuon events with the dilepton invariant mass, M_{ee} or $M_{\mu\mu}$ in the interval $76-106$ GeV/c^2, to reduce $Z^0 \rightarrow \ell^+\ell^-X$ background. DØ separates $t\bar{t}$ from Z's in this window by demanding larger $\not\!\!E_T$ than in the region outside.

Large $\not\!\!E_T$ ($\not\!\!E_T > 25$ GeV) is required due to the two undetected neutrinos from W decays. In addition CDF requires that $\Delta\phi(\not\!\!E_T, \ell \text{ or } j) > 20^0$ if $|\not\!\!E_T| < 50$ GeV [3] to eliminate poorly measured $\not\!\!E_T$'s due to mismeasured energies of lepton or jets, and also to reduce the background due to Z$\rightarrow$ $\tau^+\tau^-$ (see Figure 1 left).

[3] $\Delta\phi(\not\!\!E_T, \ell \text{ or } j)$ is the azimuthal angle between $\overrightarrow{\not\!\!E_T}$ and the nearest lepton or jet.

Each b-quark fragments and hadronizes into a shower of hadrons known as a jet. We require at least two highly energetic jets in each event. They are much harder (typically about 50 GeV) than the soft jets originating from initial state QCD radiation. Finally, we require that H_T [4] be large. The results from CDF and DØ are summarized in Tables 1 and 2. In Run I we observed a few events with improbably large $\not\!\!E_T$ or lepton P_T relative to the SM expectations. The current limited number of events does not show the same behavior (Fig 1). However larger datasets are needed to draw any conclusion.

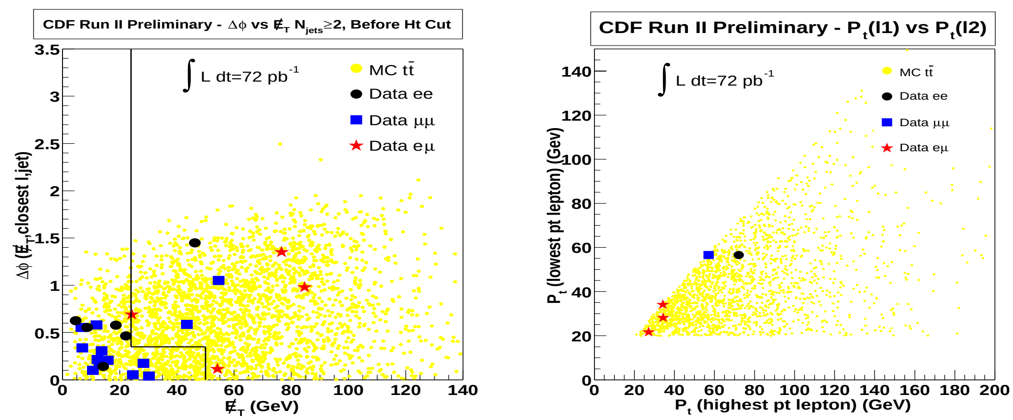

Figure 1: Left: the 5 CDF $t\bar{t}$ dilepton candidates observed in 72 pb^{-1} are shown in the plane $\Delta\phi(\not\!\!E_T, nearest\ \ell$ or $j)$ versus $\not\!\!E_T$ in comparison with Monte Carlo (MC) Herwig $t\bar{t}$. Right: the highest lepton P_T vs the second highest lepton P_T are shown for the 5 CDF candidates compared with the MC Herwig $t\bar{t}$.

Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
Backgrounds	0.103±0.056	0.093±0.054	0.100±0.037	0.30±0.12
Expected $t\bar{t}\to\ell\nu_\ell b\ell^{'}\overline{\nu}_{\ell^{'}}\overline{b}$	0.47±0.05	0.59±0.07	1.44±0.16	2.5±0.3
Data	1	1	3	5

Table 1: Preliminary Run II CDF results in the $t\bar{t}$ dilepton channel for a data sample of 72 pb^{-1}

3.2 $\sigma_{t\bar{t}}$ measurements in the *lepton+jets* channel

The event selection consists of two phases: both CDF and DØ start with a preselected sample of W candidate events with a high-P_T, isolated lepton and large $\not\!\!E_T$. Cosmic rays, photon conversions, Drell-Yan and $t\bar{t}$ dilepton candidate events are removed. The second phase of the

[4] H_T is the scalar sum of transverse energies of reconstructed objects in an event

Source	ee	$\mu\mu$	$e\mu$
$\mathcal{L}(pb^{-1})$	48.2	42.6	33.0
Backgrounds	1.00±0.49	0.60±0.30	0.07±0.01
Expected $t\bar{t}\to\ell\nu_\ell b\ell'\overline{\nu}_{\ell'}\overline{b}$	0.25±0.02	0.30±0.04	0.50±0.01
Data	4	2	1

Table 2: Preliminary Run II DØ results in the $t\bar{t}$ dilepton channel. Luminosities in each channel are shown in the table.

selection reduces further the background, and depending on the approach chosen, we differentiate three analyses: a CDF analysis which relies on the identification of a b-jet using the *displaced secondary vertex (SECVTX)* of a b-jet due to the long lifetime of a b quark, a DØ *topological* analysis, which requires four or more energetic jets in the event and a second DØ analysis which requires at least a b-jet tagged using a *Soft Muon Tag (SMT)*.

The CDF *Secondary Vertex Tag* analysis selects the events with one e or μ with $P_T > 20\ GeV/c$, $\not\!\!E_T > 20\ GeV$ and at least three high E_T jets. To further increase the signal-to-background ratio, CDF uses the silicon detector to identify the b-quark displaced vertices. A jet is b-tagged if it contains a secondary vertex with at least two charged tracks and $\frac{L_{xy}}{\sigma_{xy}} > 3$ [5]. A typical displacement for L_{xy} is about 3 mm, while σ_{xy} is about 150 μm. The efficiency for identifying at least one of the b quarks from $t\bar{t}$ decays is (45 ±1± 4) %. There are three sources of backgrounds: b-mistags, W/Z+heavy flavor production and non-W (or fake-W) events. The mistags from light quarks and gluon jets are evaluated using the negative rate of L_{xy} extracted from inclusive jet data and applied to W+ multijets data. The W/Z+heavy flavor (g$\to b\bar{b}, c\bar{c}$) background is evaluated from W+ multijets data, the b tag rate and the flavor composition in W+ multijets events. The non-W background is evaluated from the W+multijets data topology in the isolation versus $\not\!\!E_T$ plane. Background rates in the non-isolated regions are extrapolated into the low isolation, large $\not\!\!E_T$ signal region.(see results in Table 3).

Source	W+1*jet*	W+2*jets*	W+3*jets*	W≥4*jets*
Background	33.8±5.0	16.4±2.4	2.88±0.05	0.87±0.2
SM Background plus $t\bar{t}$	34.0±5.0	18.7±2.4	7.4±1.4	7.6±2.0
Data before tagging	4913	768	99	26
Data (≥1b-tag)	31	26	7	8

Table 3: Preliminary Run II CDF results in the $t\bar{t}$ *lepton plus jets* analysis with displaced vertex b-tagging. The sample luminosity is 57.5 pb^{-1}.

The DØ *topological* analysis does not make use of b-tagging. A data sample enriched in W events is first preselected by demanding an e or μ with $P_T > 20\ GeV/c$, $\not\!\!E_T > 20\ GeV$. Then,

[5] L_{xy} is the distance in the transverse plane to the beam direction, between the secondary and the primary vertex. σ_{xy} is the resolution in the determination of L_{xy}.

the QCD background is evaluated from data for each jet multiplicity. The $W+\geq 4$ *jets* background is estimated using the Berends empirical scaling law [3]. To further reduce background the topological cuts are applied: at least four energetic jets and large values of H_T and $\mathcal{A}$ [6] are required (see results in Table 4).

The DØ *Soft Muon Tag* analysis has the same preselection as the *topological* analysis. The topological requirements on H_T and $\mathcal{A}$ are looser and at least three high-E_T jets are required. Background is highly reduced by asking for one low momentum μ in a jet. This μ comes from the semileptonic b decays (see results in Table 5).

Channel	All BG	Exp Signal	N_{obs}	$\mathcal{L}(pb^{-1})$
e+jets	2.7±0.6	1.8	4	49.5
μ+jets	2.7±1.1	2.4	4	40

Table 4: Preliminary Run II DØ results in the $t\bar{t}$ *lepton plus jets topologic* analysis

Channel	All BG	Exp Signal	N_{obs}	$\mathcal{L}(pb^{-1})$
e+jets	0.2±0.1	0.5	2	49.5
μ+jets	0.7±0.4	0.8	0	40

Table 5: Preliminary Run II DØ results in the $t\bar{t}$ *lepton plus jets Soft Muon Tag* analysis

3.2.1 Summary of Top Cross Section Measurements

The $t\bar{t}$ production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV has been determined based on the number of observed $t\bar{t}$ candidates in a given channel N_{obs}, the estimated background N_{bkg}, the integrated luminosity $\mathcal{L}$ and the $t\bar{t}$ acceptance A for a top mass of 175 GeV/c^2 :

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{A \cdot \int \mathcal{L}}. \quad (1)$$

We obtain the following Run II results:

- CDF *dilepton channels*: $\sigma_{t\bar{t}} = 13.2 \pm 5.9(stat) \pm 1.5(sys) \pm 0.8(lum)$ pb.
- CDF *lepton plus jets channels*: $\sigma_{t\bar{t}} = 5.3 \pm 1.9(stat) \pm 0.8(sys) \pm 0.3(lum)$ pb.
- DØ *dilepton channels*: $\sigma_{t\bar{t}} = 29.9^{+21.0}_{-15.7}(stat)^{+14.1}_{-6.1}(sys) \pm 3.0(lum)$ pb.
- DØ *lepton plus jets channels*: $\sigma_{t\bar{t}} = 5.8^{+4.3}_{-3.4}(stat)^{+4.1}_{-2.6}(sys) \pm 0.6(lum)$ pb.
- DØ *all combined channels*: $\sigma_{t\bar{t}} = 8.5^{+4.5}_{-3.6}(stat)^{+6.3}_{-3.5}(sys) \pm 0.8(lum)$ pb.

All results are in agreement with the NLO prediction: $6.70^{+0.71}_{-0.88}$ pb [4].

[6]The aplanarity $\mathcal{A}$ measures the relative activity perpendicular to the plane of maximum activity; it is a measure of the flatness of the event, larger values of $\mathcal{A}$ correspond to spherical events.

4 Top Mass Measurements

Radiative corrections to the W-boson mass relates the W-boson mass with the top quark mass and Higgs boson mass. Precise measurements of the top mass together with W-boson mass provide an indirect constraint on the SM Higgs boson mass.

4.1 CDF Run II Top Mass in the *Lepton+jets* Channel

The events are selected as for the CDF cross section measurement in the lepton+jets channel, except that at least 4 high-E_T jets are required to compensate for the fact that no b-tagging is used. The measurement involves a constrained fit of kinematics at the parton level.

For each event there are up to 24 solutions compatible with the $t\bar{t}$ lepton+jets decay hypothesis at the parton level. There are 12 possible assignments of the three quark partons to the four jets. For each of these there are up to 2 solutions for the longitudinal momentum of the neutrino $p_{\nu z}$. Energy-momentum conservation at production and decay vertices together with additional constraints such as $m_t = m_{\bar{t}}$, theoretical value of Γ_t, PDG values of M_W and Γ_W provide a system of 20 constraints with 18 unknowns. A 2-C fit is used to determine the top mass and $p_{\nu z}$. Out of the many possible solutions for an event, the one with the minimum χ^2 is chosen as the best top mass estimate.

Mass templates are generated for top masses from 150 to 200 GeV/c^2 with a 5 GeV/c^2 steps. To extract the top mass and the statistical uncertainty a continuous likelihood is used.

Using a data sample of 72 pb^{-1}, 33 events pass all the selection cuts, with an estimated 13 background events. Assuming these events are $t\bar{t}$ lepton+jets, their mass is reconstructed (Fig 2a) and fitted to a distribution of $t\bar{t}$ and W+jets background templates. The constrained fit returned a mass M_{top}=171.2 $\pm^{+14.4}_{-12.5}(stat)$ $\pm^{+9.9}_{-9.9}(syst)$ GeV/c^2.

The systematic uncertainty is quite large and is mainly dominated by the uncertainty on the jet energy scale, which is around 9.3 GeV. This will be reduced once a better understanding of the calorimeter is achieved (Run I uncertainty was 4.4 GeV). By using silicon detector to tag at least a b-jet and by lowering the E_T to 8 GeV for the fourth jet. CDF obtained a sample of 11 events with 1 background event in a sample of 57.5 pb^{-1}. This is a 3 times increase in S/B when requiring at least a b-tag. The mass distribution for these events (Fig 2b) is very promising and a result will be available in the summer 2003.

4.2 DØ improved Run I top mass measurement in the *lepton+jets* channel

The standard method DØ used in Run I to measure the top mass in the lepton+jet channel was similar with the one used recently by CDF (Section 4.1). As we mentioned, an event there could have up to 24 solutions when no b-jets are tagged. This method has some drawbacks. Out of all these solutions few of them could have acceptable χ^2, but we keep only the one with the smallest χ^2. In many cases this might not be correct one. The number of wrong assignments is reduced when extra knowledge like tagging a b-jet or more is used.

DØ has developed a likelihood method proposed by Kondo et al [5]. Each event has associated a probability to be signal P_{top} or background P_{bck}. The probability for background is

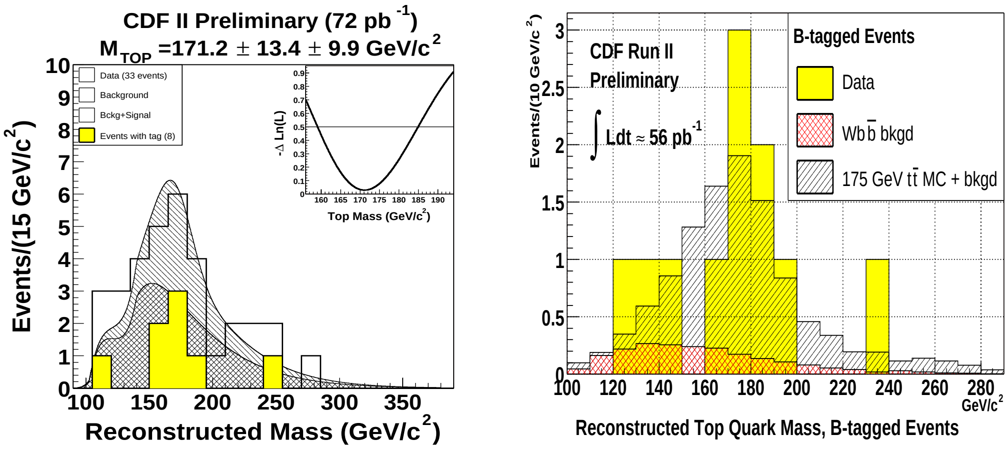

Figure 2: a) Left side: the top mass distribution obtained by the CDF for events with no b tagging requirement, in 72 pb^{-1}. b) Right side: the top mass template using events with at least a b-jet tagged, using 57.7 pb^{-1} of the data.

defined purely in terms of the matrix element contained in VECBOS. The only background considered is W+4 jets (80 % of total background), the other backgrounds being negligible. The signal probability uses the leading-order matrix element for the $t\bar{t}$ production and decay, therefore only events with four jets are considered. Each probability is convoluted with a transfer function which relates objects at the parton level to the objects observed (after reconstruction) in the detector.

For this measurement 125 pb^{-1} of data taken in Run I by DØ is used. Out of the 91 events selected and used by the previous analyses, only 77 are kept after requiring exactly four jets. To further reduce the background only the events with a low P_{bck} are further selected (Fig. 3 a, left). The remaining 22 events are used in a global likelihood fit (Fig. 3 a and b, right) to extract a top mass M_{top} = 180.1 ± 3.6 (stat) ± 4.0 (syst) GeV/c^2. The previous best measurement published by DØ was M_{top} = 173.3 ± 5.6 (stat) ± 5.5 (syst) GeV/c^2. The reduction in the statistical uncertainty corresponds to an increase by a factor of 2.4 in statistics. This is mainly due to the fact that all the right combinations enter in the final likelihood fit. The systematic error is dominated by the jet energy scale uncertainty and there are studies underway trying to reduce it. One can fit the W mass (Fig. 3 c and d) at the same time as top mass. This might help to better constrain the jet energy scale so as to reproduce the W mass very precisely.

5 Summary and Prospects

Top Physics in Run II, still in an early stage, is getting close to the precision achieved in Run I and has great future potential. The benchmark measurements were reestablished and many improvements are underway (better detector understanding, increase of the b-tagging efficiencies, inclusion of the forward leptons into analyses). We are enthusiastic about the top physics prospects at the Tevatron until the first LHC results and we will be able to test the

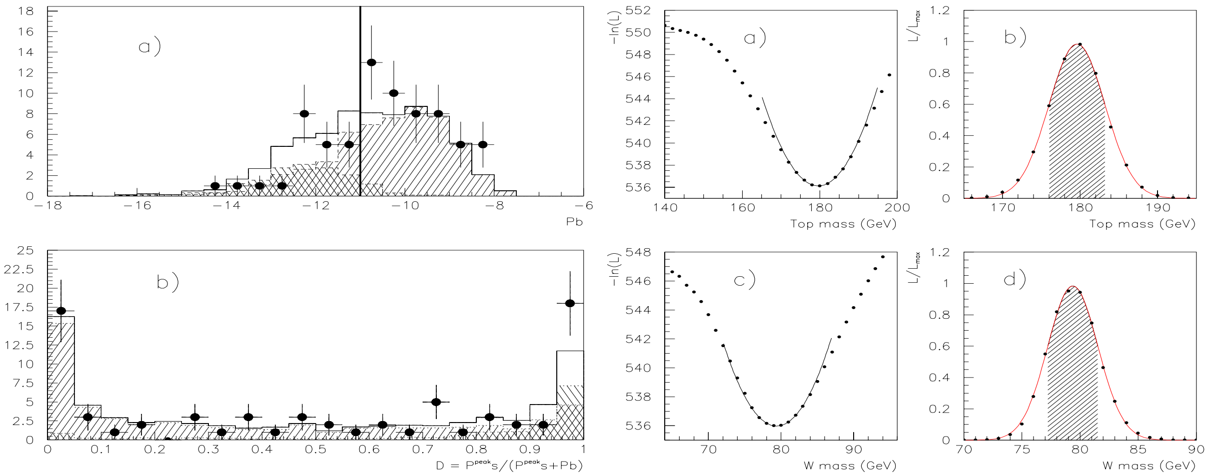

Figure 3: DØ Run I Mass Measurement. Left: a) Background probability distribution; shaded histograms correspond to background and signal events; the events with P_{bck} are rejected. b) Ratio $P_{top}/(P_{bck}+\ P_{top})$ shows the discriminating power of the method. Right: a) and b) -ln(likelihood) shows the fitted top mass value and its uncertainty. c) and d) -ln(likelihood) shows the fitted W mass value when the top mass is fixed to its fitted value.

SM to even greater precision in the next few years.

Using the first 2 fb^{-1} we should measure the top quark mass to at least 2 % precision and the total cross section to better than 7 % precision. In addition, we should observe single top and measure its production cross section with 20 % uncertainty. Also we will be able to search for new physics such as non-SM $t\bar{t}$ production, non-SM decays of top quark or supersymmetry.

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