TOP QUARK PHYSICS AT THE TEVATRON RESULTS AND PROSPECTS*

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The methodology of CDF and D0 top quark analyzes and their underlying assumptions are summarized. The CDF and D0 top mass averages, obtained from measurements in several channels and based on about 100 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{\mathrm{s}} = 1.8$ TeV collected by each experiment in Run I, are: $M_{\mathrm{t}} = 176.1 \pm 4.0(\mathrm{stat}) \pm 5.1(\mathrm{syst})$ GeV/c^2 and $M_{\mathrm{t}} = 172.1 \pm 5.2(\mathrm{stat}) \pm 4.9(\mathrm{syst})$ GeV/c^2, respectively. The combined Tevatron measurement of the top quark mass is $M_{\mathrm{t}} = 174.3 \pm 3.2(\mathrm{stat}) \pm 4.0(\mathrm{syst})$ GeV/c^2. The CDF measurement of the $t\bar{t}$ cross section (assuming $M_{\mathrm{t}} = 175$ GeV/c^2) is $\sigma_{tt} = 6.5\pm^{1.6}_{1.4}$ pb, and the D0 value (assuming $M_{\mathrm{t}} = 172.1$ GeV/c^2) is $\sigma_{tt} = 5.9 \pm 1.7$ pb. In anticipation of much larger statistics, prospects for top physics in Tevatron Run II are summarized. The fact that top quark analyzes are among the best windows to physics beyond the Standard Model is emphasized.

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1. Introduction

The top quark was expected in the Standard Model (SM) of electroweak interactions as a partner of the b-quark in a SU(2) doublet of the weak isospin, in the third family of quarks. The first published evidence appeared in a CDF [1] paper in 1994, and its observation (discovery) was reported by CDF [2] and D0 [3] in the same issue of PRL in 1995.

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2. Top mass and cross section measurements

The techniques used in CDF and D0 are variations of simple event counting. Both experiments follow identical steps:

(i) identify events with the expected top signature;
(ii) calculate the expected SM backgrounds;
(iii) count excess events above the expected backgrounds;
(iv) apply corrections for the acceptance, reconstruction inefficiencies and other biases.

All CDF and D0 analyzes assume that each event in the selected samples contains a pair of massive objects of the same mass ($t\bar{t}$ quarks) which subsequently decay as predicted in the SM. Information about the kinematics of the event is used in a variety of fitting techniques. A one-to-one mapping between the observed leptons and jets and the fitted partons is assumed. Leptons are measured best, jets not as well (better in D0 than in CDF), while the missing transverse energy, $\not{E}_{\mathrm{T}}$, has the largest error.

One should remember: *(i)* it is *assumed* that the selected sample of events contains just the $t\bar{t}$ events and the SM background; this is the simplest and the most natural hypothesis since the top quark is expected in the SM; *(ii)* some of the acceptance corrections are strongly varying functions of the top quark mass, M_{t}, and, consequently, the value of the measured cross section depends on the value of M_{t}, which has to be determined independently; *(iii)* the combinatorics of the jets–lepton(s) combinations (only one of many possible combinations is correct) adds to the complexity of the problem.

All CDF and D0 searches impose stringent identification, selection and transverse energy, E_{T}, cuts on leptons and jets to minimize the SM and misidentification backgrounds. Except for dilepton samples, in which backgrounds are expected to be small, various techniques of tagging b-quarks are employed to improve the signal to background ratio. Soft-Lepton Tagging (SLT) is used by both CDF and D0, and the secondary vertex tagging, using a silicon vertex detector (SVX), by CDF. D0, not equipped with a SVX, makes much greater use of various kinematic variables to reduce backgrounds. The largest SM background is the QCD W+jets production. Both CDF and D0 use VECBOS [4] calculations to estimate shapes of the background distributions due to this process. Presently available samples of the top event candidates are small, and the measurements of σ_{tt} and M_{t} are limited by the statistical errors.

In the lepton+jets final state there is sufficient number of kinematical constraints to perform a genuine fit; one may, or may not, use $\not{E}_{\mathrm{T}}$ as a starting point for the transverse energy of the missing neutrino. In their published analyzes both CDF and D0 use $\not{E}_{\mathrm{T}}$. CDF defines four independent samples

TABLE I

Results of D0 [5] and CDF [6] direct top searches.

Channel	D0 sample	D0 background	CDF sample	CDF background
dilepton	5	1.4 ± 0.4	9	2.4 ± 0.5
lepton+jets SVX tagged			34	9.2 ± 1.5
lepton+jets soft-lepton tagged	11	2.4 ± 0.5	40	22.6 ± 2.8
lepton+jets topological cuts	19	8.7 ± 1.7		
all-jets	41	24.8 ± 2.4	187	142 ± 12
$e\nu$	4	1.2 ± 0.4		
$e\tau, \mu\tau$			4	≈ 2

of lepton+jets events, and measures the top quark mass in each of them. D0 uses two multivariate discriminant analyzes, LB — Low Bias and NN — Neural Network, which use four variables to construct the top likelihood discriminant, D, to select the top enriched and background enriched samples of events, which are the basis of D0 top mass and cross section analyzes.

In the dilepton mode the situation is more complicated, as the problem is under-constrained (two missing neutrinos). Several techniques were developed. All obtain a probability density distribution as a function of M_{t}, whose shape allows identifying the most likely mass which satisfies a hypothesis that a pair of top quarks were produced in an event. D0 developed two methods, the Neutrino phase space weighting technique (νWT) and the average matrix element weighting technique (MWT), a modified form of Dalitz–Goldstein [7] and Kondo [8] methods. Three techniques of measuring of the top quark mass have been developed in CDF. Two use $\not{E}_{\mathrm{T}}$ (the "neutrino weighting" and the "Minuit fitting" methods), one does not (a modification of the Dalitz–Goldstein (D–G) method, which instead includes information about the parton distribution functions, transverse momentum of the $t\bar{t}$ system and angular correlations among the top decay products in the definition of likelihood). The result obtained with the "neutrino weighting" method (essentially the D0 νWT) was used in the CDF and CDF/D0 combined mass analysis. CDF also performed kinematical fits using a sample of all-jets events selected using SVX tagging. Results are summarized in Fig. 1.

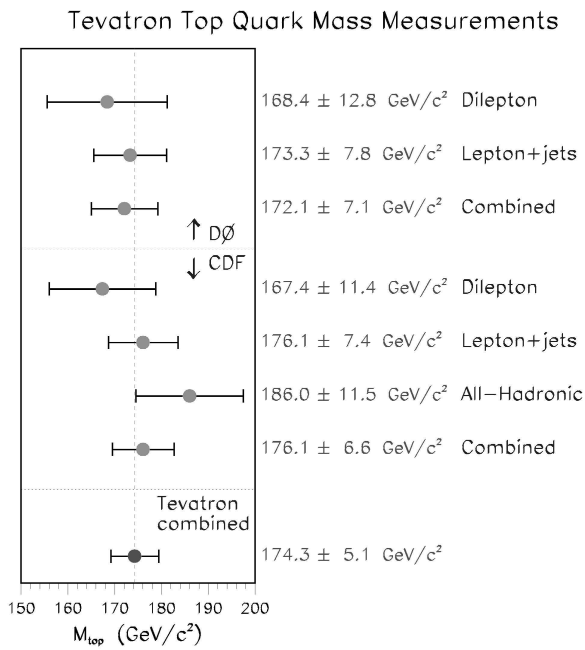

Fig. 1. CDF and D0 measurements of the top quark mass using Tevatron Run I data[1]. The Tevatron (CDF+D0) average for Run I was obtained by combining five CDF and D0 results in a similar manner to the way the CDF and D0 averages were obtained. Systematic errors which do not depend directly on the Monte Carlo simulations (jet energy scale, backgrounds ...) were taken as uncorrelated, while the errors which depend on the Monte Carlo model (ISR, FSR, PDF ...) were treated as 100% correlated between the experiments, since both CDF and D0 rely on identical MC models.

Both CDF and D0 measure the $t\bar{t}$ cross section in four different samples each, and combine their results using a likelihood technique which takes into account correlations in the uncertainties. A summary of all results is presented in Fig. 2.

[1] For completeness, an analysis of CDF data using the "Minuit fitting" method yields $M_{\rm t} = 170.7 \pm 10.6(\text{stat}) \pm 4.6(\text{syst})$ GeV/c^2, and that using the D–G method, which uses a single, "best' combination of leptons and jets in an event, gives: $M_{\rm t} = 157.1 \pm 10.9(\text{stat}) \pm^{4.4}_{3.7}(\text{syst})$ GeV/c^2.

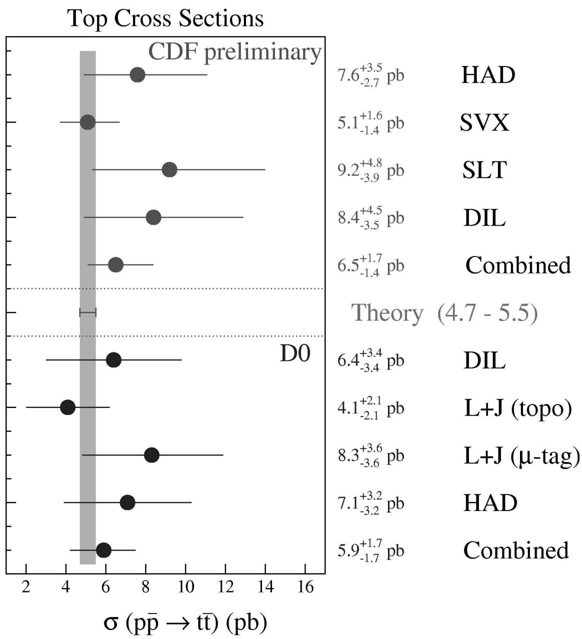

Fig. 2. CDF and D0 measurements of the top pair production cross section. For comparison, the range of theoretical predictions [9] for $t\bar{t}$ pair production cross section is also shown.

3. Prospects for Run II. Is it only top?

In Run IIa, which started at the end of 2001, CDF and D0 expect to collect 2 fb^{-1} of luminosity each. With the new Main Injector, the $p\bar{p}$ collisions take place at $\sqrt{s} = 1.96$ TeV, where the $t\bar{t}$ cross section is $\approx$35% larger than in Run I. CDF has a new calorimeter with a much better energy resolution in the pseudorapidity range $1.1 < |\eta| < 3.5$, and a new SVX with double the Run I tagging efficiency. CDF also added a time-of-flight system and its muon coverage has been extended to cover the range $|\eta| < 2$. D0 has a new SVX to allow better b-tagging, and has added a solenoid to allow momentum reconstruction for charged particles. D0 has excellent lepton ($|\eta| < 2$ for muons, $|\eta| < 2.5$ for electrons) and tracking coverage ($|\eta| < 3$).

With the increased integrated luminosity (20×), combined with improvements to CDF and D0 detectors and larger $t\bar{t}$ cross section, the number of reconstructed top events will be 20–70× larger than in Run I, depending on the final state and tagging requirements. The systematic effects will dominate uncertainties in the measurements of σ_{tt} and $M_{\rm t}$. Both experiments estimate that the error on $M_{\rm t}$ will reach $\Delta M_{\rm top} =$ 2–3 GeV$/c^2$ (compared with 7 GeV$/c^2$ in Run I). The $t\bar{t}$ cross section should be measured with an error of about 8% (about 30% in Run I). Analysis of single top production offers a direct access to the Wtb vertex and should allow the measurement of the $|V_{tb}|$ element of Cabibbo–Kobayashi–Maskawa matrix. Anomalous couplings would lead to anomalous angular distributions and larger production rates. The expected SM cross sections are of the order of 1–2 pb.

Perhaps more importantly, the samples of $t\bar{t}$ and single top candidates are among the best places to look for new physics. Because of the top quark mass being large, event selection cuts in top analyzes are virtually identical to those applied in many analyses looking for physics beyond the SM (Supersymmetry, Technicolor, *etc.*). The measured $t\bar{t}$ cross section values depend on the top quark mass, which has been determined in CDF and D0 using various kinematical fitting techniques *and* assuming that events are just the $t\bar{t}$ events and the SM background. If the sample is not exclusively due to the $t\bar{t}$ events and the SM background, the mass measurements may be incorrect. If additional processes were present then the number of observed events would not agree then with the MC predictions obtained for the measured value of $M_{\rm t}$. It is thus imperative to compare various distributions of the reconstructed top quarks, and especially those of the $t\bar{t}$ -system, with the SM predictions. Discrepancies could indicate new physics. Both CDF and D0 made numerous comparisons. No significant disagreements were found, as perhaps expected given the still limited statistics. However, there exist a few hints that the simplest hypothesis that the top candidate events are just the $t\bar{t}$ events and SM background may not be entirely correct. With a luminosity of 2 fb^{-1} per experiment they should be monitored carefully, as they may be offering us glimpses of new physics [10].

(i) CDF $t\bar{t}$ cross section seems a little high compared to the theoretical predictions. Also, the indirect measurements of $M_{\rm t}$, based on the consistency checks of the SM *excluding* the Tevatron top mass measurements, prefer lower $M_{\rm t}$ ($\approx$ 150–167 GeV/c^2), and a low Higgs mass ($\approx$ 60–130 GeV/c^2).

(ii) There is an excess of W+2jet and W+3jet events (13 where 4.4 ± 0.6 are expected) with double tagged jets (tagged both with SVX and SLT) in the tagged jet multiplicity distribution in the CDF. In addition, the kinematical properties of those events don't agree well with the SM predictions [11].

(iii) There may be a hint of an increase of the reconstructed top quark mass with a number of jets in an event.

(iv) Two (out of 9) CDF dilepton events yield poor fits to the $t\bar{t}$ hypothesis and have unexpectedly large $\not{E}_{\rm T}+\Sigma E_{\rm t}^{\rm lepton}$. One such event exists in the D0 sample.

(v) The distributions of the $t\bar{t}$ mass, in both CDF and D0, seem to have a few more events than expected in the high mass region.

(vi) The transverse momentum distribution of the $t\bar{t}$ system for the sample of 32 CDF tagged lepton+jets events, seems a little harder than expected, based on the Monte Carlo calculations. D0 data does not show any deviations from SM expectations.

vii The rapidity distribution of the $t\bar{t}$ system for the sample of 32 CDF tagged lepton+jets events (which variable probes directly the *fitted* longitudinal component of the neutrino momenta) has a strikingly different shape than that based on MC simulations. However, the D0 pseudorapidity plot is in good agreement with expectations.

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