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Krzysztof Sliwa
For the CDF Collaboration

Tufts University
Medford, Massachusetts 02155

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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TOP MASS AND CROSS SECTION RESULTS FROM CDF AND D0 AT THE FERMILAB TEVATRON

KRZYSZTOF SLIWA
CDF COLLABORATION
Tufts University, Department of Physics and Astronomy
Medford, Massachusetts 02155,USA
E-mail: sliwa@tuhep9.phy.tufts.edu,krzysztof.sliwa@cern.ch

Measurements of the top quark mass and the $t\bar{t}$ production cross section, obtained by CDF and D0 Collaborations at the Tevatron, are presented. The methodology of analyses and their underlying assumptions are summarized. The CDF and D0 top mass averages, based on $\approx$ 100 pb-1 of data collected by each experiment in Run-I, and obtained from a set of selected measurements in several channels are $\mathrm{M}_t = 176.0 \pm 4.0(stat) \pm 5.1(syst)\ GeV/c^2$ and $\mathrm{M}_t = 172.1 \pm 5.2(stat) \pm 4.9(syst)\ GeV/c^2$, respectively. The combined Tevatron top quark mass is $\mathrm{M}_t = 174.3 \pm 3.2(stat) \pm 4.0(syst)\ GeV/c^2$, where the correlations between CDF and D0 averages were taken into account. The CDF measurement of the $t\bar{t}$ cross section (assuming $\mathrm{M}_t = 175\ GeV/c^2$) is $\sigma_{tt} = 7.6\pm^{1.8}_{1.5}$ pb, and the D0 value (assuming $\mathrm{M}_t = 172.1\ GeV/c^2$) is $\sigma_{tt} = 5.9 \pm 1.7$ pb. In anticipation of the much increased statistics in Run-II, the fact that top quark physics is one of the best windows to new physics beyond the Standard Model is emphasized.

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. Search for the top quark was the primary physics goal in Run-I. 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. Both experiments have analysed fully their Run-I data for some time now, and only a few new results on top quark are presented in this paper. A summary of the top quark mass and the $t\bar{t}$ cross section measurements, analysis techniques used and a perspective view on top quark physics after its first 6 years (or so) is the subject of this paper.

In anticipation of Run-II, in which the number of reconstructed $t\bar{t}$ events is expected to be at least 20x larger than in Run-I, the question of whether all available results are consistent with the simplest hypothesis that data contains just the $t\bar{t}$ events and Standard Model background is re-visited.

2 Top Mass and Cross Section Measurements: Methodology

2.1 Measurement of Cross Section

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. This paper reports on measurements of the $t\bar{t}$ pair-production cross section. Results on the single top production cross section are summarized by Liu Yi-Cheng in another paper presented at this conference [4].

One should remember two facts: 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.

2.2 Direct Measurement of Top Mass

All mass measurement techniques used by CDF and D0 assume that each event in the selected sample 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 techiniques. A one-to-one mapping between the observed leptons and jets and the fitted partons is assumed.

Again, two things to remember: i) it is *assumed* that the selected sample of events contains just the $t\bar{t}$ events and the SM background; ii) the combinatorics of the jets-lepton(s) combinations (only one of many possible combinations is correct) adds to the complexity of the problem.

2.3 Indirect Measurement of Top Mass

Precision measurements of various electro-weak parameters, whose values depend on M_t indirectly (via radiative corrections), are compared with values predicted by theoretical calculations in the consistency checks of the SM. Data from LEP-I, LEP-II, SLD, CDF, D0, ν-scattering results and other experiments, including or excluding the direct measurements of the top quark mass, can be used to yield the most likely top quark mass, consistent with the predicted values of the measured electroweak observables. Results are model dependent, as one has to assume a particular theory (e.g. SM or MSSM) to make such comparisons possible. An additional uncertainty come from the unknown Higgs boson mass, which also enters the calculations of radiative corrections.

3 Signatures of $t\bar{t}$ Pair Production

The dominant production mechanism of $t\bar{t}$ pairs at $\sqrt{s} = 1.8\ TeV$ is a gg or $q\bar{q}$ fusion via strong interactions; for top quark masses above $M_t \approx 120\ GeV/c^2$ the $q\bar{q}$ fusion dominates.

Assuming SM decays, there are three classes of final states, all with 2 b-quarks jets: i) *di-leptons*, when both W decays are leptonic, with 2 jets and missing transverse energy ($\not{E}_T$), $BF \approx 4/81$ for e, μ final states; ii) *lepton+jets*, when one W decays leptonically and the other into quarks, with 4 jets and $\not{E}_T$, $BF \approx 24/81$ for e, μ; iii) *all-hadronic*, when both W's decay into quarks, with 6 jets and no $\not{E}_T$, $BF \approx 36/81$.

4 Top Mass and Cross section measurements.

4.1 Direct Searches

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 di-lepton samples, in which backgrounds are expected to be small, various techniques of tagging b-quarks are employed. "Soft-lepton" tagging 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 [5] calculations to estimate shapes of the background distributions due to this process. Presently available samples of the top event candidates are small, and the top cross section and mass measurements are still dominated by the statistical errors. This will no longer be true in Run-II.

Table 1. Results of D0 [6] and CDF [7] direct top searches.

channel	D0 sample	D0 background	CDF sample	CDF background
di-lepton	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

4.2 Mass Measurement in lepton+jets channel

The measured lepton and jets' four-momenta are treated as the corresponding input lepton and quarks' four-momenta in the kinematical fits. Leptons are measured best, jets not as well (better in D0 than in CDF), while the $\not{E}_T$ has the largest error. In the lepton+jets and all-jets final states there is sufficient number of kinematical constraints to perform a genuine fit. In the lepton+jets channel one may, or may not, use $\not{E}_T$ as a starting point for the transverse energy of the missing neutrino. In their published analyses both CDF and D0 use $\not{E}_T$.

CDF defines four independent samples of lepton+jets events, and measures the top quark mass in each of them. The results are summarized in Table 2, and presented in Figure 1. The dominant systematic uncertainties (in GeV/c^2) are: jet energy measurement (4.4); final state radiation (2.2); initial state radiation (1.8); shape of background spectrum (1.3); b-tag biases (0.4); parton distribution function (0.3), yielding the total systematic error of 5.3 GeV/c^2.

Table 2. CDF top mass measurements in lepton+jets samples.

subsample	N	expected background fraction	M_t (GeV/c^2)
SVX double tagged	5	5±3 %	170.1±9.3
SVX single tagged	15	13±3 %	178.1±7.9
SLT tagged (no SVX tag)	14	40±9 %	$142\pm^{33}_{14}$
no tag (all jets $E_T \geq 15$ GeV)	42	56±15 %	181±9

The combined CDF result from the lepton+jets channel is:

$$M_t{=}175.9\pm4.8(\mathrm{stat})\pm5.3(\mathrm{syst})\ \mathrm{GeV}/c^2$$

D0 uses two multivariate discriminant analyses, 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 analyses. The dominant systematic uncertainties (in GeV/c^2) are: jet energy measurement (4.0); background model (2.5); signal model (1.9); fitting technique (1.5); calorimeter noise (1.3), yielding the total systematic error of 5.5 GeV/c^2. A two-dimensional likelihood fit is performed in the M_{fit} vs D plane. A parabolic fit to the distribution of log(fit likelihood) vs M_{fit} yields the result, M_t, corresponding to the minimum. Results of fits, plotted in the signal-rich (a) and background-rich regions (b), are shown in Figure 2. The combined D0 result from the LB and NN methods in the lepton+jets channel, with the correlations between the methods (88±4 %) taken into account, is:

$$M_t{=}173.3\pm5.6(\mathrm{stat})\pm5.5(\mathrm{syst})\ \mathrm{GeV}/c^2.$$

4.3 Mass Measurement in di-lepton channel

In the di-lepton 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, and that their decay products correspond to a given combination of leptons and jets. $\not{E}_T$ may, or may not, be used. D0 developed two methods, the Neutrino Phase Space weighting technique (νWT) and the Average Matrix Element technique (MWT), a modified form of Dalitz-Goldstein [8] and Kondo [9] methods. The combined result, from the νWT and MWT methods, is:

$$M_t{=}168.4\pm12.3(\mathrm{stat})\pm3.6(\mathrm{syst})\ \mathrm{GeV}/c^2.$$

Three techniques of measurements of the top quark mass have been developed in CDF. Two use $\not{E}_T$ (the "neutrino weighting" and the "Minuit fitting" methods), one does not (a modification of the Dalitz-Goldstein method, which instead includes information about the parton distribution functions, transverse energy 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) result is:

$$M_t=167.4\pm^{10.7}_{9.8}(\text{stat})\pm4.8(\text{syst})\ \text{GeV}/c^2.$$

This result was available already last summer, and it was used in the CDF and CDF/D0 combined mass analyses. An analysis using the "Minuit fitting" method yields:

$$M_t=170.7\pm10.6(\text{stat})\pm4.6(\text{syst})\ \text{GeV}/c^2.$$

The Dalitz-Goldstein technique, which uses a single, "best" combination of leptons and jets in an event, gives:

$$M_t=157.1\pm10.9(\text{stat})\pm^{4.4}_{3.7}(\text{syst})\ \text{GeV}/c^2.$$

Table 3. Dominant systematic uncertainties in top mass measurements in the dilepton mode in CDF("neutrino weighting") and D0.

source of uncertainty	CDF	D0
jet energy scale	3.8	2.4
signal model (ISR,FSR)	2.8	1.8
Monte Carlo generators	0.6	0.0
background modelling	0.3	1.1
fitting technique	0.7	1.5
calorimeter noise	0.0	1.3
total	4.8	3.6

4.4 Mass Measurement in all-jets channel

Kinematical fits were performed in CDF to a sample of events selected using SVX tagging. The systematic uncertainty in this mode has been revised since last summer. The uncertainty due to the fitting technique was found overly conservative and has been removed. An uncertainty due to the gluon radiation is now evaluated in the same way as in the lepton+jets and di-lepton channels. The new value of this error is 1.8 GeV/c^2 (it was 8.0 GeV/c^2). Other dominant errors are (in GeV/c^2): jet energy scale (5.0); background model (1.7); Monte Carlo generators (0.8); Monte Carlo statistics (0.6); initial state radiation (0.1). Overall, the systematic error was reduced from 12 GeV/c^2 to 5.7 GeV/c^2. A parabolic fit to the likelihood distribution obtained from fitting the data to a combination of signal and SM background templates yields:

$$M_t=186.0\pm10.0(\text{stat})\pm5.7(\text{syst})\ \text{GeV}/c^2.$$

5 Combined Top Mass Measurements

The CDF (D0) mass measurements in three (two) channels are combined in each of the experiments, taking statistical uncertainties as uncorrelated. The systematic errors due to the energy scale, signal model (ISR and FSR) and MC generator are taken as 100% correlated, and all other systematic errors are taken as uncorrelated.

Table 4. Summary of the results used in the combined CDF, D0, and the joint CDF+D0 measurements of the top quark mass (all results in in GeV/c^2).

channel	CDF	D0
di-leptons	167.4±10.3±4.8	168.4±12.3±3.6
lepton+jets	175.9±4.8±5.3	173.3±5.6±5.5
all-jets	186.0±10.0±5.7	
combined	176.0±4.0±5.1	172.1±5.2±4.9

The Tevatron (CDF+D0) average for Run-I was obtained from the five CDF and D0 results in a similar manner to the way it was done to obtain the CDF and D0 averages. Systematic errors which do not depend directly on the Monte Carlo simulations (jet energy scale, backgrounds...) are taken as uncorrelated between the experiments, while those systematic errors which depend on the Monte Carlo model (ISR, FSR, PDF dependence...) are treated as 100% correlated between the experiments, since both CDF and D0 rely on identical MC models. The result is:

$$M_t = 174.3 \pm 3.2(\mathrm{stat}) \pm 4.0(\mathrm{syst})\ \mathrm{GeV/c^2}.$$

6 $t\bar{t}$ Pair Production Cross Section

Table 5. CDF measurements of the $t\bar{t}$ pair production cross section in individual channels, together with the relevant values of acceptancies, trigger and tagging efficiencies, and the number of observed and expected backgrounds events.

	l+jets	l+jets	di-leptons	all-jets	all-jets
TAG type	SVX	SLT		SVX	double SVX
$\epsilon_{tagging}$	0.39±0.03	0.18±0.02		0.42±0.04	0.11±0.02
geometrical and kinematic cuts acceptance	0.104±0.01	0.104±0.01	0.0076±0.0008	0.106±0.021	0.263±0.045
trigger acceptance	0.90±0.07	0.90±0.07	0.98±0.01	$0.998\pm^{0.002}_{0.009}$	$0.998\pm^{0.002}_{0.009}$
total acceptance	0.037±0.005	0.017±0.003	0.0074±0.0008	0.044±0.01	0.030±0.01
number of events	34	40	9	187	157
background	9.2±1.5	22.6±2.8	2.4±0.5	142±12	120±18
σ_{tt} (in pb)	$6.2\pm^{2.1}_{1.7}$	$9.2\pm^{4.3}_{3.6}$	$8.2\pm^{4.4}_{3.4}$	$9.6\pm^{4.4}_{3.6}$	$11.5\pm^{7.7}_{7.0}$

CDF combines the above cross sections using a likelihood technique which takes into account correlations in the uncertainties. Assuming the top quark mass of 175 GeV/c^2 (in calculating all the corrections) the CDF value of the $t\bar{t}$ pair production cross section is:

$$\sigma_{tt} = 7.6\pm^{1.8}_{1.5}\ \mathrm{pb}$$

D0 measures the $t\bar{t}$ cross section in 4 different samples. (See R. Raja's [10] paper presented at this conference for more information on the D0 all-jets analysis).

The D0 combined value (at M_t=172.1 GeV/c^2) is:

Table 6. D0 measurements of the $t\bar{t}$ cross section, assuming M_t=172.1.

channel	cross section (pb)
di-lepton + $e\nu$	6.4±3.3
lepton+jets (topological)	4.1±2.1
lepton+jets (μ-tagged)	8.3±3.5
all+jets	7.1±3.2

$$\sigma_{tt}=5.9\pm1.7 \text{ pb}$$

For comparison, the theoretical predictions [11] for $t\bar{t}$ pair production cross section fall in the range of 4.7-5.5 pb, for M_t=175 GeV/c^2.

7 Is The Hypothesis Correct ?

As a consequence of the top quark mass being large, the event selection cuts in top analyses are virtually identical to those applied in analyses looking for physics beyond the SM (Supersymmetry, Technicolor, et cetera...). The measured cross section value depends on the top quark mass, which has been measured in CDF and D0 using various kinematical fitting techniques, with an assumption that events are just the $t\bar{t}$ events and the SM background. If the sample is not due to the top quark events, or not exclusively due to the $t\bar{t}$ events and the SM background, the mass measurements may be incorrect. If an additional process were present, it would most likely lead to an increase in the number of observed events. The number of observed events would not agree then with the MC predictions obtained with the measured value of M_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 should be expected given the still limited statistics. There exist just 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. One should keep those hints in mind when Run-II begins in year 2000, as they may be offering us glimpses to new physics.

- CDF $t\bar{t}$ cross section seem a little high compared to the theoretical predictions, however, they agree within the huge errors. It is interesting to note that the indirect measurements of M_t, based on the consistency checks of the SM *excluding* the Tevatron top mass measurements, prefer lower M_t ($\approx$ 150-167 GeV/c^2), and a low Higgs mass ($\approx$ 60-130 GeV/c^2).

- It has been noticed by many that there is a hint of an increase of the reconstructed top quark mass with a number of jets in an event; it is not significant, the values are consistent within errors.

- There seem to be a small excess of the number of W+2 jet events, with both jets SVX tagged, in the tagged jet multiplicity distribution in the CDF W events.

- Two (out of 9) CDF di-lepton events have unexpectedly large $\not{E}_T + \Sigma E_t^{lepton}$, both give poor fits to the $t\bar{t}$ hypothesis. One such event exists in the D0 sample. (The 3 events were flagged by Hall and Barnett [12] as the candidates for SUSY events.)

- 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, however, the effect is not significant as the errors are large.

- The transverse momentum distribution of the $t\bar{t}$ system for the sample of 32 CDF tagged lepton+jets events, which are the basis of the CDF top mass measurement, seems a little harder than expected, based on the Monte Carlo calculations. However, an analogous distribution based on D0 data is in good agreement with the theory predictions.

- The rapidity distribution (Figure 3) of the $t\bar{t}$ system for the sample of 32 CDF tagged lepton+jets events has a strikingly different shape than that based on the Monte Carlo simulations. The rapidity variable probes directly the fitted longitudinal component of the neutrino momenta, and as such is perhaps more sensitive than others to the original hypothesis made while fitting the events. However, an analogous plot based on D0 events (Figure 4) is in good agreement with the MC expectations, which may simply mean that the CDF distribution is a result on an unlikely fluctuation.

8 Top Mass and Cross section: SUMMARY

Combined CDF results from Run-I:

$$M_t = 176.0 \pm 6.5\ GeV/c^2$$
$$\sigma_{tt} = 7.6 \pm^{1.8}_{1.5}\ pb\ (for\ M_t = 175\ GeV/c^2)$$

Combined D0 results from Run-I:

$$M_t = 172.1 \pm 7.1\ GeV/c^2$$
$$\sigma_{tt} = 5.9 \pm 1.7\ pb\ (for\ M_t = 172.1\ GeV/c^2)$$

Combined CDF and D0 result from Run-I:

$$M_t = 174.3 \pm 5.1\ GeV/c^2$$

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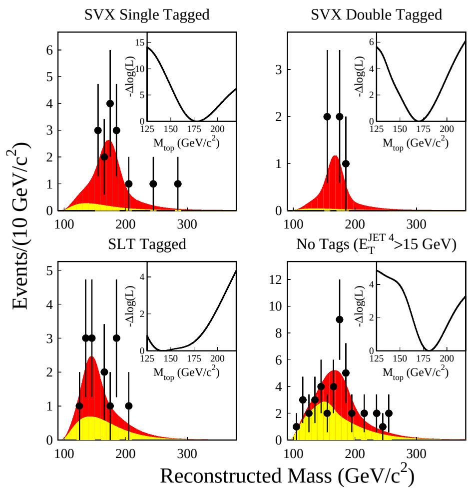

Figure 1. CDF measurements of the top quark mass in the lepton+jets samples.

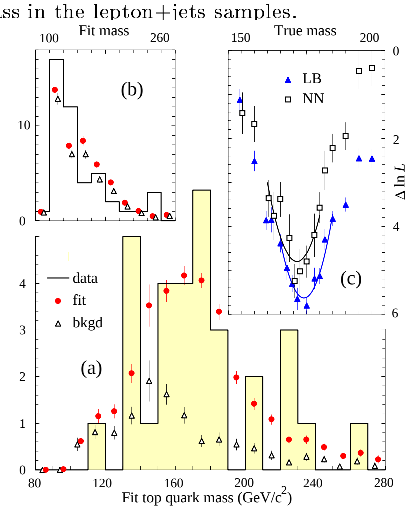

Figure 2. D0 measurements of the top quark mass in the lepton+jets events.

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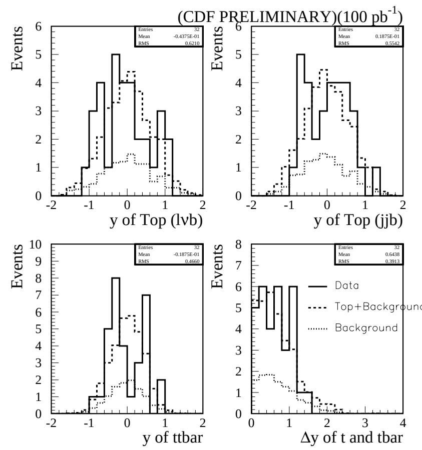

Figure 3. CDF distributions of the rapidity for $t\bar{t}$ system and the fitted top quarks in the sample of 32 tagged lepton+jets events.

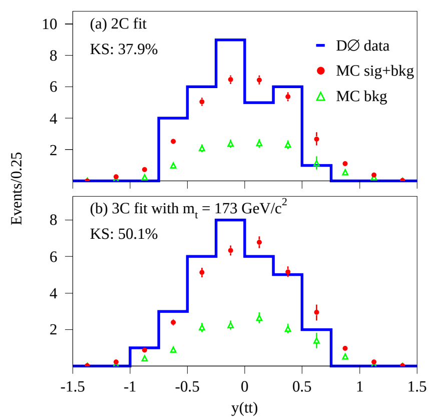

Figure 4. D0 distribution of the rapidity of $t\bar{t}$ system in the lepton+jets events.

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