# TOP QUARK PHYSICS AT THE TEVATRON RESULTS AND PROSPECTS*

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Measurements of the top quark mass and the $t\bar{t}$ and single top production cross sections, obtained by CDF and D0 Collaboration at the Tevatron, are presented. The methodology of CDF and D0 top quark analyses and their underlying assumptions are summarized. The CDF and D0 top mass averages, based on about 100 pb$^{-1}$ of data from collisions of $p\bar{p}$ at $\sqrt{s} = 1.8\,\mathrm{TeV}$ collected by each experiment in Run-I, and obtained from measurements in several channels, are $M_{\mathrm{t}} = 176.1 \pm 4.0$ (stat) $\pm$ 5.1 (syst) GeV$/c^2$ and $M_{\mathrm{t}} = 172.1 \pm 5.2$ (stat) $\pm$ 4.9 (syst) GeV$/c^2$, respectively. The combined Tevatron top quark mass is $M_{\mathrm{t}} = 174.3 \pm 3.2$ (stat) $\pm 4.0$ (syst) GeV$/c^2$. The CDF measurement of the $t\bar{t}$ cross section (assuming $M_{\mathrm{t}} = 175\,\mathrm{GeV}/c^2$) is $\sigma_{tt} = 6.5 \pm^{1.7}_{1.4}$ 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 the increased amount of data in Run-II, prospects are presented. The fact that top quark analyses are among the best windows to new 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. Searching for the top quark was the primary physics objective 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

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have finished their analyses of 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's mass and the $t\bar{t}$ and single top production cross section measurements is presented. A closer look at the analysis techniques used and a perspective view on top quark physics after its first 7 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 20 times larger than in Run-I, the question of whether all available results are consistent with the simplest hypothesis, adopted by both CDF and D0 experiments in Run-I, that data contains just the $t\bar{t}$ events and the Standard Model backgrounds is re-visited.

## 2. Signatures of $t\bar{t}$ pair production and single top production

At Fermilab Tevatron energy, $\sqrt{s} = 1.8$ TeV, the dominant production mechanism for top quarks is $t\bar{t}$ pair production by a quark–antiquark or gluon–gluon initial state via the strong interaction; for top quark masses above $M_{\mathrm{t}} \approx 120\,\mathrm{GeV}/c^2$ the $q\bar{q}$ fusion dominates. Assuming the Standard Model decays, there are three classes of final states, all with two $b$-quarks jets:

*(i)* *di-leptons*, when both $W$ decays are leptonic, with 2 jets and missing transverse energy ($\not\!\!E_{\mathrm{T}}$), BF $\approx 4/81$ for $e, \mu$ final states;

*(ii)* *lepton+jets*, when one $W$ decays leptonically and the other into quarks, with 4 jets and $\not\!\!E_{\mathrm{T}}$, BF $\approx 24/81$ for $e, \mu$;

*(iii)* *all-hadronic*, when both $W$'s decay into quarks, with 6 jets and no $\not\!\!E_{\mathrm{T}}$, BF $\approx 36/81$. The backgrounds to the possible $t\bar{t}$ signal coming from the $W$+jets process of QCD have been feared to be much larger than the top signal and must be addressed. The QCD multijet production background is even more important for all-hadronic final states, in which both $W$ bosons decay into quarks.

The two dominant electroweak processes leading to a single top quark production are: (a) $s$-channel $W^*$ production and its subsequent decay into $t$ and $b$ quark/antiquarks, leading to a final state with a $W$ and two $b$-quark jets; (b) $t$-channel $W$-gluon fusion process, leading to a final state with a $W$ and two jets but only one of them being due to the $b$-quark.

## 3. Top mass and cross section measurements: methodology

### *3.1. 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 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 and the single top production cross section. One should remember two facts: first, 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; second, some of the acceptance corrections are strongly varying functions of the top quark mass, $M_{\rm t}$, and, consequently, the value of the measured cross section depends on the value of $M_{\rm t}$, which has to be determined independently.

### *3.2. 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 techniques. A one-to-one mapping between the observed leptons and jets and the fitted partons is assumed.

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

### *3.3. Indirect measurement of top mass*

Precision measurements of various electro-weak parameters, whose values depend on $M_{\rm t}$ indirectly (via radiative corrections), are compared with the corresponding values predicted by the theoretical calculations in the consistency checks of the SM. Data from LEP-I, LEP-II, SLD, CDF, D0, $\nu$-scattering results and other precision 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 Minimal Supersymmetric Standard Model) to make such comparisons possible. An additional uncertainty comes from the unknown Higgs boson mass, which also enters into calculations of the radiative corrections. The results of such global fits are summarized in Sec. 8, where the question of overall consistency of all electroweak measurements is examined within the framework of the Standard Model.

## 4. Top mass and cross section measurements

### *4.1. Direct searches*

All CDF and D0 searches impose stringent identification, selection and transverse energy ($E_{\mathrm{T}}$) 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 to reduce backgrounds. "Soft-lepton" tagging is used by both CDF and D0, and the secondary vertex tagging, which uses a Silicon Vertex (SVX) detector, 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, summarized in Table I, 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.

### *4.2. Mass measurement in lepton+jets channel*

In the lepton+jets and all-jets final states there is sufficient number of kinematical constraints to perform a genuine fit. 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 (in Run-I better in D0 than in CDF), while the missing transverse energy, $\not{E}_{\mathrm{T}}$, has the largest error. In the lepton+jets channel 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 analyses both CDF and D0 use $\not{E}_{\mathrm{T}}$. However, one should remember that even in a genuine $t\bar{t}$ event only one out of a large number of possible lepton–jet combinations is the correct one. Quite often the incorrect combination may yield a false solution with a comparable or even a better $\chi^2$ than the correct combination. It is very important how the likelihood is defined; it may include just the conservation of energy and

TABLE I

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

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

momentum, or some dynamical factors reflecting the expected production and decay characteristics of $t\bar{t}$ events. 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 II, and presented in Fig. 1.

TABLE II

CDF top mass measurements in lepton+jets samples.

| Subsample | N | Expected background fraction | $M_{\mathrm{t}}$ (GeV/$c^2$) |
|---|---|---|---|
| SVX double tagged | 5 | $5 \pm 3$ % | $170.1 \pm 9.3$ |
| SVX single tagged | 15 | $13 \pm 3$ % | $178.1 \pm 7.9$ |
| SLT tagged (no SVX tag) | 14 | $40 \pm 9$ % | $142\pm^{33}_{14}$ |
| no tag (all jets $E_{\mathrm{T}} \geq 15$ GeV) | 42 | $56 \pm 15$ % | $181 \pm 9$ |

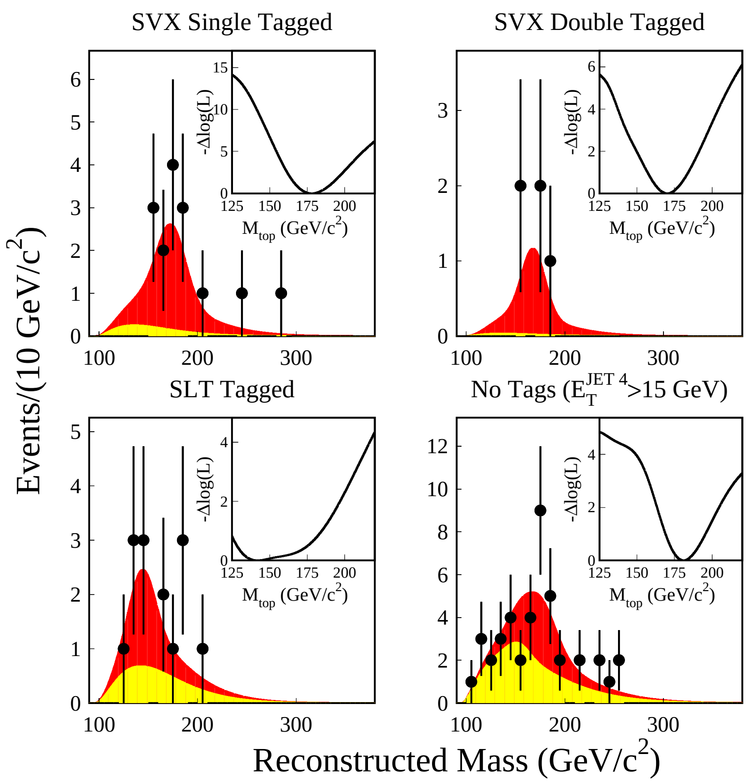


Fig. 1. CDF measurements of the top quark mass in lepton+jets samples.

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$/c^2$.

The combined CDF result from the lepton+jets channel is

$$M_{\mathrm{t}} = 175.9 \pm 4.8\,(\mathrm{stat}) \pm 5.3\,(\mathrm{syst})\ \mathrm{GeV}/c^2\,.$$

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 $M_{\mathrm{fit}}$ *vs* D plane. A parabolic fit to the distribution of log (fit likelihood) *vs* $M_{\mathrm{fit}}$ yields the result, $M_{\rm t}$, corresponding to the minimum. Results of fits, plotted in the signal-rich (a) and background-rich regions (b), are shown in Fig. 2.

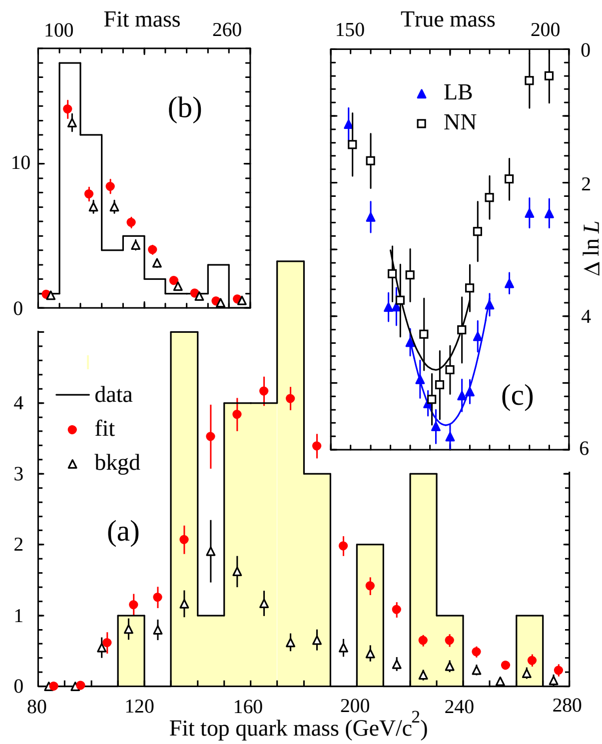


Fig. 2. D0 measurements of the top quark mass in the lepton+jets events.

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

$$M_{\rm t} = 173.3 \pm 5.6\,({\rm stat}) \pm 5.5\,({\rm syst})\;{\rm GeV}/c^2\,.$$

### *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 $M_{\rm t}$, 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. $\not\!\!E_{\rm T}$ may, or may not, be used. D0 developed two methods, the neutrino phase space weighting technique ($\nu$WT) and the average matrix element technique (MWT), a modified form of Dalitz–Goldstein [7] and Kondo [8] methods. The combined result, from the $\nu$WT and MWT methods, is

$$M_{\rm t} = 168.4 \pm 12.3\,({\rm stat}) \pm 3.6\,({\rm syst})\,{\rm GeV}/c^2\,.$$

Three techniques of measurements of the top quark mass have been developed in CDF. Two use $\not\!\!E_{\rm T}$ (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 $\nu$WT) result is

$$M_{\rm t} = 167.4 \pm^{10.7}_{9.8}\,({\rm stat}) \pm 4.8\,({\rm syst})\,{\rm GeV}/c^2\,.$$

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:

$$M_{\rm t} = 170.7 \pm 10.6\,({\rm stat}) \pm 4.6\,({\rm syst})\,{\rm GeV}/c^2\,.$$

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

$$M_{\rm t} = 157.1 \pm 10.9\,({\rm stat}) \pm^{4.4}_{3.7}\,({\rm syst})\,{\rm GeV}/c^2\,.$$

TABLE III

Dominant systematic uncertainties in top mass measurements in the dilepton mode in CDF ("neutrino weighting") and D0 (all errors in GeV/$c^2$).

| 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 modeling | 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 dominant errors are (in GeV/$c^2$): jet energy scale (5.0); final state radiation (1.8); background model (1.7); Monte Carlo generators (0.8); Monte Carlo statistics (0.6); initial state radiation (0.1); yielding the total systematic error of 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

$$M_{\rm t} = 186.0 \pm 10.0\,({\rm stat}) \pm 5.7\,({\rm syst})\,{\rm GeV}/c^2\,.$$

## 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.

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

$$M_{\rm t} = 174.3 \pm 3.2\,({\rm stat}) \pm 4.0\,({\rm syst})\,{\rm GeV}/c^2\,.$$

TABLE IV

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

| Channel | CDF | D0 |
|---|---|---|
| di-leptons | 167.4±10.3±4.8 | 168.4±12.3±3.6 |
| lepton+jets | 176.1±4.8±5.3 | 173.3±5.6±5.5 |
| all-jets | 186.0±10.0±5.7 | — |
| combined | $176.1 \pm 4.0 \pm 5.1$ | $172.1 \pm 5.2 \pm 4.9$ |

TABLE V

CDF measurements of the $t\bar{t}$ pair production cross section in individual channels, together with the relevant values of acceptances, 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 |
| $\varepsilon_{\text{tagging}}$ | 0.505±0.051 | 0.157±0.016 | | 0.544±0.057 | 0.17±0.05 |
| geometrical and kinematical cuts acceptance | 0.078±0.01 | 0.078±0.01 | 0.0074±0.0008 | 0.099±0.016 | 0.263±0.045 |
| trigger acceptance | 0.90±0.07 | 0.90±0.07 | 0.98±0.01 | $0.998\pm^{0.002}_{0.009}$ | $0.998\pm^{0.002}_{0.009}$ |
| acceptance | 0.035±0.005 | 0.011±0.002 | 0.0074±0.0008 | 0.054±0.01 | 0.045±0.015 |
| number of events | 29 | 25 | 9 | 187 | 157 |
| background | 6.7±1.0 | 13.22±1.22 | 2.4±0.5 | 144±12 | 120±18 |
| $\sigma_{tt}$ (in pb) | $5.1\pm^{1.6}_{1.4}$ | $9.2\pm^{4.8}_{3.9}$ | $8.2\pm^{4.4}_{3.4}$ | $7.4\pm^{3.8}_{3.1}$ | $7.8\pm^{5.2}_{4.6}$ |

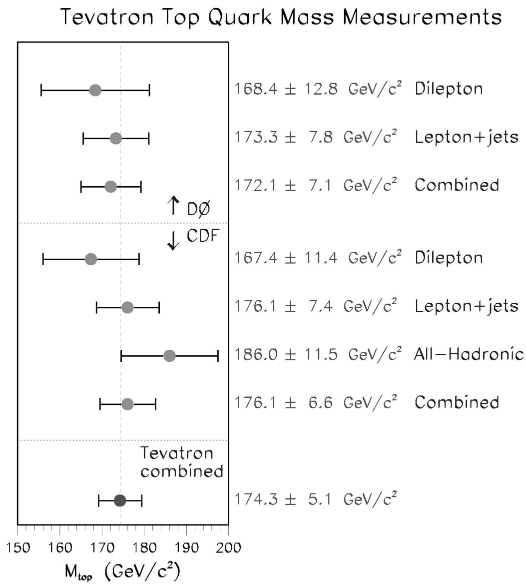


Fig. 3. CDF and D0 measurements of the top quark mass using Tevatron Run-I data.

## 6. $t\bar{t}$ pair production cross section

CDF combines the above cross section 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

$$\sigma_{tt} = 6.5 \pm^{1.7}_{1.4} \text{ pb}\,.$$

D0 measures the $t\bar{t}$ cross section in 4 different samples.

| Channel | events | cross section (pb) |
|---|---|---|
| di-lepton + $e\nu$ | 9 | $6.4 \pm 3.3$ |
| lepton+jets (topological) | 19 | $4.1 \pm 2.1$ |
| lepton+jets ($\mu$-tagged) | 11 | $8.3 \pm 3.5$ |
| all+jets | 41 | $7.1 \pm 3.2$ |

The D0 combined value (at $M_{\rm t}$=172.1 GeV$/c^2$) is

$$\sigma_{tt} = 5.9 \pm 1.7\,\text{pb}\,.$$

For comparison, the theoretical predictions [9] 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. Single top production

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 larger production rates, while the Standard Model cross section predictions are: 0.72±0.04 pb [10] and 1.70±0.20 pb [11], for $s$-channel and $t$-channel processes, respectively. Both D0 and CDF experiments conducted searches, although their sensitivity with the Run-I statistics is insufficient to detect signals of predicted magnitude. The CDF search for single top production was based on a fit to the $H_\mathrm{T}$ distribution for $W$+1,2,3 jet events, and assumed the Monte Carlo simulated shapes of $H_\mathrm{T}$ distributions for QCD and $t\bar{t}$ backgrounds. CDF finds a limit for the single top production cross section $\sigma = 13.5$ pb at 95% CL. D0 employed an array of neural nets to derive limits of $\sigma = 17$ pb at 95% CL ($s$-channel) and $\sigma = 22$ pb at 95% CL ($t$-channel).

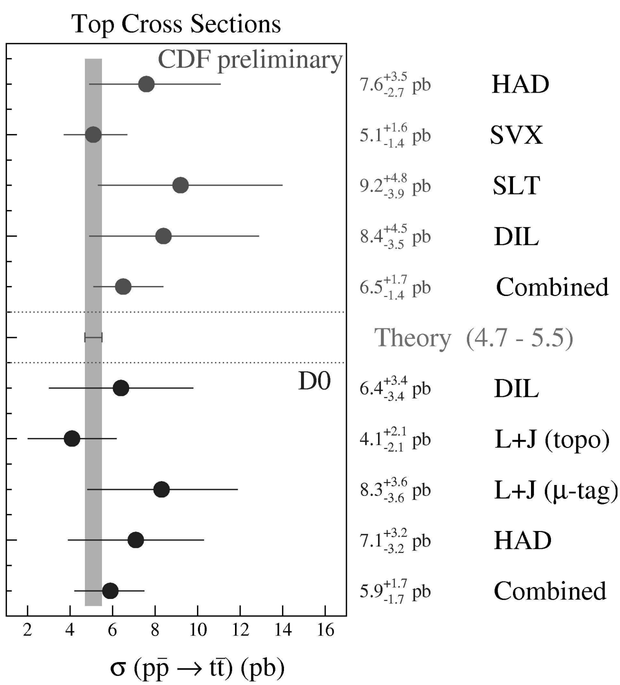


Fig. 4. CDF and D0 measurements of the top pair production cross section. For comparison, the range of theoretical predictions [9] for $t\bar{t}$ pair production cross section is also shown.

## 8. Standard model consistency checks: Higgs boson mass *vs* $M_t$

The precision measurements of electroweak parameters at LEP, SLC, FNAL and other precision experiments can be used to verify the consistency of the Standard Model and to infer bounds and constraints on its basic parameters. The leading-order top quark corrections are quadratic in top quark mass, $M_t$, which allows quite precise "determination" of $M_t$ *indirectly* from other electroweak measurements. The dependence of the leading order corrections to the Higgs boson mass, $M_H$, is logarithmic, and the bounds on Higgs mass are weaker with the current measurement errors. It is worthwhile to note that the value of $M_{\rm top} \approx 175$ GeV/$c^2$ could be obtained *indirectly* from global fits to the electroweak parameters measured at LEP, LEP-II, SLC and $\nu$ experiments but *only* if one *assumes* $M_H \approx 300$ GeV/$c^2$. The fact that this particular value of $M_H$=300 GeV/$c^2$ was used in the electroweak fits — consistency checks of the Standard Model from 1993–1996 was not emphasized when claims were made that LEP "predicted" the top quark mass of about 175 GeV/$c^2$ in advance of CDF and D0 direct measurements. It is also interesting to note that a set of fits to the electroweak parameters in which both $M_t$ and $M_H$ are treated as free parameters were consistently pointing to a low Higgs mass (60–150 GeV/$c^2$) and a lower top quark mass (157–169 GeV/$c^2$). With all the excitement surrounding searches for a light Higgs at LEP-II the fact that the low mass Higgs would also point to the lower value of $M_t$ was not always remembered. With the precise measurements of $M_W$, $M_t$ and final results from LEP and LEP-II available, the most recent consistency checks of the Standard Model performed with global fits to all electroweak measurements give poor fits. This could be an indication of the "new physics" beyond the Standard Model.

## 9. Prospects for Run-II. Is it only top?

In Run-IIa, which started at the end of 2001, CDF and D0 are each expected to collect 2 fb$^{-1}$ of integrated luminosity. With the new Main Injector, the $p\bar{p}$ collisions take place at $\sqrt{s} = 1.96$ TeV, and the $t\bar{t}$ cross section is $\approx 35\%$ larger than at Run-I. Because of different beam crossing time (396 ns and 132 ns later, instead of 3.5 $\mu$s in Run-I) the number of multiple interactions per event will be less 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 doubled 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

TABLE VI

Results of the consistency checks of the Standard Model performed by LEP Electroweak Working Group [12]. Indirect measurements of $M_{\rm t}$ obtained using the global fits to electroweak parameters in years 1993–1996 assume $M_H = 300\,{\rm GeV}/c^2$, and the second errors correspond to varying $M_H$ in the range 60–1000 GeV/$c^2$. With more precise measurements available, starting in 1997 the global fits allow indirect determination of both $M_{\rm t}$ and $M_H$ (all masses in GeV/$c^2$).

| Year | | LEP | All data | $M_H$ (GeV/$c^2$) |
|---|---|---|---|---|
| 1993 | $M_{\rm t}$ | $166\pm^{17}_{19}\pm^{19}_{22}$ | $164\pm^{16}_{17}\pm^{17}_{21}$ | 300 |
| | $\chi^2$/NDF | 3.5/8 | 4.1/11 | |
| 1994 | $M_{\rm t}$ | $173\pm^{12}_{13}\pm^{18}_{20}$ | $171\pm^{11}_{12}\pm^{18}_{19}$ | 300 |
| | $\chi^2$/NDF | 7.6/9 | 4.4/11 | |
| 1995 | $M_{\rm t}$ | $170\pm10\pm^{17}_{29}$ | $178\pm8\pm^{17}_{20}$ | 300 |
| | $\chi^2$/NDF | 18/9 | 28/14 | |
| 1996 | $M_{\rm t}$ | $171\pm8\pm^{17}_{19}$ | $177\pm7\pm^{16}_{19}$ | 300 |
| | $\chi^2$/NDF | 10/9 | 24/14 | |

| Year | | LEP | All data | Exclude $M_{\rm t}$, $M_W$ |
|---|---|---|---|---|
| 1997 | $M_{\rm t}$ | $158\pm^{14}_{11}$ | $173.1\pm5.4$ | $157\pm^{10}_{9}$ |
| | $M_H$ | $83\pm^{168}_{49}$ | $115\pm^{116}_{66}$ | $41\pm^{64}_{21}$ |
| | $\chi^2$/NDF | 8/9 | 17/15 | 14/12 |
| 1998 | $M_{\rm t}$ | $160\pm^{13}_{9}$ | $171.1\pm4.9$ | $158\pm^{9}_{8}$ |
| | $M_H$ | $60\pm^{127}_{35}$ | $76\pm^{85}_{47}$ | $32\pm^{41}_{15}$ |
| | $\chi^2$/NDF | 4/9 | 15/15 | 13/12 |
| 1999 | $M_{\rm t}$ | $172\pm^{11}_{11}$ | $173.2\pm4.5$ | $167\pm^{11}_{8}$ |
| | $M_H$ | $134\pm^{268}_{81}$ | $77\pm^{69}_{39}$ | $55\pm^{84}_{27}$ |
| | $\chi^2$/NDF | 11/9 | 23/15 | 21/12 |
| 2000 | $M_{\rm t}$ | $179\pm^{13}_{10}$ | $174.3\pm^{4.4}_{4.1}$ | $169\pm^{10}_{8}$ |
| | $M_H$ | $135\pm^{262}_{83}$ | $60\pm^{52}_{29}$ | $56\pm^{75}_{27}$ |
| | $\chi^2$/NDF | 13/9 | 21/15 | 19/12 |
| 2001 | $M_{\rm t}$ | $186\pm^{13}_{11}$ | $175.8\pm^{4.4}_{4.3}$ | $169\pm^{12}_{9}$ |
| | $M_H$ | $260\pm^{404}_{155}$ | $88\pm^{53}_{35}$ | $81\pm^{109}_{40}$ |
| | $\chi^2$/NDF | 15.5/8 | 22.9/15 | 18.9/12 |

| Year | | LEP | All data | Exclude $M_{\rm t}$ |
|---|---|---|---|---|
| 2002 | $M_{\rm t}$ | $184\pm^{13}_{11}$ | $174.3\pm^{4.5}_{4.3}$ | $180\pm^{11}_{9}$ |
| | $M_H$ | $228\pm^{367}_{136}$ | $81\pm^{52}_{33}$ | $117\pm^{161}_{63}$ |
| | $\chi^2$/NDF | 13.3/9 | 29.7/15 | 17.9/12 |

(20 times), combined with improvements to CDF and D0 detectors and larger $t\bar{t}$ cross section, the number of reconstructed top events will increase by a factor of $\approx$ 20–70, depending on the final state and tagging require-

ments. Both experiments estimate that they will measure the top quark mass with an error of $\Delta M_{\rm top} = 2$–$3\,{\rm GeV}/c^2$ (compared with 7 GeV/$c^2$ in Run-I) and the $t\bar{t}$ cross section with an uncertainty of about 8% (about 15% in Run-I). The biggest challenge for both experiments will be reducing the systematic errors to take full advantage of expected large statistics. As mentioned before, analysis of single top production based on Run-II data should allow a study of the $Wtb$ vertex and the measurement of the $|V_{tb}|$ element of Cabibbo–Kobayashi–Maskawa matrix. Should the couplings were different than those predicted in the Standard Model, angular distributions will exhibit anomalies, and the production cross sections will be larger than the expected 1–2 pb.

TABLE VII

Prospects for CDF and D0 experiments in Tevatron Run-II, compared with the corresponding values of selected characteristics from Run-I.

| | Run-I | Run-IIa CDF | Run-IIa D0 |
|---|---|---|---|
| "typical" luminosity (cm$^{-2}$s$^{-1}$) | $1.6\times10^{30}$ | $8.6\times10^{31}$ | $8.6\times10^{31}$ |
| integrated luminosity | 110 pb$^{-1}$ | 2 fb$^{-1}$ | 2 fb$^{-1}$ |
| dilepton events | 10/exp | 140 | 200 |
| lepton+$\geq$4 jets | 20/exp | 1500 | 1800 |
| lepton+$\geq$3 jets+$\geq$ 1b jet tag | 30/exp | 1400 | 1400 |
| lepton+$\geq$4 jets+$\geq$ 2b jet tag | 5/exp | 610 | 450 |
| $\Delta M_{\rm t}$ | 7 GeV/$c^2$ | 2–3 GeV/$c^2$ | 2–3 GeV/$c^2$ |
| $\Delta\sigma(t\bar{t})$ | 30% | 8% | 8% |

Perhaps even more importantly, the $t\bar{t}$ and single top events constitute background to any new physics. As a consequence of the large top mass, the event selection cuts in top analyses 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, whose value has been determined in CDF and D0 using various kinematical fitting techniques *and* the assumption 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 an additional process were present, the number of observed events would not agree then with the MC predictions obtained with 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 should be 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 the luminosity of 2 fb$^{-1}$ per experiment they should be monitored carefully, as they may be offering us glimpses of new physics.

*(i)* CDF $t\bar{t}$ cross section seems a little high compared to the theoretical predictions; it would be more consistent with the lower value of $M_{\rm t}$; the indirect measurements of $M_{\rm t}$, based on the global checks of the SM *excluding* the direct $M_{\rm t}$ measurements, also prefer lower $M_{\rm t}$ ($\approx$ 157–169 GeV/$c^2$)

*(ii)* There is an excess of $W$+2jet and $W$+3jet events (13 where 4.4$\pm$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 [13].

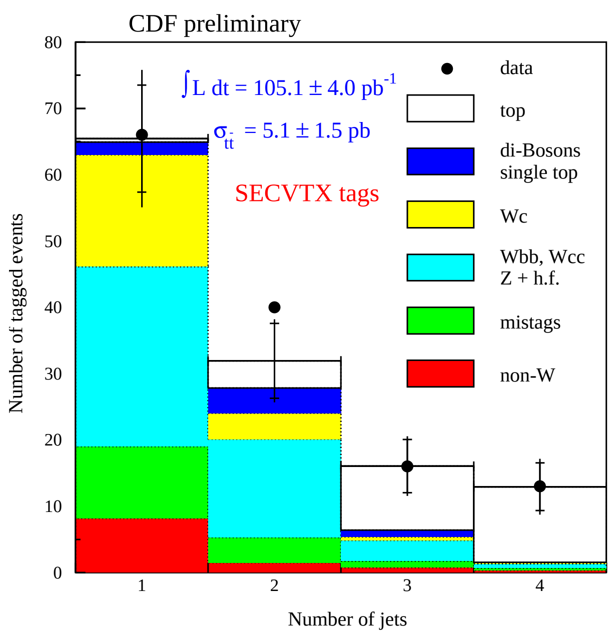


Fig. 5. Number of $W$+$N$ jets events as a function of the number of jets, $N$, for CDF top candidates with at least one of jets tagged with SVX, the CDF vertex detector. The excess in $W$+2jet events is more pronounced if jets are tagged both with SVX and SLT.

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

*(iv)* Two (out of 9) CDF di-lepton events poorly fit the $t\bar{t}$ hypothesis and have unexpectedly large $\not{E}_{\rm T} + \Sigma E_t^{\rm lepton}$. 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 (Fig. 6) 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 MC simulations. The rapidity variable probes directly the *fitted* longitudinal component of the neutrino momenta and, as such, is perhaps more sensitive than other variables to the correctness of the original hypothesis that the fitted events are the $t\bar{t}$ events.

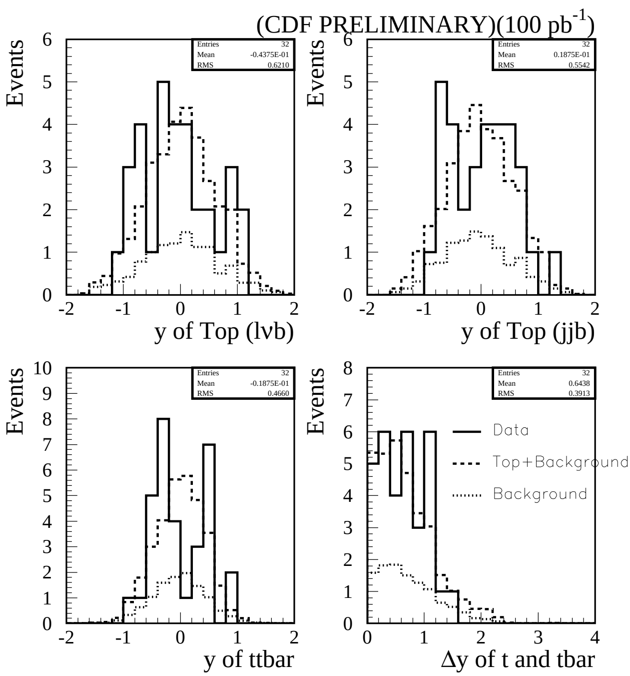


Fig. 6. CDF distributions of the rapidity for top, antitop and the $t\bar{t}$ system of the fitted top quarks in the sample of 32 tagged lepton+jets events.

However, the D0 pseudorapidity plot (Fig. 7) is in good agreement with expectations [14].

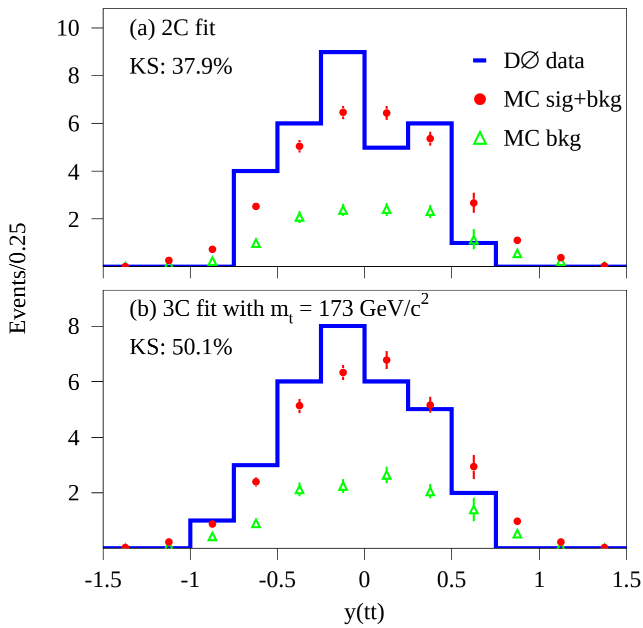


Fig. 7. D0 distribution of the rapidity of $t\bar{t}$ system in the lepton+jets events.

I would like to thank the Conference Organizers for their very warm hospitality and for making the Epiphany 2003 an exceptionally well organized conference. It was an especially memorable experience for me; I still vividly remember my times as a student, and later an assistant, at the Institute of Physics of the Jagellonian University where the conference was held.

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