t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}$ e Top = +1

THE TOP QUARK

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A. Introduction: The top quark is the $Q = 2/3$, $T_3 = +1/2$ member of the weak-isospin doublet containing the bottom quark (see the review on the "Standard Model of Electroweak Interactions" for more information). This note summarizes the properties of the top quark (mass, production cross section, decay branching ratios, *etc.*), and provides a discussion of the experimental and theoretical issues involved in their determination

B. Top quark production at the Tevatron: All direct measurements of production and decay of the top quark have been made by the CDF and DØ experiments in $p\overline{p}$ collisions at the Fermilab Tevatron collider. The first studies were performed during Run I, at $\sqrt{s} = 1.8$ TeV, which was completed in 1996. The most recent, and highest-statistics, measurements are from Run II, which started in 2001 at $\sqrt{s} = 1.96$ TeV. This note will discuss primarily results from Run II.

In hadron collisions, top quarks are produced dominantly in pairs through the QCD processes $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. At 1.96 TeV (1.8 TeV), the production cross section in these channels is expected to be approximately 7 pb (5 pb) for m_t = 175 GeV/c^2, with a contribution of 85% (90%) from $q\overline{q}$ annihilation [1]. Somewhat smaller cross sections are expected from electroweak single-top production mechanisms, namely from $q\overline{q}' \to t\overline{b}$ [2] and $qb \to q't$ [3], mediated by virtual s-channel and t-channel W bosons, respectively. The combined rate for the single-top processes at 1.96 TeV is approximately 3 pb for $m_t = 175$ GeV/c^2 [4]. The identification of top quarks in the electroweak single-top channel is much more difficult than in the QCD $t\overline{t}$ channel, due to a less distinctive signature and significantly larger backgrounds.

In top decay, the Ws and Wd final states are expected to be suppressed relative to Wb by the square of the CKM matrix elements V_{ts} and V_{td}. Assuming unitarity of the three-generation CKM matrix, these matrix element values can be estimated to be less than 0.043 and 0.014, respectively (see the review "The Cabibbo-Kobayashi-Maskawa Mixing Matrix" in the current edition for more information). With a mass above the Wb threshold, and V_{tb} close to unity, the decay width of the top quark is expected to be dominated by the two-body channel $t \rightarrow Wb$. Neglecting terms of order m_b^2/m_t^2, α_s^2 and $(\alpha_s/\pi)M_W^2/m_t^2$, the width predicted in the Standard Model (SM) is [5]:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]. \tag{1}$$

The width increases with mass, changing, for example, from 1.02 GeV/c^2 for $m_t = 160$ GeV/c^2 to 1.56 GeV/c^2 for $m_t = 180$ GeV/c^2 (we use $\alpha_s(M_Z) = 0.118$). With its correspondingly short lifetime of $\approx 0.5 \times 10^{-24}$ s, the top quark is expected to decay before top-flavored hadrons or $t\overline{t}$-quarkonium bound states can form [6]. The order α_s^2 QCD corrections to Γ_t are also available [7], thereby improving the overall theoretical accuracy to better than 1%.

The final states for the leading pair-production process can be divided into three classes:

A. $t\overline{t} \rightarrow W^+ b\, W^- \overline{b} \rightarrow q\, \overline{q}'\, b\, q''\, \overline{q}'''\, \overline{b}$, (46.2%)

B. $t\overline{t} \rightarrow W^+ \, b \, W^- \, \overline{b} \rightarrow q \, \overline{q}' \, b \, \ell \, \overline{\nu}_\ell \, \overline{b} + \overline{\ell} \, \nu_\ell \, b \, q \, \overline{q}' \, \overline{b}$, (43.5%)

C. $t\overline{t} \rightarrow W^+ \, b \, W^- \, \overline{b} \rightarrow \overline{\ell} \, \nu_\ell \, b \, \ell' \, \overline{\nu}_{\ell'} \, \overline{b}$, (10.3%)

The quarks in the final state evolve into jets of hadrons. A, B, and C are referred to as the all-jets, lepton+jets (ℓ+jets), and dilepton ($\ell\ell$) channels, respectively. Their relative contributions, including hadronic corrections, are given in parentheses. While ℓ in the above processes refers to e, μ, or τ, most of the results to date rely on the e and μ channels. Therefore, in what follows, we will use ℓ to refer to e or μ, unless noted otherwise.

The initial and final-state quarks can radiate (or emit) gluons that can be detected as additional jets. The number of jets reconstructed in the detectors depends on the decay kinematics as well as on the algorithm for reconstructing jets used by the analysis. The transverse momenta of neutrinos are reconstructed from the imbalance in transverse momentum measured in each event (missing E_T).

The observation of $t\overline{t}$ pairs has been reported in all of the above decay classes. As discussed below, the production and decay properties of the top quark extracted from the three decay classes are consistent within their experimental uncertainty. In particular, the $t \rightarrow Wb$ decay mode is supported through the reconstruction of the $W \rightarrow jj$ invariant mass in events with two identified b-jets in the $\ell\nu_\ell b\overline{b}jj$ final state [8]. Also the CDF and DØ measurements of the top quark mass in lepton+jets events, where the jet energy scale is calibrated *in situ* using the invariant mass of the hadronically decaying W boson [9,10], support this decay mode.

The extraction of top-quark properties from Tevatron data relies on good understanding of the production and decay mechanisms of the top quark, as well as of the background processes. For the background, the jets are expected to have a steeply falling E_T spectrum, to have an angular distribution peaked at small angles with respect to the beam, and to contain b- and c-quarks at the few percent level. On the contrary, for the top signal, the b fraction is expected to be $\approx$ 100% and the jets rather energetic, since they come from the decay of a massive object. It is therefore possible to improve the S/B ratio by requiring the presence of a b quark, or by selecting very energetic and central kinematic configurations, or both.

Background estimates can be checked using control samples with fewer jets, where there is little top contamination (0 or 1 jet for dilepton channels, 1 or 2 jets for lepton+jets channels, and, $\leq$ 4 jets or multijets ignoring b-tagging for the all-jets channel).

Next-to-leading order Monte Carlo programs have recently become available for both signal and background processes [11], but for the backgrounds the jet multiplicities required in $t\bar{t}$ analyses are not yet available. To date only leading-order (LO) Monte Carlo programs have been used in the analyses. Theoretical estimates of the background processes (W or Z bosons + jets and dibosons+jets) using LO calculations have large uncertainties. While this limitation affects estimates of the overall production rates, it is believed that the LO determination of event kinematics and of the fraction of W+multi-jet events that contain b- or c-quarks are relatively accurate [12].

C. Measured top properties: Current measurements of top properties are based on Run II data with integrated luminosities up to 760 pb^{-1} for CDF, and up to 370 pb^{-1} for DØ.

C.1 $t\bar{t}$ Production Cross Section: Both experiments determine the $t\bar{t}$ production cross section, $\sigma_{t\bar{t}}$, from the number of observed top candidates, estimated background, $t\bar{t}$ acceptance, and integrated luminosity. The cross section has been measured in the dilepton, lepton+jets and all jets decay modes. To separate signal from background, the experiments use identification of jets likely to contain b-quarks ("b-tagging") and/or discriminating kinematic observables. Techniques used for b-tagging include identification of a secondary vertex ("vtx b-tag"), a probability that a jet contains a secondary vertex based on the measured impact parameter of tracks ("jet probability"), or identification of a muon from a semileptonic b decay ("soft μ b-tag"). Due to the lepton identification (ID) requirements in the ℓ+jets and $\ell\ell$ modes, in particular the p_T requirement, the sensitivity is primarily to e and μ decays of the W with only a small contribution from $W \rightarrow \tau\nu$ due to secondary $\tau \rightarrow (e, \mu)\nu X$ decays. In the $\ell\ell$ mode when only one lepton is required to satisfy lepton ID criteria (ℓ+track), there is greater sensitivity to $W \rightarrow \tau\nu$. CDF uses a missing-$\not{E}_T$+jets selection in the ℓ+jets mode, that does not require specific lepton-ID and therefore has significant acceptance to $W \rightarrow \tau\nu$ decays, including hadronic τ decays, in addition to $W \rightarrow e\nu, \mu\nu$ decays. In a direct search for the tau decay mode of $t\bar{t}$ pairs in the lepton+hadronic tau channel, the ratio $r_\tau \equiv B(t \rightarrow b\tau\nu)/B_{SM}(t \rightarrow b\tau\nu)$ is found to be $r_\tau < 5.2$ at 95% CL [13]. Table 1 shows the measured cross sections from DØ and CDF, together with the range of theoretical expectations.

The theory calculations at next-to-leading order including soft gluon resummation [1] are in good agreement with all the measurements. The increased precision of combined measurements from larger Run II samples can serve to constrain, or probe, exotic production mechanisms or decay channels that are predicted by some models [14–17]. Such non-SM effects would yield discrepancies between theory and data. New sources of

Table 1: Cross section for $t\overline{t}$ production in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV from CDF and DØ ($m_t = 175$ GeV/c^2), and theory. Also shown are final results from Run I at $\sqrt{s} = 1.8$ TeV from CDF ($m_t = 175$ GeV/c^2) & DØ ($m_t = 172.1$ GeV/c^2). Uncertainties given are the quadrature sum of statistical and systematic uncertainties of each measurement.

$\sigma_{t\bar{t}}(pb)$	Source	$\int \mathcal{L}$dt (pb^{-1})	Ref.		Method
$6.7^{+2.2}_{-1.7}$	DØ	230	[22]		ℓ + jets/kinematics
$8.6^{+1.7}_{-1.6}$	DØ	230	[23]		ℓ + jets/vtx b-tag
$8.1^{+1.4}_{-1.3}$	DØ	370	[24]	†	ℓ + jets/vtx b-tag
$7.9^{+1.7}_{-1.6}$	DØ	370	[25]	†	ℓ + jets/0-2 vtx b-tags
$8.6^{+3.4}_{-3.0}$	DØ	220-240	[26]		$\ell\ell$
$8.6^{+2.7}_{-2.3}$	DØ	370	[27]	†	$\ell\ell$
$11.1^{+6.0}_{-4.6}$	DØ	160	[28]	†	$e\mu$/vtx b-tag
$8.6^{+2.3}_{-2.1}$	DØ	370	[29]	†	ℓ+track/vtx b-tag + $e\mu$
$5.2^{+3.0}_{-2.7}$	DØ	350	[30]	†	all-jets/vtx b-tags
12.1 ± 6.7	DØ	360	[31]	†	all-jets/vtx b-tags
$7.1^{+1.9}_{-1.7}$	DØ	220-240	[32]	†	combined
$5.6^{+1.5}_{-1.3}$	CDF	160	[33]		ℓ + jets/vtx b-tag
8.2 ± 1.2	CDF	695	[34]	†	ℓ + jets/vtx b-tag
8.9 ± 1.5	CDF	320	[35]	†	ℓ + jets/jet prob b-tag
$5.3^{+3.5}_{-3.4}$	CDF	190	[36]		ℓ + jets/soft μ b-tag
6.6 ± 1.9	CDF	190	[37]		ℓ + jets/kinematics
6.0 ± 1.1	CDF	760	[38]	†	ℓ + jets/kinematics
6.0 ± 2.0	CDF	160	[39]		ℓ + jets/kin+vtx b-tag
$6.0^{+1.5}_{-1.4}$	CDF	310	[40]		ℓ + jets/miss.-$\not{E}_T$+jets
$7.0^{+2.9}_{-2.4}$	CDF	200	[41]		$\ell\ell$
8.3 ± 1.9	CDF	750	[42]	†	$\ell\ell$
10.1 ± 2.6	CDF	360	[43]	†	ℓ+track
$8.0^{+3.9}_{-3.0}$	CDF	310	[44]	†	all-jets/kin+vtx b-tags
7.3 ± 0.9	CDF	760	[45]	†	combined
$5.8 - 7.4$	Theory ($\sqrt{s}$=1.96 TeV)		[1]		$m_t = 175$ GeV/c^2
$6.5^{+1.7}_{-1.4}$	CDF Run I	105	[50]		all combined
5.7 ± 1.6	DØ Run I	110	[51,52]		all combined
$4.5 - 5.7$	Theory ($\sqrt{s}$=1.8 TeV)		[1]		$m_t = 175$ GeV/c^2
$5.0 - 6.3$	Theory ($\sqrt{s}$=1.8 TeV)		[1]		$m_t = 172.1$ GeV/c^2

† Prelim. result, not yet submitted for publication as of April 2006.

top could also modify kinematic distributions, such as the invariant mass of the $t\bar{t}$ pair or the transverse momentum (p_T) of the top quark. Run I studies of the $t\bar{t}$ invariant mass by CDF and DØ [18,19] and of p_T distributions by CDF [20] show no deviation from expected behavior. DØ [21] also found these kinematic distributions to be consistent with expectations of the SM in Run I. In Run II, distributions of primary kinematic variables such as the lepton p_T, missing E_T, and angular variables have been investigated [22–46] and found to be consistent with the SM. Also, the $t\bar{t}$ invariant mass distributions have been studied [47,48]. These tests are presently statistics limited and will be more incisive with larger data sets in Run II.

C.2 Top Quark Mass Measurements: The top mass has been measured in the lepton+jets, dilepton and the all-jets channel by both CDF and DØ. At present, the most precise measurements come from the lepton+jets channel containing four or more jets and large missing E_T. The samples for the mass measurement are selected using topological (topo) or b-tagging methods. In this channel, four basic techniques are employed to extract the top mass. In the first, the so-called "template method" (TM) [49], an over-constrained (2C) kinematic fit is performed to the hypothesis $t\bar{t} \to W^+ b W^- \overline{b} \to \ell \, \bar{\nu}_\ell \, b \, q \, \overline{q}' \, \overline{b}$ for each event, assuming that the four jets of highest E_T originate from the four quarks in $t\bar{t}$ decay. There are 24 possible solutions, reflecting the allowed assignment of the final-state quarks to jets and the two possible solutions for the longitudinal momentum, p_z, of the neutrino when the W mass constraint is imposed on the leptonic W decay. The number of solutions is reduced to 12 when a jet is b-tagged and assigned as one of the b quarks, and to 4 when the event has two such b-tags. A χ^2 variable describes the agreement of the measurements with each possible solution under the $t\bar{t}$ hypothesis given jet energy resolutions. The solution with the lowest χ^2 is defined as the best choice, resulting in one value for the reconstructed top quark mass per event. The distribution of reconstructed top quark mass from the data events is then compared to templates modeled from a combination of signal and background distributions for a series of assumed top masses. The best fit value for the top quark mass and its uncertainty are obtained from a maximum likelihood fit. In the second method, the "Matrix Element/Dynamic Likelihood Method" (ME/DLM), similar to that originally suggested by Kondo et al. [53] and Dalitz and Goldstein [54], a probability for each event is calculated as a function of the top mass, using a LO matrix element for the production and decay of $t\bar{t}$ pairs. All possible assignments of reconstructed jets to final-state quarks are used, each weighted by a probability determined from the matrix element. The correspondence between measured four-vectors and parton-level four-vectors is taken into account using probabilistic transfer functions. In a third method, the "Ideogram Method" [55], which combines some of the features of the above two techniques, each event is compared to the signal and background mass spectrum, weighted by the χ^2 probability of the kinematic fit for all 24 jet-quark combinations and an event probability. The latter is determined from the signal fraction in the sample and the event-by-event purity, as determined from a topological discriminant in Monte Carlo events.

With at least four jets in the final state, the dominant systematic uncertainty on the top quark mass is from the uncertainty on the jet energy scale. For the first time CDF (TM, ME) and DØ (ME) have reduced the jet energy scale uncertainty by performing a simultaneous, *in situ* fit to the $W \to jj$ hypothesis.

The fourth technique [56] relies solely on tracking and thus avoids the jet energy scale uncertainty. The method exploits the fact that, in the rest frame of the top quark, the boost given to the bottom quark has a Lorentz $\gamma_b \approx 0.4\, m_t/m_b$. The measurement of the transverse decay length L_{xy} of the b-hadrons from the top quark decay is therefore sensitive to the mass of the top quark.

Additional determinations of the top mass come from the dilepton channel with two or more jets and large missing E_T, and from the all-jets channel. The dilepton channel, with two unmeasured neutrinos, is underconstrained by one measurement. It is not possible to extract a value for the top quark mass without adding additional information. The general idea is based on the fact that, assuming a value for m_t, the $t\bar{t}$ system can be reconstructed up to an eight-fold ambiguity from the choice of associating leptons and quarks to jets and due to the two solutions for the p_z of each neutrino. Two basic techniques are employed: one based on templates and one using matrix elements. The first class of techniques incorporates additional information to render the kinematic system solvable. In this class, there are two techniques that assign a weight as a function of top mass for each event based on solving for either the azimuth, ϕ, of each neutrino given an assumed η, $(\eta(\nu))$ [57,58], or for η of each neutrino given an assumed ϕ, $(\phi(\nu))$ [59]. A modification of the latter method, $(\mathcal{M}WT)$ [57], solves for η of each neutrino requiring the sum of the neutrino $\vec{p}_T$'s to equal the measured missing E_T vector. In another technique, $(p_z(t\bar{t}))$ [59], the kinematic system is rendered solvable by the addition of the requirement that the p_z of the $t\bar{t}$ system, equal to the sum of the p_z of the t and $\overline{t}$, be zero within a Gaussian uncertainty of 180 GeV/c. In most of the techniques in this class, a single mass per event is extracted and a top mass value found using a Monte Carlo template fit to the single-event masses in a manner similar to that employed in the lepton+jets TM technique. The DØ ($\eta(\nu)$) analysis uses the shape of the weight distribution as a function of m_t in the template fit. The second class, ME/DLM, uses weights based on the LO matrix element for an assumed mass given the measured four-vectors (and integrating over the unknowns) to form a joint likelihood as a function of the top mass for the ensemble of fitted events.

In the all-jets channel there is no unknown neutrino momentum to deal with, but the S/B is the poorest. Both CDF and DØ use events with 6 or more jets, of which at least one is b-tagged. In addition, DØ uses a neural network selection based on eight kinematic variables, and a top-quark mass is reconstructed from the jet-quark combination that best fits the hadronic W-mass constraint and the equal-mass constraint for the two top quarks. At CDF, events with one b-tagged jet are required to pass a strict set of kinematic criteria, while events with two b-tagged jets are required to exceed a minimum total energy. The top quark mass for each event is then reconstructed applying the same fitting technique used in the ℓ+jets mode. At both, CDF and DØ, the resulting mass distribution is compared to Monte Carlo templates for various top quark masses and the background distribution, and a maximum likelihood technique is used to extract the final measured value of m_t and its uncertainty.

The results are shown in Table 2. The systematicuncertainty (second uncertainty shown) is comparable to the statistical uncertainty, and is primarily due to uncertainties inthe jet energy scale and in the Monte Carlo modeling. In the Run II analyses, CDF and DØ have controlled the jet energy scale uncertainty via *in situ* $W \rightarrow jj$ calibration using the same $t\bar{t}$ events, as mentioned above.

The Tevatron Electroweak Working Group (TevEWWG), responsible forthe combined CDF/DØ average top mass in Table 2, took account of correlations between systematic uncertainties in the different measurements in a sophisticated manner [60,61]. The Particle Data Group (PDG) uses their combination of published Run-I and Run-II top mass measurements [60], $m_t = 174.2 \pm 3.3$ GeV/c^2 (statistical and systematic uncertainties combined in quadrature), as our PDG best value. The latest TevEWWG world average [61], also including published and some preliminary Run-II results, yields $m_t = 172.5 \pm 2.3$ GeV/c^2 (statistical and systematic uncertainties combined in quadrature). The ultimate precision from the Tevatron experiments is expected to be better than 2.0 GeV/c^2 per experiment.

Given the experimental technique used to extract the top mass, these mass values should be taken as representing the top *pole mass* (see the review "Note on Quark Masses" in the current edition for more information). The top pole mass, like any quark mass, is defined up to an intrinsic ambiguity of order $\Lambda_{QCD} \sim 200$ MeV [62].

Current global fits performed within the SM or its minimal supersymmetric extension, in which the top mass measurements play a crucial role, provide indications for a relatively light Higgs (see the review "H^0 Indirect Mass Limits from Electroweak Analysis" in the Particle Listings of the current edition for more information). Such fits including Z-pole data [78] and direct measurements of the mass and width of the

W-boson [79] yield $m_t = 179.4^{+12.1}_{-\ 9.2}$ GeV/c^2. A fit including additional electroweak precision data (see the review "Electroweak Model and Constraints on New Physics" in this *Review*) yields $m_t = 172.3^{+10.2}_{-\ 7.6}$ GeV/c^2 (OUR EVALUATION). Both indirect evaluations are in good agreement with the direct top-quark mass measurements.

C.3 Top Quark Electric Charge: The top quark is the only quark whose electric charge has not been measured through a production threshold in e^+e^- collisions. Since the CDF and DØ analyses on top quark production do not associate the b, $\bar{b}$ and $W^{\pm}$ uniquely to the top or antitop, decays such as $t \to W^+\bar{b}, \bar{t} \to W^-b$ are not excluded. A charge 4/3 quark of this kind would be consistent with current electroweak precision data. The $Z \to \ell^+\ell^-$ and $Z \to b\bar{b}$ data can be fitted with a top quark of mass $m_t = 270$ GeV/c^2, provided that the right-handed b quark mixes with the isospin +1/2 component of an exotic doublet of charge −1/3 and −4/3 quarks, $(Q_1, Q_4)_R$ [17,80]. CDF and DØ study the top quark charge in double-tagged lepton+jets events. Assuming the top and antitop quarks have equal but opposite electric charge, then reconstructing the charge of the b-quark through jet charge discrimination techniques, the $|Q_{top}| = 4/3$ and $|Q_{top}| = 2/3$ scenarios can be differentiated. CDF and DØ both have already collected sufficient data to obtain sensitivity to the $|Q_{top}| = 4/3$ case. DØ finds that $|Q_{top}| = 4/3$ is excluded at 94% CL [81], showing that the top quark is indeed consistent with being the Standard Model $|Q_{top}| = 2/3$ quark.

C.4 Top Branching Ratio & $|V_{tb}|$: CDF and DØ report direct measurements of the $t \to Wb$ branching ratio [82,83,84]. Comparing the number of events with 0, 1 and 2 tagged b jets in the lepton+jets channel, and for CDF also in the dilepton

Table 2: Measurements of top quark mass from CDF and DØ. $\int \mathcal{L}$dt is given in pb^{-1}.

m_t (GeV/c^2)	Source	$\int \mathcal{L}$dt	Ref.	Method
$173.3 \pm 5.6 \pm 5.5$	DØ Run I	125	[21]	ℓ+jets, TM
$180.1 \pm 3.6 \pm 3.9$	DØ Run I	125	[63] ⋆△	ℓ+jets, ME
$168.4 \pm 12.3 \pm 3.6$	DØ Run I	125	[64] ⋆△	$\ell\ell$, $\eta(\nu)/\mathcal{M}WT$
$178.5 \pm 13.7 \pm 7.7$	DØ Run I	110	[65]	all jets
179.0 ± 5.1	DØ Run I	110-125	[63]	DØ combined
$177.5 \pm 5.8 \pm 7.1$	DØ Run II	160	[66] †	ℓ+jets/topo, Ideogram
$169.9 \pm 5.8^{+7.8}_{-7.1}$	DØ Run II	230	[67] †	ℓ+jets/topo, TM
$170.6 \pm 4.2 \pm 6.0$	DØ Run II	230	[67] †	ℓ+jets/b-tag, TM
$169.2^{+5.0+1.5}_{-7.4-1.4}$	DØ Run II	370	[10] †	ℓ+jets/topo, ME($W \to jj$)
$170.6^{+4.0}_{-4.7} \pm 1.4$	DØ Run II	370	[10] † △	ℓ+jets/b-tag, ME($W \to jj$)
$176.6 \pm 11.2 \pm 3.8$	DØ Run II	370	[68] † △	$\ell\ell$/b-tag, $\mathcal{M}WT$
$175.6 \pm 10.7 \pm 6.0$	DØ Run II	370	[69] †	$\ell\ell$, $\eta(\nu)$
$176.1 \pm 5.1 \pm 5.3$	CDF Run I	110	[58,70,71]⋆△	ℓ + jets
$167.4 \pm 10.3 \pm 4.8$	CDF Run I	110	[58] ⋆△	$\ell\ell$
$186.0 \pm 10.0 \pm 5.7$	CDF Run I	110	[58,72]⋆△	all jets
176.1 ± 6.6	CDF Run I	110	[58,71]	CDF combined
$173.5^{+3.7}_{-3.6} \pm 1.3$	CDF Run II	318	[9] ⋆	ℓ+jets/b-tag, TM($W \to jj$)
$173.4 \pm 2.5 \pm 1.3$	CDF Run II	680	[73] † △	ℓ+jets/b-tag, TM($W \to jj$)
$173.2^{+2.6}_{-2.4} \pm 3.2$	CDF Run II	318	[9]	ℓ+jets/b-tag, DLM
$174.1 \pm 2.5 \pm 1.3$	CDF Run II	680	[74] †	ℓ+jets/b-tag, ME($W \to jj$)
$183.9^{+15.7}_{-13.9} \pm 5.6$	CDF Run II	695	[56] †	ℓ+jets/b-tag, L_{xy}
$165.2 \pm 6.1 \pm 3.4$	CDF Run II	340	[75] ⋆	$\ell\ell$, ME
$164.5 \pm 4.5 \pm 3.1$	CDF Run II	750	[76] † △	$\ell\ell$, ME
$170.7^{+6.9}_{-6.5} \pm 4.6$	CDF Run II	359	[59,75]	$\ell\ell$, $\eta(\nu)$
$169.7^{+8.9}_{-9.0} \pm 4.0$	CDF Run II	340	[59,75]	$\ell\ell$, $\phi(\nu)$
$169.5^{+7.7}_{-7.2} \pm 4.0$	CDF Run II	340	[59,75]	$\ell\ell$, $p_z(t\bar{t})$
$172.0 \pm 1.6 \pm 2.2$	CDF Run I+II	110-750	[77] †	CDF Combined
$174.2 \pm 2.0 \pm 2.6$*	CDF,DØ (I+II)	110-340	[60] †	pub. results, PDG best
$172.5 \pm 1.3 \pm 1.9$**	CDF,DØ (I+II)	110-750	[61] †	publ. or prelim. results

* PDG uses this TevEWWG result as its best value. It is a combination of published Run I + II measurements (labeled with ⋆), yielding a χ^2 of 5.8 for 6 deg. of freedom.

**The TevEWWG world average is a combination of published Run I and preliminary or pub. Run-II meas. (labeled with △), yielding a χ^2 of 8.1 for 8 deg. of freedom.

† Preliminary result, not yet submitted for publication as of April 2006.

channel, and using the known b-tagging efficiency, the ratio $R = B(t \to Wb)/\sum_{q=d,s,b} B(t \to Wq)$ can be extracted. DØ performs a simultaneous fit for the number of $t\bar{t}$ events and the ratio R. A deviation of R from unity would imply either non-SM top decay, a non-SM background to $t\bar{t}$ production, or a fourth generation of quarks. Assuming that all top decays have a W boson in the final state, that only three generations of fermions exist, and that the CKM matrix is unitary, CDF and DØ also extract the CKM matrix-element $|V_{tb}|$. The results of these measurements are summarized in Table 3.

Table 3: Measurements and 95% CL lower limits of $R = B(t \to Wb)/B(t \to Wq)$ and $|V_{tb}|$ from CDF and DØ.

R or $\lvert V_{tb}\rvert$	Source	$\int \mathcal{L}$dt (pb^{-1})	Ref.
$R = 0.94^{+0.31}_{-0.24}$	CDF Run I	109	[82]
$R = 1.12^{+0.27}_{-0.23}$	CDF Run II	160	[83]
$R > 0.61$	CDF Run II	160	[83]
$R = 1.03^{+0.19}_{-0.17}$	DØ Run II	230	[84]
$R > 0.64$	DØ Run II	230	[84]
$\lvert V_{tb}\rvert > 0.75$	CDF Run I	109	[82]
$\lvert V_{tb}\rvert > 0.78$	CDF Run II	160	[83]
$\lvert V_{tb}\rvert > 0.78$	DØ Run II	230	[84]

A more direct measurement of the Wtb coupling constant will be possible when enough data are accumulated to detect the s-channel and t-channel single-top production processes. The cross sections for these processes are proportional to $|V_{tb}|^2$, and no assumption is needed on the number of families or on the unitarity of the CKM matrix in extracting $|V_{tb}|$. Separate measurements of the s and t-channel processes provide sensitivity to physics beyond the SM [85]. CDF gives 95% CL limits of 3.2 and 3.1 pb for the single-top production rates in the s-channel and t-channel, respectively, as well as a combined limit of 3.4 pb [86]. DØ gives 95% CL limits of 5.0 and 4.4 pb, for the s-channel and t-channel, respectively [87,88]. Comparison with the expected SM rates of 0.88 ± 0.11 pb for the s-channel and 1.98 ± 0.25 pb for the t-channel [4] indicates that a few fb^{-1} will be required before significant measurements can be made.

C.5 W-Boson Helicity: Studies of decay angular distributions provide a direct check of the V–A nature of the Wtb coupling and information on the relative coupling of longitudinal and transverse W bosons to the top quark. In the SM, the fraction of decays to longitudinally polarized W bosons is expected to be [89] $\mathcal{F}_0^{\rm SM} = x/(1+x)$, $x = m_t^2/2M_W^2$ ($\mathcal{F}_0^{\rm SM} \sim 70\%$ for $m_t = 175$ GeV/c^2). Fractions of left- or right-handed W bosons are denoted as $\mathcal{F}_-$ and $\mathcal{F}_+$, respectively. In the SM $\mathcal{F}_-$ is expected to be $\approx 30\%$ and $\mathcal{F}_+ \approx 0\%$. CDF and DØ use various techniques to measure the helicity of the W boson in top quark decays in both the lepton+jets events and dilepton channels. The first method uses a kinematic fit, similar to that used in the lepton+jets mass analyses but with the top quark mass constrained to 175 GeV/c^2, to improve the reconstruction of final state observables and render the under-constrained dilepton channel solvable. The distribution of the helicity angle ($\cos\theta^*$) between the lepton and the b quark in the W rest frame, provides the most direct measure of the W helicity. The second method (p_T^ℓ) uses the different lepton p_T spectra from longitudinally or transversely polarized W-decays to determine the relative contributions. A third method uses the invariant mass of the lepton and the b-quark in top decays ($M^2_{\ell b}$) as an observable, which is directly related to $\cos\theta^*$. Finally, the Matrix Element method (ME), described for the top quark mass measurement, has also been used, forming a 2-dimensional likelihood $\mathcal{L}(m_{top}, \mathcal{F}_0)$, where the mass-dependence is integrated out so that only the sensitivity to the W-helicity in the top quark decay is exploited. The results of all CDF and DØ analyses, summarized in Table 4, are in agreement with the SM expectation, but with large statistical uncertainties.

Table 4: Measurement and 95% CL upper limits of the W helicity in top quark decays from CDF and DØ.

W helicity	Source	$\int\mathcal{L}$dt (pb^{-1})	Ref.	Method
$\mathcal{F}_0 = 0.91 \pm 0.39$	CDF Run I	106	[94]	p_T^ℓ
$\mathcal{F}_0 = 0.56 \pm 0.32$	DØ Run I	125	[95]	ME
$\mathcal{F}_0 = 0.74^{+0.22}_{-0.34}$	CDF Run II	200	[96]	$M^2_{\ell b}$+p_T^ℓ
$\mathcal{F}_+ < 0.18$	CDF Run I	110	[97]	$M^2_{\ell b}$+p_T^ℓ
$\mathcal{F}_+ < 0.27$	CDF Run II	200	[96]	$M^2_{\ell b}$+p_T^ℓ
$\mathcal{F}_+ < 0.24$	DØ Run II	230-370	[98,99] †	$\cos\theta^*$+p_T^ℓ

† Preliminary result, not yet submitted for publication as of April 2006.

C.6 $t\bar{t}$ ***Spin Correlations:*** DØ has searched for evidence of spin correlation of $t\bar{t}$ pairs [90]. The t and $\bar{t}$ are expected to be unpolarized but to be correlated in their spins. Since top quarks decay before hadronizing, their spins at production are transmitted to their decay daughter particles. Spin correlation is studied by analyzing the joint decay angular distribution of one t daughter and one $\overline{t}$ daughter. The sensitivity to top spin is greatest when the daughters are down-type fermions (charged leptons or d-type quarks), in which case, the joint distribution is [91–93]

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1+\kappa\cdot\cos\theta_+\cdot\cos\theta_-}{4}, \tag{2}$$

where θ_+ and θ_- are the angles of the daughters in the top rest frames with respect to a particular spin quantization axis, the optimal choice being the off-diagonal basis [91]. In this basis, the SM predicts maximum correlation with $\kappa = 0.88$ at the Tevatron. In Run I, DØ analyzed six dilepton events and obtained a likelihood as a function of κ, which weakly favored the SM ($\kappa = 0.88$) over no correlation ($\kappa = 0$) or anticorrelation ($\kappa = -1$, as would be expected for $t\bar{t}$ produced via an intermediate scalar). DØ quotes a limit $\kappa > -0.25$ at 68% CL.

C.7 Non-SM $t\bar{t}$ Production: Motivated by the large mass of the top quark, several models suggest that the top quark plays a role in the dynamics of electroweak symmetry breaking. One example is topcolor [14], where a large top quark mass can be generated through the formation of a dynamic $t\bar{t}$ condensate, X, which is formed by a new strong gauge force coupling preferentially to the third generation. Another example is topcolor-assisted technicolor [15], predicting a heavy Z' boson that couples preferentially to the third generation of quarks with cross sections expected to be visible at the Tevatron. CDF and DØ have searched for $t\bar{t}$ production via intermediate, narrow-width, heavy vector bosons X in the lepton+jets channels. The possible $t\bar{t}$ production via an intermediate resonance

X is sought for as a peak in the spectrum of the invariant $t\bar{t}$ mass. CDF and DØ exclude narrow width heavy vector bosons X in the top-assisted technicolor model [100] with mass $M_X < 480$ GeV/c^2 and $M_X < 560$ GeV/c^2, respectively, in Run I [18,19], and $M_X < 725$ GeV/c^2 and $M_X < 680$ GeV/c^2 in Run II [47,48].

C.8 Non-SM Top Decays: Both CDF and DØ have searched for non-SM top decays [101–103], particularly those expected in supersymmetric models, such as $t \to H^+ b$, followed by $H^+ \to \tau^+\bar{\nu}$ or $c\bar{s}$. The $t \to H^+ b$ branching ratio has a minimum at $\tan\beta = \sqrt{m_t/m_b} \simeq 6$, and is large in the region of either $\tan\beta \ll 6$ or $\tan\beta \gg 6$. In the former range, $H^+ \to c\bar{s}$ is dominant, while $H^+ \to \tau^+\bar{\nu}$ dominates in the latter range. These studies are based either on direct searches for these final states, or on top "disappearance". In the standard lepton+jets or dilepton cross section analyses, any charged Higgs decays are not detected as efficiently as $t \to W^\pm b$, primarily because the selection criteria are optimized for the standard decays, and because of the absence of energetic isolated leptons in Higgs decays. A significant $t \to H^+ b$ contribution would give rise to measured $t\bar{t}$ cross sections that would be lower than the prediction from the SM (assuming that non-SM contributions to $t\bar{t}$ production are negligible).

In Run II, CDF has searched for charged Higgs production in dilepton, lepton+jets and lepton+hadronic tau final states, considering possible H^+ decays to $c\bar{s}$, $\tau\bar{\nu}$, t^*b or W^+h^0 in addition to the Standard Model decay $t \to W^+ b$ [103]. Depending on the top and Higgs decay branching ratios, which are scanned in a particular 2-Higgs Doublet benchmark Model, the number of expected events in these decay channels can show an excess or deficit when compared to SM expectations. A model-independent interpretation, yields a limit of $B(t \rightarrow H^{\pm}b) < 0.91$ at 95% CL for $m_{H^{\pm}} \approx 100$ GeV and $B(t \rightarrow H^{\pm}b) < 0.4$ in the tauonic model with $B(H^{\pm} \rightarrow \tau\nu) = 100\%$ [103]. More details, and the results of these studies for the exclusion in the $m_{H^{\pm}}, \tan\beta$ plane, can be found in the review "Search for Higgs bosons" and in the "H^{+} Mass Limits" section of the Higgs Particle Listings of the current edition.

In the Standard Model the top quark lifetime is expected to be about 0.5×10^{-24} s ($c\tau_t \approx 3 \times 10^{-10}$ μm), while additional quark generations, non-standard top quark decays or other extensions of the Standard Model could yield long-lived top quarks in the data. CDF has studied the top quark lifetime by measuring the distance between the initial $p\bar{p}$ scattering and the leptonic $W^{\pm}$ decay vertex in lepton+jets events [104]. The measured lifetime is consistent with zero and an upper limit $c\tau_t < 52.5$ μm is found at 95% CL.

CDF reported a search for flavor changing neutral current (FCNC) decays of the top quark $t \rightarrow q\gamma$ and $t \rightarrow qZ$ in the Run I data [105], for which the SM predicts such small rates that any observation would be a sign of new physics. CDF assumes that one top decays via FCNC while the other decays via Wb. For the $t \rightarrow q\gamma$ search, two signatures are examined, depending on whether the W decays leptonically or hadronically. For leptonic W decay, the signature is $\gamma\ell$ and missing E_T and two or more jets, while for hadronic W decay, it is $\gamma + \geq 4$ jets. In either case, one of the jets must have a secondary vertex b tag. One event is observed ($\mu\gamma$) with an expected background of less than half an event, giving an upper limit on the top branching ratio of $B(t \rightarrow q\gamma) < 3.2\%$ at 95% CL. In the search for $t \rightarrow qZ$, CDF considers $Z \rightarrow \mu\mu$ or ee

and $W \to qq'$, giving a Z + four jets signature. One $\mu\mu$ event is observed with an expected background of 1.2 events, giving an upper limit on the top branching ratio of $B(t \to qZ) < 0.33$ at 95% CL. Both the γ and Z limits are non-background subtracted estimates.

Constraints on FCNC couplings of the top quark can also be obtained from searches for anomalous single-top production in e^+e^- collisions, via the process $e^+e^- \to \gamma, Z^* \to t\overline{q}$ and its charge-conjugate ($q = u, c$), or in $e^{\pm}p$ collisions, via the process $e^{\pm}u \to e^{\pm}t$. For a leptonic W decay, the topology is at least a high-p_T lepton, a high-p_T jet and missing E_T, while for a hadronic W decay the topology is three high-p_T jets. Limits on the cross section for this reaction have been obtained by the LEP collaborations [106] in e^+e^- collisions and by H1 [107] and ZEUS [108] in $e^{\pm}p$ collisions. When interpreted in terms of branching ratios in top decay [109,110], the LEP limits lead to typical 95% CL upper bounds of $B(t \to qZ) < 0.137$, which are stronger than the direct CDF limit. Assuming no coupling to the Z boson, the 95% CL limits on the anomalous FCNC coupling $\kappa_\gamma < 0.17$ and < 0.27 by ZEUS and H1, respectively, are stronger than the CDF limit of $\kappa_\gamma < 0.42$, and improve over LEP sensitivity in that domain. The H1 limit is slightly weaker than the ZEUS limit due to an observed excess of five candidates events over an expected background of 1.31 ± 0.22. If this excess is attributed to FCNC top quark production, this leads to a total cross section of $\sigma(ep \to e + t + X, \sqrt{s} = 319 \text{ GeV}) = 0.29^{+0.15}_{-0.14}$ pb [107,111].

Appendix. Expected Sensitivity at the LHC:

The top pair production cross section at the LHC is predicted at NLO to be about 800 pb [112]. There will be 8 million $t\bar{t}$ pairs produced per year at a luminosity of 10^{33} cm^{-2} s^{-1}.

Such large event samples will permit precision measurements of the top quark parameters. The statistical uncertainties on m_t will become negligible, and systematic uncertainties better than ± 2 GeV/c^2 are anticipated [113–115].

Precision measurements of the top pair production cross section are expected to be limited by the estimated 5-10% accuracy on the luminosity determination [113], but far more accurate measurements would be available from the ratio of the $t\bar{t}$ production to inclusive W or Z production.

Single top production will also be of keen interest at the LHC. While observation of single top production and the first measurements of $|V_{tb}|$ are likely at the Tevatron, the precision will be limited by the sample size. At the LHC, a $|V_{tb}|$ measurement at the 5% level per experiment is projected with 30 fb^{-1} [114].

Tests of the V-A nature of the tWb vertex through a measurement of the W helicity will be extended from the Tevatron to the LHC. Current estimates are that the longitudinal fraction can be measured with a precision of about 5% [114] with 10 fb^{-1} of data.

Top-antitop spin correlations, should be relatively easy to observe and measure at the LHC, where the preferred dilepton mode will have large event samples, despite the small branching fraction. At the LHC, where $t\bar{t}$ is dominantly produced through gluon fusion, the correlation is such that the top quarks are mainly either both left or both right handed. The CMS collaboration [114] estimates that the relative asymmetry (defined as the difference in the fraction of like-handed and the fraction of oppositely-handed $t\bar{t}$ pairs) can be measured to about 10% accuracy with 30 fb^{-1} of data.

In addition to these SM measurements, the large event samples will allow sensitive searches for new physics. The search for heavy resonances that decay to $t\bar{t}$, already begun at the Tevatron, will acquire enhanced reach both in mass and $\sigma\cdot$B. The ATLAS collaboration [113] has studied the reach for a 5σ discovery of a narrow resonance decaying to $t\bar{t}$. With 30 fb^{-1}, it is estimated that a resonance can be discovered at 4 TeV/c^2 for $\sigma \cdot B = 10$ fb, and at 1 TeV/c^2 for $\sigma \cdot B = 1000$ fb. FCNC decays $t \rightarrow Zq, \gamma q, gq$, can take place in the SM, or in the MSSM, but at rates too small to be observed even at the LHC. As such, searches for these decay modes can provide sensitive tests of other extensions of the SM [113].

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t-Quark Mass in $p\overline{p}$ Collisions

OUR EVALUATION of 174.2 ± 2.0 ± 2.6 GeV (TEVEWWG 06A) is an average of top mass measurements from Tevatron Run-I (1992–1996) and Run-II (2001−present) that were published at the time of preparing this *Review*. This average was provided by the Tevatron Electroweak Working Group (TEVEWWG) and takes correlated uncertainties properly into account. Our previous average of 178.0 ± 2.7 ± 3.3 GeV (TEVEWWG 04) was based on measurements from Run-I only. Including the most recent unpublished top mass measurements from Run-II, the TEVEWWG reports an average top mass of 172.5 ± 1.3 ± 1.9 GeV (TEVEWWG 06). See the note "The Top Quark" in these Quark Particle Listings.

For earlier search limits see the *Review of Particle Physics*, Phys. Rev. **D54**,1 (1996).

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
174.2± 3.3 OUR EVALUATION	See comments in the header above.		
$173.5^{+3.7}_{-3.6} \pm 1.3$	[1,2] ABULENCIA 06D	CDF	lepton + jets
165.2± 6.1± 3.4	[3,4] ABULENCIA 06G	CDF	dilepton
180.1± 3.6± 3.9	[5,6] ABAZOV 04G	D0	lepton + jets
176.1± 5.1± 5.3	[7] AFFOLDER 01	CDF	lepton + jets
167.4±10.3± 4.8	[8,9] ABE 99B	CDF	dilepton
168.4±12.3± 3.6	[6] ABBOTT 98D	D0	dilepton
186 ±10 ± 5.7	[8,10] ABE 97R	CDF	6 or more jets
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$173.2^{+2.6}_{-2.4} \pm 3.2$	[1,11] ABULENCIA 06D	CDF	lepton + jets
178.5±13.7± 7.7	[12,13] ABAZOV 05	D0	6 or more jets
176.1± 6.6	[14] AFFOLDER 01	CDF	lepton + jets, dileptons, all-jets
172.1± 5.2± 4.9	[15] ABBOTT 99G	D0	di-lepton, lepton+jets
176.0± 6.5	[9,16] ABE 99B	CDF	dilepton, lepton+jets, and all jets
173.3± 5.6± 5.5	[6,17] ABBOTT 98F	D0	lepton + jets
175.9± 4.8± 5.3	[8,18] ABE 98E	CDF	lepton + jets
161 ±17 ±10	[8] ABE 98F	CDF	dilepton
172.1± 5.2± 4.9	[19] BHAT 98B	RVUE	dilepton and lepton+jets
173.8± 5.0	[20] BHAT 98B	RVUE	dilepton, lepton+jets, and all jets
173.3± 5.6± 6.2	[6] ABACHI 97E	D0	lepton + jets
$199^{+19}_{-21} \pm 22$	ABACHI 95	D0	lepton + jets
176 ± 8 ±10	ABE 95F	CDF	lepton + *b*-jet
$174 \pm 10\ ^{+13}_{-12}$	ABE 94E	CDF	lepton + *b*-jet

[1] Result is based on 318 pb^{-1} of data at $\sqrt{s} = 1.96$ TeV.

[2] Template method.

[3] Result is based on 340 pb^{-1} of data at $\sqrt{s} = 1.96$ TeV.

[4] Matrix element technique.

[5] This result is obtained by re-analysis of the lepton + jets candidate events that led to ABBOTT 98F. It is based upon the maximum likelihood method which makes use of the leading order matrix elements.

[6] Result is based on 125 ± 7 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV.

[7] AFFOLDER 01 result uses lepton + jets topology. It is based on ∼ 106 pb^{-1} of data at $\sqrt{s}= 1.8$ TeV.

[8] Result is based on 109 ± 7 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV.

[9] See AFFOLDER 01 for details of systematic error re-evaluation.

[10] ABE 97R result is based on the first observation of all hadronic decays of $t\overline{t}$ pairs. Single b-quark tagging with jet-shape variable constraints was used to select signal enriched multi-jet events. The updated systematic error is listed. See AFFOLDER 01, appendix C.

[11] Dynamical likelihood method.

[12] Result is based on 110.2 ± 5.8 pb^{-1} at $\sqrt{s} = 1.8$ TeV.

[13] ABAZOV 05 result is based on the all hadronic decays of $t\overline{t}$ pairs. Single b-quark tagging via the decay chain $b \rightarrow c \rightarrow \mu$ was used to select signal enriched multijet events. The result was obtained by the maximum likelihood method after bias correction.

[14] AFFOLDER 01 is obtained by combining the measurements in the lepton + jets [AFFOLDER 01], all-jets [ABE 97R, ABE 99B], and dilepton [ABE 99B] decay topologies.

[15] ABBOTT 99G result is obtained by combining the D0 result m_t (GeV) $= 168.4 \pm 12.3 \pm 3.6$ from 6 di-lepton events (see also ABBOTT 98D) and m_t (GeV) $= 173.3 \pm 5.6 \pm 5.5$ from lepton+jet events (ABBOTT 98F).

[16] ABE 99B result is obtained by combining the CDF results of m_t (GeV)$=167.4\pm10.3\pm4.8$ from 8 dilepton events, m_t (GeV)$=175.9 \pm 4.8 \pm 5.3$ from lepton+jet events (ABE 98E), and m_t (GeV)$=186.0 \pm 10.0 \pm 5.7$ from all-jet events (ABE 97R). The systematic errors in the latter two measurements are changed in this paper.

[17] See ABAZOV 04G.

[18] The updated systematic error is listed. See AFFOLDER 01, appendix C.

[19] BHAT 98B result is obtained by combining the DØ results of m_t(GeV)$=168.4 \pm 12.3 \pm 3.6$ from 6 dilepton events and m_t(GeV)$=173.3 \pm 5.6 \pm 5.5$ from 77 lepton+jet events.

[20] BHAT 98B result is obtained by combining the DØ results from dilepton and lepton+jet events, and the CDF results (ABE 99B) from dilepton, lepton+jet events, and all-jet events.

Indirect *t*-Quark Mass from Standard Model Electroweak Fit

"OUR EVALUATION" below is from the fit to electroweak data described in the "Electroweak Model and Constraints on New Physics" section of this Review. This fit result does not include direct measurements of m_t.

The RVUE values are based on the data described in the footnotes. RVUE's published before 1994 and superseded analyses are now omitted. For more complete listings of earlier results, see the 1994 edition (Physical Review **D50** 1173 (1994)).

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
$172.3^{+10.2}_{-7.6}$ OUR EVALUATION			

• • • We do not use the following data for averages, fits, limits, etc. • • •

$162 \pm 15 {}^{+25}_{-5}$	[21] ABBIENDI	01A	OPAL	Z parameters
170.7 ± 3.8	[22] FIELD	00	RVUE	Z parameters without b-jet + Direct
$171.2^{+3.7}_{-3.8}$	[23] FIELD	99	RVUE	Z parameters without b jet + Direct
$172.0^{+5.8}_{-5.7}$	[24] DEBOER	97B	RVUE	Electroweak + Direct
157^{+16}_{-12}	[25] ELLIS	96C	RVUE	Z parameters, m_W, low energy
$175 \pm 11 {}^{+17}_{-19}$	[26] ERLER	95	RVUE	Z parameters, m_W, low energy
$180 \pm 9 {}^{+19}_{-21} \mp 2.6 \pm 4.8$	[27] MATSUMOTO	95	RVUE	
$157^{+36}_{-48}{}^{+19}_{-20}$	[28] ABREU	94	DLPH	Z parameters
$158^{+32}_{-40} \pm 19$	[29] ACCIARRI	94	L3	Z parameters
$190^{+39}_{-48}{}^{+12}_{-14}$	[30] ARROYO	94	CCFR	ν_μ iron scattering
$184^{+25}_{-29}{}^{+17}_{-18}$	[31] BUSKULIC	94	ALEP	Z parameters
153 ± 15	[32] ELLIS	94B	RVUE	Electroweak
$177 \pm 9 {}^{+16}_{-20}$	[33] GURTU	94	RVUE	Electroweak
$174^{+11}_{-13}{}^{+17}_{-18}$	[34] MONTAGNA	94	RVUE	Electroweak
$171 \pm 12 {}^{+15}_{-21}$	[35] NOVIKOV	94B	RVUE	Electroweak
160^{+50}_{-60}	[36] ALITTI	92B	UA2	m_W, m_Z

[21] ABBIENDI 01A result is from fit with free α_s when m_H is fixed to 150 GeV. The second errors are for m_H= 90 GeV (lower) and 1000 GeV (upper). The fit also finds $\alpha_s = 0.125 \pm 0.005^{+0.004}_{-0.001}$.

[22] FIELD 00 result updates FIELD 99 by using the 1998 EW data (CERN-EP/99-15). Only the lepton asymmetry data are used together with the direct measurement constraint m_t=173.8 ± 5.0 GeV, $\alpha_s(m_Z) = 0.12$, and $1/\alpha(m_Z) = 128.896$. The result is from a two parameter fit with free m_t and m_H, yielding also $m_H = 38.0^{+30.5}_{-19.8}$ GeV.

[23] FIELD 99 result is from the two-parameter fit with free m_t and m_H, yielding also $m_H = 47.2^{+29.8}_{-24.5}$ GeV. Only the lepton and charm-jet asymmetry data are used together with the direct measurement constraint m_t= 173.8 ± 5.0 GeV, and $1/\alpha(m_Z)$= 128.896.

[24] DEBOER 97B result is from the five-parameter fit which varies m_Z, m_t, m_H, α_s, and $\alpha(m_Z)$ under the constraints: m_t=175 ± 6 GeV, $1/\alpha(m_Z)$=128.896 ± 0.09. They found $m_H = 141^{+140}_{-77}$ GeV and $\alpha_s(m_Z)$=0.1197 ± 0.0031.

[25] ELLIS 96C result is a the two-parameter fit with free m_t and m_H, yielding also $m_H = 65^{+117}_{-37}$ GeV.

[26] ERLER 95 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding $\alpha_s(m_Z) = 0.127(5)(2)$.

[27] MATSUMOTO 95 result is from fit with free m_t to Z parameters, M_W, and low-energy neutral-current data. The second error is for $m_H = 300^{+700}_{-240}$ GeV, the third error is for $\alpha_s(m_Z) = 0.116 \pm 0.005$, the fourth error is for $\delta\alpha_{\mathrm{had}} = 0.0283 \pm 0.0007$.

[28] ABREU 94 value is for $\alpha_s(m_Z)$ constrained to 0.123 ± 0.005. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[29] ACCIARRI 94 value is for $\alpha_s(m_Z)$ constrained to 0.124 ± 0.006. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[30] ARROYO 94 measures the ratio of the neutral-current and charged-current deep inelastic scattering of ν_μ on an iron target. By assuming the SM electroweak correction, they obtain $1-m_W^2/m_Z^2 = 0.2218 \pm 0.0059$, yielding the quoted m_t value. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[31] BUSKULIC 94 result is from fit with free α_s. The second error is from m_H=300^{+700}_{-240} GeV.

[32] ELLIS 94B result is fit to electroweak data available in spring 1994, including the 1994 A_{LR} data from SLD. m_t and m_H are two free parameters of the fit for $\alpha_s(m_Z) = 0.118 \pm 0.007$ yielding m_t above, and $m_H = 35^{+70}_{-22}$ GeV. ELLIS 94B also give results for fits including constraints from CDF's direct measurement of m_t and CDF's and DØ 's production cross-section measurements. Fits excluding the A_{LR} data from SLD are also given.

[33] GURTU 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.125 \pm 0.005^{+0.003}_{-0.001}$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP, M_W, νN, and SLD electroweak data available in spring 1994.

[34] MONTAGNA 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.124$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Errors in $\alpha(m_Z)$ and m_b are taken into account in the fit. Uses LEP, SLC, and M_W/M_Z data available in spring 1994.

[35] NOVIKOV 94B result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.125 \pm 0.005 \pm 0.002$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP and CDF electroweak data available in spring 1994.

[36] ALITTI 92B assume $m_H = 100$ GeV. The 95%CL limit is $m_t < 250$ GeV for $m_H < 1$ TeV.

t DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$W q (q = b, s, d)$			
Γ_2	$W b$			
Γ_3	$\ell \nu_\ell$ anything		[a,b] (9.4±2.4) %	
Γ_4	$\tau \nu_\tau b$			
Γ_5	$\gamma q(q=u,c)$		[c] < 5.9 × 10^{-3}	95%
	$\Delta T = 1$ weak neutral current (*T1*) modes			
Γ_6	$Z q(q=u,c)$	*T1*	[d] < 13.7 %	95%

[a] ℓ means e or μ decay mode, not the sum over them.

[b] Assumes lepton universality and W-decay acceptance.

[c] This limit is for $\Gamma(t \rightarrow \gamma q)/\Gamma(t \rightarrow W b)$.

[d] This limit is for $\Gamma(t \rightarrow Z q)/\Gamma(t \rightarrow W b)$.

t BRANCHING RATIOS

$\Gamma(Wb)/\Gamma(Wq(q=b,s,d))$ Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN
$\mathbf{1.12^{+0.21}_{-0.19}{}^{+0.17}_{-0.13}}$	[37] ACOSTA 05A	CDF

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID	TECN
$0.94^{+0.26}_{-0.21}{}^{+0.17}_{-0.12}$	[38] AFFOLDER 01C	CDF

[37] ACOSTA 05A result is from the analysis of lepton + jets and di-lepton + jets final states of $t\bar{t}$ candidate events with $\sim$ 162 pb^{-1} of data at $\sqrt{s}$ = 1.96 TeV. The first error is statistical and the second systematic. It gives R > 0.61, or $|V_{tb}|$ > 0.78 at 95% CL.

[38] AFFOLDER 01C measures the top-quark decay width ratio $R = \Gamma(Wb)/\Gamma(Wq)$, where q is a d, s, or b quark, by using the number of events with multiple b tags. The first error is statistical and the second systematic. A numerical integration of the likelihood function gives $R >$ 0.61 (0.56) at 90% (95%) CL. By assuming three generation unitarity, $|V_{tb}| = 0.97^{+0.16}_{-0.12}$ or $|V_{tb}|$ > 0.78 (0.75) at 90% (95%) CL is obtained. The result is based on 109 pb^{-1} of data at $\sqrt{s}$ = 1.8 TeV.

$\Gamma(\ell\nu_\ell\,\text{anything})/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	DOCUMENT ID	TECN
0.094±0.024	[39] ABE 98X	CDF

[39] ℓ means e or μ decay mode, not the sum. Assumes lepton universality and W-decay acceptance.

$\Gamma(\tau\nu_\tau b)/\Gamma_{\text{total}}$ Γ_4/Γ

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	DOCUMENT ID	TECN	COMMENT
	[40] ABE 97V	CDF	$\ell\tau$ + jets

[40] ABE 97V searched for $t\bar{t} \to (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ events in 109 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. They observed 4 candidate events where one expects $\sim$ 1 signal and $\sim$ 2 background events. Three of the four observed events have jets identified as b candidates.

$\Gamma(\gamma q(q=u,c))/\Gamma_{\text{total}}$ Γ_5/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0132	95	[41] AKTAS 04	H1	$B(t \to \gamma u)$
<0.0059	95	[42] CHEKANOV 03	ZEUS	$B(t \to \gamma u)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0465	95	[43] ABDALLAH 04C	DLPH	$B(\gamma c$ or $\gamma u)$
<0.041	95	[44] ACHARD 02J	L3	$B(t \to \gamma c$ or $\gamma u)$
<0.032	95	[45] ABE 98G	CDF	$t\bar{t} \to (Wb)(\gamma c$ or $\gamma u)$

[41] AKTAS 04 looked for single top production via FCNC in $e^{\pm}$ collisions at HERA with 118.3 pb^{-1}, and found 5 events in the e or μ channels. By assuming that they are due to statistical fluctuation, the upper bound on the $tu\gamma$ coupling $\kappa_{tu\gamma}$ < 0.27 (95% CL) is obtained. The conversion to the partial width limit, when $B(\gamma c) = B(Zu) = B(Zc) = 0$, is from private communication, E. Perez, May 2005.

[42] CHEKANOV 03 looked for single top production via FCNC in the reaction $e^{\pm}p \to e^{\pm}(t$ or $\bar{t})$ X in 130.1 pb^{-1} of data at $\sqrt{s}$=300–318 GeV. No evidence for top production and its decay into bW was found. The result is obtained for m_t=175 GeV when $B(\gamma c)$=$B(Zq)$=0, where q is a u or c quark. Bounds on the effective t-u-γ and t-u-Z

couplings are found in their Fig. 4. The conversion to the constraint listed is from private communication, E. Gallo, January 2004.

[43] ABDALLAH 04C looked for single top production via FCNC in the reaction $e^+e^- \to \overline{t}c$ or $\overline{t}u$ in 541 pb^{-1} of data at $\sqrt{s}$=189–208 GeV. No deviation from the SM is found, which leads to the bound on B($t \to \gamma q$), where q is a u or a c quark, for m_t = 175 GeV when B($t \to Zq$)=0 is assumed. The conversion to the listed bound is from private communication, O. Yushchenko, April 2005. The bounds on the effective t-q-γ and t-q-Z couplings are given in their Fig. 7 and Table 4, for m_t = 170–180 GeV, where most conservative bounds are found by choosing the chiral couplings to maximize the negative interference between the virtual γ and Z exchange amplitudes.

[44] ACHARD 02J looked for single top production via FCNC in the reaction $e^+e^- \to \overline{t}c$ or $\overline{t}u$ in 634 pb^{-1} of data at $\sqrt{s}$= 189–209 GeV. No deviation from the SM is found, which leads to a bound on the top-quark decay branching fraction B(γq), where q is a u or c quark. The bound assumes B(Zq)=0 and is for m_t= 175 GeV; bounds for m_t=170 GeV and 180 GeV and B(Zq) $\neq$ 0 are given in Fig. 5 and Table 7.

[45] ABE 98G looked for $t\overline{t}$ events where one t decays into $q\gamma$ while the other decays into bW. The quoted bound is for Γ(γq)/Γ(Wb).

$\Gamma(Zq(q=u,c))/\Gamma_{\text{total}}$ Γ_6/Γ

Test for ΔT=1 weak neutral current. Allowed by higher-order electroweak interaction.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.159	95	[46] ABDALLAH	04C	DLPH	$e^+e^- \to \overline{t}c$ or $\overline{t}u$
<0.137	95	[47] ACHARD	02J	L3	$e^+e^- \to \overline{t}c$ or $\overline{t}u$
<0.14	95	[48] HEISTER	02Q	ALEP	$e^+e^- \to \overline{t}c$ or $\overline{t}u$
<0.137	95	[49] ABBIENDI	01T	OPAL	$e^+e^- \to \overline{t}c$ or $\overline{t}u$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.17	95	[50] BARATE	00S	ALEP	$e^+e^- \to \overline{t}c$ or $\overline{t}u$
<0.33	95	[51] ABE	98G	CDF	$t\overline{t} \to (Wb)\,(Zc$ or $Zu)$

[46] ABDALLAH 04C looked for single top production via FCNC in the reaction $e^+e^- \to \overline{t}c$ or $\overline{t}u$ in 541 pb^{-1} of data at $\sqrt{s}$=189–208 GeV. No deviation from the SM is found, which leads to the bound on B($t \to Zq$), where q is a u or a c quark, for m_t = 175 GeV when B($t \to \gamma q$)=0 is assumed. The conversion to the listed bound is from private communication, O. Yushchenko, April 2005. The bounds on the effective t-q-γ and t-q-Z couplings are given in their Fig. 7 and Table 4, for m_t = 170–180 GeV, where most conservative bounds are found by choosing the chiral couplings to maximize the negative interference between the virtual γ and Z exchange amplitudes.

[47] ACHARD 02J looked for single top production via FCNC in the reaction $e^+e^- \to \overline{t}c$ or $\overline{t}u$ in 634 pb^{-1} of data at $\sqrt{s}$= 189–209 GeV. No deviation from the SM is found, which leads to a bound on the top-quark decay branching fraction B(Zq), where q is a u or c quark. The bound assumes B(γq)=0 and is for m_t= 175 GeV; bounds for m_t=170 GeV and 180 GeV and B(γq) $\neq$0 are given in Fig. 5 and Table 7. Table 6 gives constraints on t-c-e-e four-fermi contact interactions.

[48] HEISTER 02Q looked for single top production via FCNC in the reaction $e^+e^- \to \overline{t}c$ or $\overline{t}u$ in 214 pb^{-1} of data at $\sqrt{s}$= 204–209 GeV. No deviation from the SM is found, which leads to a bound on the branching fraction B(Zq), where q is a u or c quark. The bound assumes B(γq)=0 and is for m_t= 174 GeV. Bounds on the effective t- (c or u)-γ and t- (c or u)- Z couplings are given in their Fig. 2.

[49] ABBIENDI 01T looked for single top production via FCNC in the reaction $e^+e^- \to \overline{t}c$ or $\overline{t}u$ in 600 pb^{-1} of data at $\sqrt{s}$= 189–209 GeV. No deviation from the SM is found, which leads to bounds on the branching fractions B(Zq) and B(γq), where q is a u or c quark. The result is obtained for m_t= 174 GeV. The upper bound becomes 9.7% (20.6%))) for m_t= 169 (179) GeV. Bounds on the effective t- (c or u)-γ and t- (c or u)-Z couplings are given in their Fig. 4.

[50] BARATE 00S looked for single top production via FCNC in the reaction $e^+ e^- \rightarrow \overline{t} c$ or $\overline{t} u$ in 411 pb^{-1} of data at c.m. energies between 189 and 202 GeV. No deviation from the SM is found, which leads to a bound on the branching fraction. The bound assumes $B(\gamma q)=0$. Bounds on the effective t- (c or u)-γ and t- (c or u)-Z couplings are given in their Fig. 4.

[51] ABE 98G looked for $t\overline{t}$ events where one t decays into three jets and the other decays into qZ with $Z \rightarrow \ell\ell$. The quoted bound is for $\Gamma(Zq)/\Gamma(Wb)$.

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t Decay Vertices in $p\overline{p}$ Collisions

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.56±0.31		[52] ABAZOV	05G	D0	$F_0 = B(t \rightarrow W_0 b)$
0.00±0.13±0.07		[53] ABAZOV	05L	D0	$F_+ = B(t \rightarrow W_+ b)$
<0.25	95	[53] ABAZOV	05L	D0	$F_+ = B(t \rightarrow W_+ b)$
<0.80	95	[54] ACOSTA	05D	CDF	$F_{V+A} = B(t \rightarrow W b_R)$
<0.24	95	[54] ACOSTA	05D	CDF	$F_+ = B(t \rightarrow W_+ b)$
0.91±0.37±0.13		[55] AFFOLDER	00B	CDF	$F_0 = B(t \rightarrow W_0 b)$
0.11±0.15		[55] AFFOLDER	00B	CDF	$F_+ = B(t \rightarrow W_+ b)$

[52] ABAZOV 05G studied the angular distribution of leptonic decays of W bosons in $t\overline{t}$ candidate events with lepton + jets final states, and obtained the fraction of longitudinally polarized W under the constraint of no right-handed current, $F_+ = 0$. It is based on 125 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV.

[53] ABAZOV 05L studied the angular distribution of leptonic decays of W bosons in $t\overline{t}$ events, where one of the W's from t or $\overline{t}$ decays into e or μ and the other decays hadronically. The fraction of the "+" helicity W boson is obtained by assuming $F_0 = 0.7$, which is the generic prediction for any linear combination of V and A currents. The first error is statistical and the second one is systematic. The results are based on 230 ± 15 pb^{-1} of data at $\sqrt{s} = 1.96$ TeV.

[54] ACOSTA 05D measures the $m^2_{\ell+b}$ distribution in $t\overline{t}$ production events where one or both W's decay leptonically to $\ell = e$ or μ, and finds a bound on the V+A coupling of the tbW vertex. By assuming the SM value of the longitudinal W fraction $F_0 = B(t \rightarrow W_0 b) = 0.70$, the bound on F_+ is obtained. If the results are combined with those of AFFOLDER 00B, the bounds become $F_{V+A} < 0.61$ (95% CL) and $F_+ < 0.18$ (95 %CL), respectively. ACOSTA 05D results are based on 109 ± 7 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV (run I).

[55] AFFOLDER 00B studied the angular distribution of leptonic decays of W bosons in $t \rightarrow Wb$ events. The ratio F_0 is the fraction of the helicity zero (longitudinal) W bosons in the decaying top quark rest frame. The first error is statistical and the second systematic. $B(t \rightarrow W_+ b)$ is the fraction of positive helicity (right-handed) positive charge W bosons in the top quark decays. It is obtained by assuming the Standard Model value of F_0.

Single *t*-Quark Production Cross Section in $p\overline{p}$ Collisions

Direct probes of the tbW coupling and possible new physics.

VALUE (pb)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 6.4	95	[56] ABAZOV	05P	D0	$p\overline{p} \rightarrow tb + X$
< 5.0	95	[56] ABAZOV	05P	D0	$p\overline{p} \rightarrow tqb + X$
<10.1	95	[57] ACOSTA	05N	CDF	$p\overline{p} \rightarrow tqb + X$
<13.6	95	[57] ACOSTA	05N	CDF	$p\overline{p} \rightarrow tb + X$

<17.8	95	[57] ACOSTA 05N	CDF	$p\overline{p} \to tb + X, tqb + X$
<24	95	[58] ACOSTA 04H	CDF	$p\overline{p} \to tb + X, tqb + X$
<18	95	[59] ACOSTA 02	CDF	$p\overline{p} \to tb + X$
<13	95	[60] ACOSTA 02	CDF	$p\overline{p} \to tqb + X$

[56] ABAZOV 05P bounds single top-quark production from either the *s*-channel *W*-exchange process, $q'\overline{q} \to t\overline{b}$, or the *t*-channel *W*-exchange process, $q'g \to qt\overline{b}$, based on $\sim 230\,\mathrm{pb}^{-1}$ of data at $\sqrt{s}$=1.96 TeV.

[57] ACOSTA 05N bounds single top-quark production from the *t*-channel *W*-exchange process ($q'g \to qt\overline{b}$), the *s*-channel *W*-exchange process ($q'\overline{q} \to t\overline{b}$), and from the combined cross section of *t*- and *s*-channel. The results are based on $\sim$ 162 pb^{-1} of data at $\sqrt{s}$ = 1.96 TeV.

[58] ACOSTA 04H bounds single top-quark production from the *s*-channel *W*-exchange process, $q'\overline{q} \to t\overline{b}$, and the *t*-channel *W*-exchange process, $q'g \to qt\overline{b}$. It is based on $\sim 106\,\mathrm{pb}^{-1}$ of data at $\sqrt{s}$ = 1.8 TeV (run I).

[59] ACOSTA 02 bounds the cross section for single top-quark production via the *s*-channel *W*-exchange process, $q'\overline{q} \to t\overline{b}$. It is based on $\sim 106\,\mathrm{pb}^{-1}$ of data at $\sqrt{s}$=1.8 TeV.

[60] ACOSTA 02 bounds the cross section for single top-quark production via the *t*-channel *W*-exchange process, $q'g \to qt\overline{b}$. It is based on $\sim 106\,\mathrm{pb}^{-1}$ of data at $\sqrt{s}$=1.8 TeV.

Single *t*-Quark Production Cross Section in *ep* Collisions

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (pb)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.55	95	[61] AKTAS 04	H1	$e^{\pm}p \to e^{\pm}tX$

[61] AKTAS 04 looked for single top production via FCNC in $e^{\pm}$ collisions at HERA with 118.3 pb^{-1}, and found 5 events in the *e* or μ channels while 1.31 ± 0.22 events are expected from the Standard Model background. No excess was found for the hadronic channel. The observed cross section of $\sigma(ep \to etX) = 0.29^{+0.15}_{-0.14}$ pb at $\sqrt{s} = 319$ GeV gives the quoted upper bound if the observed events are due to statistical fluctuation.

$t\overline{t}$ production cross section in $p\overline{p}$ collisions

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (pb)	*DOCUMENT ID*	*TECN*	*COMMENT*
$8.6^{+1.6}_{-1.5}\pm0.6$	[62] ABAZOV 05Q	D0	ℓ + n jets
$8.6^{+3.2}_{-2.7}\pm1.1\pm0.6$	[63] ABAZOV 05R	D0	di-lepton + n jets
$6.7^{+1.4}_{-1.3}{}^{+1.6}_{-1.1}\pm0.4$	[64] ABAZOV 05X	D0	ℓ + jets / kinematics
$5.3\pm3.3^{+1.3}_{-1.0}$	[65] ACOSTA 05S	CDF	ℓ + jets / soft μ *b*-tag
$6.6\pm1.1\pm1.5$	[66] ACOSTA 05T	CDF	ℓ + jets / kinematics
$6.0^{+1.5}_{-1.6}{}^{+1.2}_{-1.3}$	[67] ACOSTA 05U	CDF	ℓ + jets / kinematics + vtx *b*-tag
$5.6^{+1.2}_{-1.1}{}^{+0.9}_{-0.6}$	[68] ACOSTA 05V	CDF	ℓ + n jets
$7.0^{+2.4}_{-2.1}{}^{+1.6}_{-1.1}\pm0.4$	[69] ACOSTA 04I	CDF	di-lepton + jets + missing ET

[62] ABAZOV 05Q measures the top-quark pair production cross section at $\sqrt{s}$=1.96 TeV with $\sim$ 230 pb^{-1} of data, based on the analysis of W plus n-jet events where W decays into e or μ plus neutrino, and at least one of the jets is b-jet like. The first error is statistical and systematic, and the second accounts for the luminosity uncertainty. The result assumes m_t = 175 GeV; the mean value changes by (175$-m_t$(GeV)) $\times$ 0.06 pb in the mass range 160 to 190 GeV.

[63] ABAZOV 05R measures the top-quark pair production cross section at $\sqrt{s}$=1.96 TeV with 224–243 pb^{-1} of data, based on the analysis of events with two charged leptons in the final state. The first error is statistical, the second one is systematic, and the last one gives the luminosity uncertainty. The result assumes m_t = 175 GeV; the mean value changes by (175$-m_t$(GeV)) $\times$ 0.08 pb in the mass range 160 to 190 GeV.

[64] Measured at $\sqrt{s}$ = 1.96 TeV using 230 pb^{-1}. Assuming m_t = 175 GeV. The last error accounts for the luminosity uncertainty.

[65] Measured at $\sqrt{s}$ = 1.96 TeV using 194 pb^{-1}. Assuming m_t = 175 GeV.

[66] Measured at $\sqrt{s}$ = 1.96 TeV using 194 $\pm$ 11 pb^{-1}. Assuming m_t = 175 GeV.

[67] Measured at $\sqrt{s}$ = 1.96 TeV using 162 $\pm$ 10 pb^{-1}. Assuming m_t = 175 GeV.

[68] ACOSTA 05V measures the top-quark pair production cross section at $\sqrt{s}$ = 1.96 TeV with $\sim$ 162 pb^{-1} data, based on the analysis of W plus n-jet events where W decays into e or μ plus neutrino, and at least one of the jets is b-jet like. Assumes m_t = 175 GeV.The first error is statistical and the latter is systematic, which include the luminosity uncertainty.

[69] ACOSTA 04I measures the top-quark pair production cross section at $\sqrt{s}$=1.96 TeV with 197 $\pm$ 12 pb^{-1} data, based on the analysis of events with two charged leptons in the final state. Assumes m_t = 175 GeV. The first error is statistical, the second one is systematic, and the last one gives the luminosity uncertainty.

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