THE TOP QUARK

Updated August 2005 by T. M. Liss (Illinois) and A. Quadt (Bonn & Rochester/New York).

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 rations, *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

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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 $t \to Wb$. 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 $t\bar{t}$-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. $t\bar{t} \to W^+ b\, W^- \bar{b} \to q\,\bar{q}'\, b\, q''\,\bar{q}'''\,\bar{b}$, (46.2%)
B. $t\bar{t} \to W^+ b\, W^- \bar{b} \to q\,\bar{q}'\, b\,\ell\,\bar{\nu}_\ell\,\bar{b} + \bar{\ell}\,\nu_\ell\, b\, q\,\bar{q}'\,\bar{b}$, (43.5%)
C. $t\bar{t} \to W^+ b\, W^- \bar{b} \to \bar{\ell}\,\nu_\ell\, b\,\ell'\,\bar{\nu}_{\ell'}\,\bar{b}$, (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 $t\bar{t}$ 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 $\ell\nu_\ell b\bar{b}jj$ 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, ≤ 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 360 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 $W \to \tau\nu$ due to secondary $\tau \to (e,\mu)\nu X$ decays. In the $\ell\ell$ mode when only one lepton is required to satisfy lepton ID criteria, there is greater sensitivity to $W \to \tau\nu$. CDF uses a missing-E_T+jets selection in the ℓ+jets mode, that does not require specific lepton-ID and therefore has significant acceptance to $W \to \tau\nu$ decays, including hadronic τ decays, in addition to $W \to e\nu, \mu\nu$ decays. 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 [36–39]. 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 the final results from Run I at $\sqrt{s}$ = 1.8 TeV from CDF (m_t = 175 GeV/c^2) and DØ (m_t = 172.1 GeV/c^2). Uncertainties given are the quadrature sum of statistical and systematic uncertainties of each measurement.

$\sigma_{t\overline{t}}(pb)$	Source	$\int \mathcal{L}$dt (pb^{-1})	Ref.	Method
$6.7^{+2.2}_{-1.7}$	DØ	230	[13]	ℓ + jets/kinematics
$8.6^{+1.7}_{-1.6}$	DØ	230	[14]	ℓ + jets/vtx b-tag
$8.1^{+1.4}_{-1.3}$	DØ	370	[15] †	ℓ + jets/vtx b-tag (update)
$7.9^{+1.7}_{-1.6}$	DØ	370	[16] †	ℓ + jets/0-2 vtx b-tags
$8.6^{+3.4}_{-3.0}$	DØ	220-240	[17]	$\ell\ell$
$8.6^{+2.7}_{-2.3}$	DØ	370	[18] †	$\ell\ell$ (update)
$11.1^{+6.0}_{-4.6}$	DØ	160	[19] †	$e\mu$/vtx b-tag
$5.2^{+3.0}_{-2.7}$	DØ	350	[20] †	all-jets/vtx b-tags
$7.1^{+1.9}_{-1.7}$	DØ	220-240	[21] †	combined
$5.6^{+1.5}_{-1.3}$	CDF	160	[22]	ℓ + jets/vtx b-tag
$8.9^{+1.5}_{-1.3}$	CDF	320	[23] †	ℓ + jets/vtx b-tag (update)
8.9 ± 1.5	CDF	320	[24] †	ℓ + jets/jet prob b-tag
$5.3^{+3.5}_{-3.4}$	CDF	190	[25]	ℓ + jets/soft μ b-tag
6.6 ± 1.9	CDF	190	[26]	ℓ + jets/kinematics
6.3 ± 1.3	CDF	350	[27] †	ℓ + jets/kinematics (update)
6.0 ± 2.0	CDF	160	[28]	ℓ + jets/kin+vtx b-tag
$6.1^{+1.8}_{-1.6}$	CDF	310	[29] †	ℓ + jets/missing-E_T+jets
$7.0^{+2.9}_{-2.4}$	CDF	200	[30]	$\ell\ell$
$8.0^{+3.9}_{-3.0}$	CDF	310	[31] †	all-jets/kin+vtx b-tags
7.1 ± 1.0	CDF	350	[32] †	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	[33]	all combined
5.7 ± 1.6	DØ Run I	110	[34,35]	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

† Preliminary result, not yet submitted for publication or not yet published as of August 2005.

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 [41,42] and of p_T distributions by CDF [43] show no deviation from expected behavior. DØ [44] 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 [13–32,45] and found to be consistent with the SM. These tests are presently statistics limited and will be more rigid 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, three basic techniques are employed to extract the top mass. In the first, the so-called "template method" (TM) [46], an over-constrained (2C) kinematic fit is performed to the hypothesis $t\bar{t} \to W^+ b\, W^- \bar{b} \to \ell\, \bar{\nu}_\ell\, b\, q\, \bar{q}'\, \bar{b}$ 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. [47] and Dalitz and Goldstein [48], for each event a probability is calculated as a function of the top mass, using a LO matrix element. 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" [49], 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) and DØ (ME) have reduced the jet energy scale uncertainty by performing a simultaneous, *in situ* fit to the $W \to jj$ hypothesis.

Less precise 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, ($\eta(\nu)$) [50,51], or for η of each neutrino given an assumed ϕ, ($\phi(\nu)$) [52]. A modification of the latter method, ($\mathcal{M}WT$) [50], 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, ($p_z(t\bar{t})$) [53], 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 $\bar{t}$, be zero within a Gaussian uncertainty of 180 GeV/c. In each 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 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 systematic uncertainty (second uncertainty shown) is comparable to the statistical uncertainty, and is primarily due to uncertainties in the 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* $W \to jj$ calibration using the same $t\bar{t}$ events, as mentioned above.

The Tevatron Electroweak Working Group (TevEWWG), responsible for the combined CDF/DØ average top mass in Table 2, took account of correlations between systematic uncertainties in the different measurements in a sophisticated manner [66]. The Particle Data Group (PDG) uses this combined top mass, $m_t = 172.7 \pm 2.9$ GeV/c^2 (statistical and systematic uncertainties combined in quadrature), as our PDG best value. 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 [67].

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 to the Z-pole data [68] or fits including direct measurements of the mass and width of the W-boson [69] provide an indirect determination of the top quark mass via radiative corrections and yield $m_t = 179.4^{+12.1}_{-\ 9.2}$ GeV/c^2, 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

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

m_t (GeV/c^2)	Source	$\int \mathcal{L}\mathrm{dt}$	Ref.	Method
$173.3 \pm 5.6 \pm 5.5$	DØ Run I	125	[44]	ℓ+jets, TM
$180.1 \pm 3.6 \pm 3.9$	DØ Run I	125	[54] $\star$	ℓ+jets, ME
$168.4 \pm 12.3 \pm 3.6$	DØ Run I	125	[55] $\star$	$\ell\ell$, $\eta(\nu)/\mathcal{M}WT$
$178.5 \pm 13.7 \pm 7.7$	DØ Run I	110	[56]	all jets
179.0 ± 5.1	DØ Run I	110-125	[54]	DØ combined
$177.5 \pm 5.8 \pm 7.1$	DØ Run II	160	[57] †	ℓ+jets/topo, Ideogram
$169.9 \pm 5.8^{+7.8}_{-7.1}$	DØ Run II	230	[58] †	ℓ+jets/topo, TM (update)
$170.6 \pm 4.2 \pm 6.0$	DØ Run II	230	[58] †	ℓ+jets/b-tag, TM
$169.5 \pm 3.0 \pm 3.6$	DØ Run II	320	[10] † $\star$	ℓ+jets/topo, ME($W \to jj$)
$155^{+14}_{-13} \pm 7$	DØ Run II	230	[59] †	$\ell\ell$, $\mathcal{M}WT$
$176.1 \pm 5.1 \pm 5.3$	CDF Run I	110	[51,60,61] $\star$	ℓ + jets
$167.4 \pm 10.3 \pm 4.8$	CDF Run I	110	[51] $\star$	$\ell\ell$
$186.0 \pm 10.0 \pm 5.7$	CDF Run I	110	[51,62] $\star$	all jets
176.1 ± 6.6	CDF Run I	110	[51,61]	CDF combined
$173.5^{+2.7}_{-2.6} \pm 3.0$	CDF Run II	318	[9] † $\star$	ℓ+jets/b-tag, TM($W \to jj$)
$173.2^{+2.6}_{-2.4} \pm 3.2$	CDF Run II	318	[63] †	ℓ+jets/b-tag, DLM
$165.3 \pm 6.3 \pm 3.6$	CDF Run II	340	[64] † $\star$	$\ell\ell$, ME
$170.6^{+7.1}_{-6.6} \pm 4.4$	CDF Run II	359	[65] †	$\ell\ell$, $\eta(\nu)$
$169.8^{+9.2}_{-9.3} \pm 3.8$	CDF Run II	340	[52] †	$\ell\ell$, $\phi(\nu)$
$170.2^{+7.8}_{-7.3} \pm 3.8$	CDF Run II	340	[53] †	$\ell\ell$, $p_z(t\bar{t})$
$172.7 \pm 1.7 \pm 2.4$ *	CDF & DØ	110-340	[66] †	PDG best

* PDG uses this TevEWWG result as its best value. It is a combination of Run I and Run II measurements (labeled with $\star$), yielding a χ^2 of 6.45 for 7 degrees of freedom.

† Preliminary result, not yet submitted for publication or not yet published as of August 2005.

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, $(Q_1, Q_4)_R$ [39,70]. 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. The analyses are ongoing, results are expected to be made public soon.

C.4 Top Branching Ratio & $|V_{tb}|$: CDF and DØ report direct measurements of the $t \rightarrow Wb$ branching ratio [71,72,16]. 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 channel, and using the known b-tagging efficiency, the ratio $R = B(t \rightarrow Wb)/\sum_{q=d,s,b} B(t \rightarrow Wq)$ can be extracted. DØ performs a simultaneous fit for the production cross section $\sigma_{t\bar{t}}$ 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 $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$ and $|V_{tb}|$ from CDF and DØ.

R or $\|V_{tb}\|$	Source	$\int \mathcal{L}$dt (pb^{-1})	Ref.
$R = 0.94^{+0.31}_{-0.24}$	CDF Run I	109	[71]
$R = 1.12^{+0.27}_{-0.23}$	CDF Run II	160	[72]
$R > 0.61$	CDF Run II	160	[72]
$R = 1.03^{+0.19}_{-0.17}$	DØ Run II	230	[16] †
$R > 0.64$	DØ Run II	230	[16] †
$\|V_{tb}\| > 0.75$	CDF Run I	109	[71]
$\|V_{tb}\| > 0.78$	CDF Run II	160	[72]
$\|V_{tb}\| > 0.80$	DØ Run II	230	[16] †

† Preliminary result, not yet submitted for publication or not yet published as of August 2005.

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 [73]. CDF gives 95% CL limits of 13.6 and 10.1 pb for the single-top production rates in the s-channel and t-channel, respectively, as well as a combined limit of 17.8 pb [74]. DØ gives 95% CL limits of 5.0 and 4.4 pb, for the s-channel and t-channel, respectively [75,76]. 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 much more data 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 [77] $\mathcal{F}_0^{\rm SM} = x/(1+x)$, $x = m_t^2/2M_W^2$ ($\mathcal{F}_0^{\rm SM} \sim 70\%$ 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 lepton+jets events. 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 choose the assignment to quarks and leptons as that with the lowest χ^2. 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. This method is also used by both experiments in the dilepton channel. 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	[78]	p_T^ℓ
$\mathcal{F}_0 = 0.56 \pm 0.32$	DØ Run I	125	[79]	ME
$\mathcal{F}_0 = 0.74^{+0.22}_{-0.34}$	CDF Run II	200	[80] †	$M^2_{\ell b}$+p_T^ℓ
$\mathcal{F}_+ < 0.18$	CDF Run I	110	[81]	$M^2_{\ell b}$+p_T^ℓ
$\mathcal{F}_+ < 0.27$	CDF Run II	200	[80] †	$M^2_{\ell b}$+p_T^ℓ
$\mathcal{F}_+ < 0.25$	DØ Run II	230-370	[82,83] †	$\cos\theta^*$+p_T^ℓ

† Preliminary result, not yet submitted for publication or not yet published as of August 2005.

C.6 $t\bar{t}$ Spin Correlations: DØ has searched for evidence of spin correlation of $t\bar{t}$ pairs [84]. 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 $\bar{t}$ 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 [85–87]

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

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 [85]. 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 [36], 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 [37], 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 [40] with mass $M_X < 480$ GeV/c^2 and $M_X < 560$ GeV/c^2, respectively, in Run I [41,42], and $M_X < 680$ GeV/c^2 in DØ Run II [88].

C.8 Non-SM Top Decays: Both CDF and DØ have searched for non-SM top decays [89–91], 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 $t \rightarrow H^+ b$ 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 $t \rightarrow W^+b$ [91]. 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 $r_\tau < 5.0$ at 95% CL [92]. 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 80 GeV $< m_{H^\pm} <$ 160 GeV [91]. 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.

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 [93], 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 $W \rightarrow qq'$, 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 [94] in e^+e^- collisions and by H1 [95] and ZEUS [96] in $e^{\pm}p$ collisions. When interpreted in terms of branching ratios in top decay [97,98], 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 [95,99].

Appendix. Expected Sensitivity at the LHC:

The top pair production cross section at the LHC is predicted at NLO to be about 800 pb [100]. There will be 8 million $t\bar{t}$ pairs produced per year at a luminosity of $10^{33}\ \text{cm}^{-2}\,\text{s}^{-1}$. 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 $\pm 2\ \text{GeV/c}^2$ are anticipated [101–103].

Precision measurements of the top pair production cross section are expected to be limited by the estimated 5-10% accuracy on the luminosity determination [101], 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} [102].

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% [102] 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 [102] 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 σ·B. The ATLAS collaboration [101] 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 [101].

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