# 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

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be less than 0.043 and 0.014, respectively (see the review "The CKM Quark-Mixing Matrix" 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 $m_b^2/m_t^2$, $\alpha_s^2$, and $(\alpha_s/\pi)M_W^2/m_t^2$, the width predicted in the Standard Model (SM) at next-to-leading-order is [5]:

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

where $m_t$ refers to the top quark pole mass. 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 $\alpha_s^2$ QCD corrections to $\Gamma_t$ 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. $t\overline{t} \to W^+ b\, W^- \overline{b} \to q\,\overline{q}'\, b\, q''\, \overline{q}'''\, \overline{b}$, (46.2%)
B. $t\overline{t} \to W^+ b\, W^- \overline{b} \to q\,\overline{q}'\, b\, \ell\, \overline{\nu}_\ell\, \overline{b} + \overline{\ell}\, \nu_\ell\, b\, q\, \overline{q}'\, \overline{b}$, (43.5%)
C. $t\overline{t} \to W^+ b\, W^- \overline{b} \to \overline{\ell}\, \nu_\ell\, b\, \ell'\, \overline{\nu}_{\ell'}\, \overline{b}$. (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 ($\ell$+jets), and dilepton ($\ell\ell$) channels, respectively. Their relative contributions, including hadronic corrections, are given in parentheses. While $\ell$ in the above processes refers to $e$, $\mu$, or $\tau$, most of the results to date rely on the $e$ and $\mu$ channels. Therefore, in what follows, we will use $\ell$ to refer to $e$ or $\mu$, unless noted otherwise.

The initial and final-state quarks can radiate 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 $p_T$, which is here also 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 [8,9]. 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 [10,11], 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 fraction of events containing $b$ jets is expected to be $\approx 100\%$, and the jets to be 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).

Electroweak $s$- and $t$-channel production of single top quarks is expected to occur at the Tevatron at a rate of $0.88 \pm 0.11$ pb for the $s$-channel, and $1.98 \pm 0.25$ pb for the $t$-channel [4], a little less than half of the $t\bar{t}$ production rate. However, significant challenges in signal and background separation have slowed the observation of this important production channel. 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 [12].

Next-to-leading-order Monte-Carlo programs have recently become available for both signal and background processes [13], but for the backgrounds, the jet multiplicities required in $t\bar{t}$ analyses are not yet available. 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 [14]. Comparison to CDF and DØ data, however, indicates the $b$- and $c$-quark fractions to be underestimated by the LO generators.

***C. Measured top properties:*** Current measurements of top properties are based on Run-II data with integrated luminosities up to 2 fb$^{-1}$ for both CDF and 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 $\mu$ $b$-tag"). CDF and DØ also use artificial neural network-based $b$-tagging algorithms that combine the properties of displaced tracks and secondary vertex information.

Due to the lepton identification (ID) requirements in the $\ell$+jets and $\ell\ell$ modes, in particular the $p_T$ requirement, the sensitivity is primarily to $e$ and $\mu$ decays of the $W$, with only a small contribution from $W \to \tau\nu$ 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 ($\ell$+track), there is greater sensitivity to $W \rightarrow \tau\nu$. CDF uses a missing-$E_T$+jets selection in the $\ell$+jets mode that does not require specific lepton-ID, and therefore has significant acceptance to $W \rightarrow \tau\nu$ decays, including hadronic $\tau$ 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% C.L. [15]. DØ finds the production cross section (and visible cross section $\sigma \cdot Br$) to be consistent with Standard Model expectations in the lepton+hadronic tau channel [16] as well as in the tau+jets channel [17]. Table 1 shows the measured cross sections from DØ and CDF. These should be compared to the theoretical calculations that yield $5.8 - 7.4$ pb for a top mass of 175 GeV/$c^2$ [1]( see Listings).

Next-to-leading-order calculations predict forward-backward asymmetries of 5-10% in $t\bar{t}$ production [18]. The CDF measurement in 1.9 fb$^{-1}$ yields $17 \pm 8\%$ [19], while the DØ measurement of this asymmetry yields $12 \pm 8\%$ at the detector level [20] using 0.9 fb$^{-1}$. Both results are presently consistent with the NLO prediction.

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 [21–24]. Such non-SM effects would yield discrepancies between theory and data. New sources of 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 [25,26], and of $p_T$ distributions by CDF [27], show no deviation from expected behavior. DØ [28] 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 [29–42] and found to be consistent

**Table 1:** Cross section for $t\bar{t}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV from CDF and DØ ($m_t = 175$ GeV/$c^2$). Only preliminary results (not yet submitted for publication as of March 2008) are shown; for published results see the Listings. 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 |
|---|---|---|---|---|
| $7.3 \pm 2.0$ | DØ | 430 | [30] | $\ell$ + jets/soft $\mu$ $b$-tag |
| $5.1 \pm 4.4$ | DØ | 350 | [17] | $\tau$ + jets |
| $6.2 \pm 1.2$ | DØ | 1050 | [31] | $\ell\ell + \ell$+track/vtx $b$-tag |
| $8.3 \pm 2.3$ | DØ | 1000 | [16] | $\ell\tau$/vtx $b$-tag |
| $12.1 \pm 6.7$ | DØ | 360 | [9] | all-jets/vtx $b$-tags |
| $7.1^{+1.9}_{-1.7}$ | DØ | 220-240 | [32] | combined |
| $8.2 \pm 1.1$ | CDF | 1120 | [33] | $\ell$ + jets/vtx $b$-tag |
| $7.8 \pm 2.0$ | CDF | 760 | [34] | $\ell$ + jets/soft $\mu$ $b$-tag |
| $6.0 \pm 1.1$ | CDF | 760 | [35] | $\ell$ + jets/kinematics |
| $6.2 \pm 1.4$ | CDF | 1200 | [36] | $\ell\ell$ |
| $8.3 \pm 1.6$ | CDF | 1100 | [37] | $\ell$+track |
| $10.1 \pm 2.2$ | CDF | 1000 | [38] | $\ell$+track+$b$-tag |
| $8.3^{+2.3}_{-1.9}$ | CDF | 1020 | [39] | all-jets/kin+vtx $b$-tags |
| $7.3 \pm 0.9$ | CDF | 760 | [40] | combined |

with the SM. Recently, CDF has measured the differential production cross section $d\sigma/dM_{t\bar{t}}$ in 2 fb$^{-1}$ [43]. Comparing the shape to the SM expectation, they find a $p$-value of 0.45. Also, the $t\bar{t}$ invariant mass distributions have been studied [44,45]. These tests are presently statistics-limited, and will be more incisive with larger data sets in Run II.

***C.2 Electroweak Single-Top Quark Production:*** DØ has reported first evidence for single-top production, applying a multivariate analysis to 900 pb$^{-1}$ of Run-II data [46]. Using a decision tree (DT) technique, they measure a cross section of $\sigma(p\bar{p} \to tb + X, tqb + X) = 4.9 \pm 1.4$ pb. The probability for such a measurement in the absence of a signal is 0.035%, corresponding to a 3.4 standard deviation significance. A more recent DØ analysis on the same data set [47], combining the

DT analysis with two independent analyses based on the matrix element method and a bayesian neural network technique, yields $\sigma(p\bar{p} \to tb + X, tqb + X) = 4.7 \pm 1.3$ pb, corresponding to a probability of 0.014, or 3.6 standard deviation significance. With 2.2 $\mathrm{fb}^{-1}$, CDF has recently reported evidence [48] with three techniques: a likelihood based on expected kinematic distributions, an event-probability-density based on matrix elements, and a neural-network approach. Combining these three approaches in a single analysis yields a cross section of $\sigma(p\bar{p} \to tb + X, tqb + X) = 2.2 \pm 0.7$ pb. The probability for this measurement in the absence of a signal is 0.0094%, corresponding to 3.7 standard deviation significance. These measurements are also used to directly determine the CKM-matrix element $|V_{tb}|$. DØ measures $|V_{tb}| = 1.3 \pm 0.2$, while the CDF measurement is $|V_{tb}| = 0.88 \pm 0.16$.

***C.3 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 $\chi^2$ 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 $\chi^2$ 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.* [50] and Dalitz and Goldstein [51], a probability for each event is calculated as a function of the top mass, using an 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" [52,53], 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 $\chi^2$ 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. An additional variation on these techniques is the "Multivariate Likelihood" (ML) technique, where an integral over the matrix element is performed for each permutation, and then summed with weights determined by the $b$-tagging information on each jet. Backgrounds are handled in the ML technique by "deweighting" events according to a background probability calculated using variables based on the topology of the event.

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. CDF (TM, ME, ML) 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 [54] relies solely on tracking, and thus avoids the jet-energy scale uncertainty. This method exploits the fact that, in the rest frame of the top quark, the boost given to the bottom quark has a Lorentz factor $\gamma_b \approx 0.4\, m_t/m_b$. 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 under-constrained by one measurement. It is not possible to extract a value for the top-quark mass from direct reconstruction without adding additional information. 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. Recently, an analytic solution to the problem has been proposed [55]. At the Tevatron, 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, $\phi$, of each neutrino given an assumed pseudorapidity, $\eta$, $(\eta(\nu))$ [56,57], or for $\eta$ of each neutrino given an assumed $\phi$, $(\phi(\nu))$ [58]. An alternative approach, $(\mathcal{M}WT)$ [56], solves for $\eta$ of each neutrino requiring the sum of the neutrino $\vec{p}_T$'s to equal the measured missing $E_T$ vector. In another technique, $(p_z(t\bar{t}))$ [58], 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 a variation of the $p_z(t\bar{t})$ technique, the theoretical relation between the top mass and its production cross section is used as an additional constraint. 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.

**Table 2:** Measurements of top-quark mass from CDF and DØ. $\int \mathcal{L}\mathrm{dt}$ is given in $\mathrm{pb}^{-1}$. Only preliminary results (not yet submitted for publication as of March 2008) are shown; for published results see the Listings. Statistical uncertainties are listed first, followed by systematic uncertainties.

| $m_t$ (GeV/$c^2$) | Source | $\int \mathcal{L}\mathrm{dt}$ | Ref. | Method |
|---|---|---|---|---|
| $169.9 \pm 5.8^{+7.8}_{-7.1}$ | DØ Run II | 230 | [68] | $\ell$+jets/topo, TM |
| $170.6 \pm 4.2 \pm 6.0$ | DØ Run II | 230 | [68] | $\ell$+jets/$b$-tag, TM |
| $172.2 \pm 1.1 \pm 1.6$ | DØ Run II | 2100 | [69] | $\ell$+jets/$b$-tag, ME($W \to jj$) |
| $176.6 \pm 11.2 \pm 3.8$ | DØ Run II | 370 | [70] | $\ell\ell$/$b$-tag, $\mathcal{M}WT$ |
| $173.7 \pm 5.4 \pm 3.4$ | DØ Run II | 1000 | [72] | $\ell\ell$, $\eta(\nu) + \mathcal{M}WT$ |
| $166.1 \pm 5.7 \pm 5.8(th)$ | DØ Run II | 1000 | [60] | $\sigma_{t\bar{t}}^{\ell+jets}$ |
| $174.1 \pm 9.1 \pm 5.1(th)$ | DØ Run II | 1000 | [60] | $\sigma_{t\bar{t}}^{\ell\ell}$ |
| $172.1 \pm 1.5 \pm 1.9$ | DØ Run I+II | 1000 | [65] | DØ combined |
| $172.7 \pm 1.8 \pm 1.2$ | CDF Run II | 1900 | [76] | $\ell$+jets/$b$-tag, ML($W \to jj$) |
| $171.8 \pm 1.9 \pm 1.0$ | CDF Run II | 1900 | [77] | $\ell$+jets/$b$-tag, TM($W \to jj$) |
| $171.9 \pm 1.7 \pm 1.0$ | CDF Run II | 1900 | [77] | $\ell$+jets TM($W \to jj$) & $\ell\ell$ $\eta(\nu)$+$H_T$ |
| $171.2 \pm 2.7 \pm 2.9$ | CDF Run II | 1900 | [78] | $\ell\ell$, ME |
| $171.6^{+3.4}_{-3.2} \pm 3.8$ | CDF Run II | 1900 | [77] | $\ell\ell$, $\eta(\nu)$+$H_T$ |
| $167.7^{+4.2}_{-4.0} \pm 3.1$ | CDF Run II | 1900 | [79] | $\ell\ell$, $\eta(\nu)$ |
| $156 \pm 20 \pm 4.6$ | CDF Run II | 1800 | [59] | $\ell\ell$, $P_T(\ell)$ |
| $177.0 \pm 3.7 \pm 1.6$ | CDF Run II | 1900 | [80] | all jets, TM($W \to jj$) |
| $171.1 \pm 3.7 \pm 2.1$ | CDF Run II | 943 | [81] | all jets, TM+ME($W \to jj$) |
| $172.9 \pm 1.2 \pm 1.5$ | CDF Run I+II | 110-2000 | [82] | CDF Combined |
| $171.2 \pm 1.2 \pm 1.8$ * | CDF,DØ (I+II) | 110-1000 | | publ. results, PDG best |
| $172.6 \pm 0.8 \pm 1.1$ ** | CDF,DØ (I+II) | 110-2100 | [61] | publ. or prelim. results |

* PDG uses this TevEWWG result as its best value. It is a combination of published Run I + II measurements, yielding a $\chi^2$ of 10.6 for 10 deg. of freedom.

**The TevEWWG world average is a combination of published Run-I and preliminary or published Run-II measurements, yielding a $\chi^2$ of 6.9 for 11 deg. of freedom.

The $P_T$ spectrum of the leptons in the dilepton channel has also been used to extract a top mass measurement [59]. The resulting statistical uncertainty of the measurement is large, but as with the $L_{xy}$ technique, it is free of the systematic uncertainty due to the jet-energy scale.

In the most recent set of CDF results, a measurement has been done using the lepton+jets and dilepton channels simultaneously. In the lepton+jets channel, the TM is used together with an *in situ* $W \rightarrow jj$ fit. In the dilepton channel, $\eta(\nu)$ is used plus a fit to the scalar sum of transverse energies ($H_T$), which is sensitive to the top mass.

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, both experiments have employed a neural network selection, based on an array of kinematic variables to improve the S/B. At DØ, 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, the top-quark mass for each event was reconstructed applying the same fitting technique used in the $\ell$+jets mode. In the most recent analysis, the *in situ* jet-energy scale calibration from the $W \rightarrow jj$ fit is also used. 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.

DØ also measures the top-quark mass via comparison of the $t\bar{t}$ production cross section with the Standard Model expectation [60]. This method has the advantage that it is very simple and sensitive to the top quark pole mass, which is a very well defined concept. The fully-inclusive cross-section calculation, used for comparison, contains current best theoretical knowledge with reduced-scheme or scale-dependence.

Recent results are shown in Table 2. See the Top Quark Listings for a complete set of published results. 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* $W \rightarrow jj$ 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 [61]. The Particle Data Group (PDG) uses their combination of published Run-I and Run-II top-mass measurements, $m_t = 171.2 \pm 2.1$ GeV/c$^2$ (statistical and systematic uncertainties combined in quadrature), as the PDG best value. The latest TevEWWG world average [61], also including published and some preliminary Run-II results, yields $m_t = 172.6 {\pm} 1.4$ GeV/c$^2$ (statistical and systematic uncertainties combined in quadrature).

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 this *Review* 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]. Ultimately, the precision of the mass measurements will be limited by the theoretical understanding of the relation between the observables and the theoretical definition of the mass.

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 "$H^0$ Indirect Mass Limits" in the Particle Listings of this *Review* for more information). Such fits, including $Z$-pole data [63] and direct measurements of the mass and width of the $W$-boson, yield $m_t = 179^{+12}_{-\ 9}$ GeV/c$^2$ [64]. A fit including additional electroweak precision data (see the review "Electroweak Model and Constraints on New Physics" in this *Review*) yields $m_t = 174.7^{+10.0}_{-\ 7.8}$ GeV/c$^2$ (OUR EVALUATION). Both indirect evaluations are in good agreement with the direct top-quark mass measurements.

***C.4 Top Quark Electric Charge:*** The top quark is the only quark whose electric charge has not been measured through production at 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, $(Q_1, Q_4)_R$ [24,85]. CDF and DØ study the top quark charge in double-tagged lepton+jets events and (CDF) single-tagged dilepton 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. For the exotic model of Chang [85] with a top-quark charge $|Q_{top}| = 4/3$, DØ yields a $p$-value, corresponding to the probability of consistency with the exotic model, of 7.8% [86]. CDF excludes the model at 87% C.L. [87]. While these two results are not directly comparable, they both indicate that the top quark is indeed consistent with being a Standard Model $|Q_{top}| = 2/3$ quark.

***C.5 Top Branching Ratio & $|V_{tb}|$:*** CDF and DØ report direct measurements of the $t \to Wb$ branching ratio [88–89]. 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 $R = B(t \to Wb)/\sum_{q=d,s,b} B(t \to Wq)$ 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 recent measurements are summarized in Table 3.

**Table 3:** Measurements and 95% C.L. lower limits of $R = B(t \to Wb)/B(t \to Wq)$ and indirect $|V_{tb}|$ from CDF and DØ. The direct measurements of $|V_{tb}|$ from the single-top analyses are shown in the bottom of the table. A complete set of published results can be found in the Listings.

| $R$ or $\|V_{tb}\|$ | Source | $\int \mathcal{L}$dt (pb$^{-1}$) | Ref. |
|---|---|---|---|
| $R = 0.97^{+0.09}_{-0.08}$ | DØ Run II | 900 | [29] |
| $R > 0.79$ | DØ Run II | 900 | [29] |
| $\|V_{tb}\| > 0.89$ | DØ Run II | 900 | [29] |
| $\|V_{tb}\| = 0.88 \pm 0.16$ | CDF Run II | 2200 | [48] |
| $\|V_{tb}\| = 1.3 \pm 0.2$ | DØ Run II | 900 | [46] |

***C.6 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 [90] $\mathcal{F}_0^{\rm SM} = x/(1+x)$, $x = m_t^2/2M_W^2$ ($\mathcal{F}_0^{\rm SM} \sim 70\%$ 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 ($p_T^\ell$) 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 ($M_{\ell b}^2$) as an observable, which is directly related to $\cos\theta^*$. Finally, the Matrix

Element method (ME) has also been used, in which a likelihood is formed from a product of event probabilities calculated from the ME for a given set of measured kinematic variables and assumed $W$-helicity fractions. The results of recent CDF and DØ analyses are summarized in Table 4; a complete set of published results can be found in the Listings. All results are in agreement with the SM expectation.

**Table 4:** Measurement and 95% C.L. upper limits of the $W$ helicity in top quark decays. Published results are given in the Listings. Results listed are preliminary and not yet submitted for publication, as of March 2008.

| $W$ Helicity | Source | $\int \mathcal{L}$dt (pb$^{-1}$) | Ref. | Method |
|---|---|---|---|---|
| $\mathcal{F}_0 = 0.66 \pm 0.12$ | CDF Run II | 1900 | [91] | $\cos\theta^*$ |
| $\mathcal{F}_0 = 0.64 \pm 0.11$ | CDF Run II | 1900 | [92] | ME |
| $\mathcal{F}_+ < 0.07$ @ 95% C.L. | CDF Run II | 1900 | [93] | $\cos\theta^*$ |

***C.7 $t\bar{t}$ Spin Correlations & Top Width:*** DØ has searched for evidence of spin correlation of $t\bar{t}$ pairs [94]. 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 [95–97]

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

where $\theta_+$ and $\theta_-$ 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 [95]. 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 $\kappa$, 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% C.L.

Related to the measurement of top-spin correlations, which require a top lifetime less than the hadronization timescale, is the measurement of the top width. The top width is expected to be of order 1 GeV/c$^2$ (Eq. 1). The sensitivity of current experiments does not approach this level, but CDF has made the first direct measurement of the top width using the mass fitting template method in lepton+jets events, fixing the top mass at 175 GeV/c$^2$ and varying the top width in constructing the Monte Carlo templates. The top width is found to be less than 12.7 GeV/c$^2$ at the 95% C.L. [98].

***C.8 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 [21], 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 [22], 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 [99], with mass $M_X < 480$ GeV/c$^2$ and $M_X < 560$ GeV/c$^2$, respectively, in Run I [25,26], and $M_X < 725$ GeV/c$^2$ and $M_X < 760$ GeV/c$^2$ in Run II [44,45]. With 955 pb$^{-1}$ of Run-II data, CDF has produced a less model-dependent limit for a narrow-width $Z'$, ruling out at the 95% C.L. a contribution greater than 0.7 pb for a $Z'$ heavier than 700 GeV/c$^2$ decaying to $t\bar{t}$ [100]; DØ excludes at the 95% C.L. that the $t\bar{t}$ signal is entirely produced through a $Z'$ resonance for $550 < m_{Z'} < 1000$ GeV/c$^2$ [20]. A recent CDF analysis has placed limits on the coupling strength of a massive gluon to $t\bar{t}$ [101]. In 1 fb$^{-1}$, DØ has set limits on scalar top-quark pair production, with subsequent decays to top quarks in the lepton+jets channel [42].

***C.9 Non-SM Top Decays:*** Both CDF and DØ have searched for non-SM top decays [102–105], particularly those expected in supersymmetric models, such as $t \rightarrow H^+ b$, followed by $H^+ \rightarrow \tau^+ \bar{\nu}$ or $c\bar{s}$. The $t \rightarrow H^+ b$ 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, $H^+ \rightarrow c\bar{s}$ is dominant, while $H^+ \rightarrow \tau^+\bar{\nu}$ 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 $t \rightarrow W^{\pm} b$, 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), and the measured cross-section ratio $\sigma_{t\bar{t}}^{\ell+jets}/\sigma_{t\bar{t}}^{\ell\ell}$ would differ from unity.

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 $t \rightarrow W^+ b$ [104]. 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% C.L. for $m_{H^{\pm}} \approx 100$ GeV, and $B(t \rightarrow H^{\pm} b) < 0.4$ in the tauonic model with $B(H^{\pm} \rightarrow \tau\nu) = 100\%$ [104]. The DØ collaboration interprets their measured cross-section ratio $\sigma_{t\bar{t}}^{\ell+jets}/\sigma_{t\bar{t}}^{\ell\ell} = 1.21^{+0.27}_{-0.26}$ using 1 fb$^{-1}$ in a model with a charged Higgs boson of mass 80 GeV/c$^2$ and the exclusive decay $H^+ \to c\bar{s}$, finding a limit of $B(t \to H^\pm b) < 0.35$ at 95% C.L. [105].

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 $0.5 \times 10^{-24}$ s ($c\tau_t \approx 3 \times 10^{-10}$ $\mu$m), 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 [106]. The measured lifetime is consistent with zero, and an upper limit $c\tau_t < 52.5$ $\mu$m is found at 95% C.L.

In 230 pb$^{-1}$ of Run-II data, DØ uses their single-top analysis to place limits on anomalous single-top quark production via the flavor-changing neutral-current (FCNC) coupling of a gluon to the top quark and a charm ($tcg$) or up quark ($tug$) [107], or via the decay of a heavy $W'$ boson to a top quark and a bottom quark in 900 pb$^{-1}$ [108]. The observed limits are at 95% C.L.: $\kappa_g^c/\Lambda < 0.15$ TeV$^{-1}$ and $\kappa_g^u/\Lambda < 0.037$ TeV$^{-1}$. DØ excludes the production of $W'$ bosons with masses below 731 GeV for a $W'$ boson with standard-model-like couplings, below 739 GeV for a $W'$ boson with right-handed couplings that is allowed to decay to both leptons and quarks, and below 768 GeV for a $W'$ boson with right-handed couplings that is only allowed to decay to quarks. CDF has recently released $W'$ limits also using the single-top analysis [109]. In 1900 pb$^{-1}$ of Run-II data, a $W'$ with Standard-Model couplings is searched for in the $t\bar{b}$ decay mode. Masses below 800 GeV are excluded, assuming that any right-handed neutrino is lighter than the $W'$, and below 825 GeV if the right-handed neutrino is heavier than the $W'$.

CDF reported a search for flavor-changing neutral-current (FCNC) decays of the top quark $t \to q\gamma$ and $t \to qZ$ in the Run-I data [110], and recently with enhanced sensitivity in Run II [111]. 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 $Wb$. The Run-I analysis included a $t \to q\gamma$ search in which 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 $B(t \to q\gamma) < 3.2\%$ at 95% C.L. In the search for $t \to qZ$, CDF considers $Z \to \mu\mu$ or $ee$ and $W \to qq'$, giving a $Z$ + four jets signature. A Run-II dataset of 1900 $\text{pb}^{-1}$ is found consistent with background expectations and a 95% C.L. on the $t \to qZ$ branching fraction of $< 3.7\%$ (for $\text{M}_{\text{top}}$=175 GeV/$\text{c}^2$) is set.

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 [112] in $e^+e^-$ collisions, and by H1 [113] and ZEUS [114] in $e^{\pm}p$ collisions. When interpreted in terms of branching ratios in top decay [115,116], the LEP limits lead to typical 95% C.L. 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% C.L. 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 $1.31 \pm 0.22$. 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 [113,117].

***Appendix. Expected Sensitivity at the LHC:***

The top pair-production cross section at the LHC is predicted at NLO to be about 800 pb [118]. There will be 8 million $t\bar{t}$ pairs produced per year at a luminosity of $10^{33}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. 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 $\pm 2$ GeV/$c^2$ per channel are anticipated [119–121].

Precision measurements of the top pair-production cross section are expected to be limited by the estimated 3-10% accuracy on the luminosity determination [119,120], 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, where a $|V_{tb}|$ measurement at the 5% level per experiment is projected with 10 $\mathrm{fb}^{-1}$ [119,120].

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% [120] with 10 $\mathrm{fb}^{-1}$ 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 [120] 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 17% accuracy with 10 $\mathrm{fb}^{-1}$ 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 [119] has studied the reach for a $5\sigma$ discovery of a narrow resonance decaying to $t\bar{t}$. With 30 $\mathrm{fb}^{-1}$, 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 [119,120].

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