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 our review on the "Standard Model of Electroweak Interactions" for more information). This note summarizes its currently measured properties, and provides a discussion of the experimental and theoretical issues involved in the determination of its parameters (mass, production cross section, decay branching ratios, *etc.*).

B. Top quark production at the Tevatron: All direct measurements of top quark production and decay have been made by the CDF and DØ experiments at the Fermilab Tevatron collider in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Here top quarks are produced dominantly in pairs from the QCD processes $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. At this energy, the production cross section in these channels is expected to be approximately 5 pb for $m_t = 175$ GeV/c^2, with a 90% contribution from $q\overline{q}$ annihilation. Smaller contributions are expected from electroweak single-top production mechanisms, namely $q\overline{q}' \to W^* \to t\overline{b}$ and $qg \to q' t\overline{b}$, the latter mediated by virtual-W exchange ("W-gluon fusion"). The combined rate from these processes is approximately 2.5 pb at $m_t = 175$ GeV/c^2 (see Ref. 1 and references therein). The expected contribution of these channels is further reduced relative to the dominant pair-production mechanisms because of larger backgrounds and poor detection efficiency.

With a mass above the Wb threshold, 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 those of order $(\alpha_s/\pi) m_W^2/m_t^2$, this is predicted in the Standard Model to be [2]:

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

The use of G_F in this equation accounts for the largest part of the one-loop electroweak radiative corrections, providing an expression accurate to better than 2%. The width increases with mass, going for example from 1.02 GeV/c^2 at m_t = 160 GeV/c^2 to 1.56 GeV/c^2 at m_t = 180 GeV/c^2 (we used $\alpha_S(\mathrm{M_Z}) = 0.118$). With such a correspondingly short lifetime, the top quark is expected to decay before top-flavored hadrons or $t\overline{t}$-quarkonium bound states can form [3]. Recently, the order α_s^2 QCD corrections to Γ_t have also been calculated [4], thereby improving the overall theoretical accuracy to better than 1%.

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}, whose values can be estimated under the assumption of unitarity of the three-generation CKM matrix to be less than 0.044 and 0.014, respectively (see our review "The Cabibbo-Kobayashi-Maskawa Mixing Matrix" in the current edition for more information). Typical final states for the leading pair-production process therefore belong to three classes:

A. $t\overline{t} \rightarrow W\,b\,W\,\overline{b} \rightarrow q\,\overline{q}'\,b\,q''\,\overline{q}'''\,\overline{b}$,

B. $t\overline{t} \rightarrow W\,b\,W\,\overline{b} \rightarrow q\,\overline{q}'\,b\,\ell\,\overline{\nu}_\ell\,\overline{b} + \overline{\ell}\,\nu_\ell\,b\,q\,\overline{q}'\,\overline{b}$,

C. $t\overline{t} \rightarrow W\,b\,W\,\overline{b} \rightarrow \overline{\ell}\,\nu_\ell\,b\,\ell'\,\overline{\nu}_{\ell'}\,\overline{b}$,

where A, B, and C are referred to as the all-jets, lepton + jets, and dilepton channels, respectively.

The final state quarks can emit radiation and will eventually evolve into jets of hadrons. The precise number of jets reconstructed by the detectors varies event by event, as it depends on the decay kinematics, as well as on the precise definition of jet used in the analysis. (Additional gluon radiation can also be emitted from the initial states.) The transverse momenta of the neutrinos are reconstructed via the large imbalance in detected transverse momentum of the event (missing E_T).

The observation of $t\overline{t}$ pairs has been reported in all of the above decay modes. As discussed below, the production and decay properties of the top quark extracted from the above three decay channels are all consistent with each other within experimental uncertainty. In particular, the $t \rightarrow Wb$ decay mode is supported through the reconstruction of the $W \to jj$ invariant mass in the $\ell\nu_\ell b\bar{b}jj$ final state [5].

The extraction of top-quark properties from Tevatron data requires a good understanding of the production and decay mechanisms of the top, as well as of the large background processes. Because only leading order QCD calculations are available for most of the relevant processes (W+3 and 4 jets, or WW+2 jets), theoretical estimates of the backgrounds have large uncertainties. While this limitation affects estimates of the overall $t\bar{t}$ production rates, it is believed that the LO determination of the event kinematics and of the fraction of W + multi-jet events containing b quarks is relatively accurate. In particular, for the background one expects the E_T spectrum of jets to fall rather steeply, the jet direction to peak at small angles to the beams, and the fraction of events with b quarks to be of the order of a few percent. On the contrary, for the top signal, the b fraction is $\sim 100\%$ and the jets are rather energetic, since they come from the decay of a massive object. It is therefore possible to improve the S/B ratio either by requiring the presence of a b quark, or by selecting very energetic and central kinematic configurations.

A detailed study of control samples with features similar to those of the relevant backgrounds, but free from possible top contamination, is required to provide a reliable check on background estimates.

C. Measured top properties: Current measurements of top properties are based on the full Run I integrated luminosity of 109 pb^{-1} for CDF and 125 pb^{-1} for DØ. DØ and CDF determine the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$ from their number of observed top candidates, estimated background, $t\bar{t}$ acceptance, and integrated luminosity, assuming the Standard-Model decay $t \to Wb$ with unity branching ratio. Table 1 shows the measured cross sections from DØ and CDF along with the range of theoretical expectations, evaluated at the m_t values used by the experiments in calculating their acceptances. The DØ values we quote [7] reflect the final analysis of the run I data, and are adjusted to the current DØ value of the top mass. The CDF results have been updated [16] to include improvements in their Monte Carlo determination of secondary-vertex tagging efficiency, calibration of the background estimate of the heavy-flavor fraction in inclusive W+jets events, and an updated total luminosity. This has brought the CDF cross section into better agreement with theoretical expectations. The agreement of both DØ and CDF $t\bar{t}$ cross sections with theory supports the hypothesis that the excess of events over background in all of these channels can be attributed to $t\bar{t}$ production.

Table 1: Cross section for $t\bar{t}$ production in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV from DØ ($m_t = 172.1$ GeV/c^2), CDF ($m_t = 175$ GeV/c^2), and theory.

$\sigma_{t\bar{t}}(pb)$	Source	Ref.	Method
2.8 ± 2.1	DØ	[6,7]	e + jets/topological
5.6 ± 3.7	DØ	[6,7]	μ + jets/topological
6.0 ± 3.6	DØ	[6,7]	e + jets/soft μ b-tag
11.3 ± 6.6	DØ	[6,7]	μ + jets/soft μ b-tag
5.1 ± 1.9	DØ	[6,7]	all ℓ + jets combined
6.0 ± 3.2	DØ	[6,7]	$\ell\ell$ + $e\nu$
7.3 ± 3.2	DØ	[7,8]	all jets
5.7 ± 1.6	DØ	[7,8]	all combined
$5.2 - 6.0$	Theory	[9–12]	$m_t = 172.1$ GeV/c^2
5.1 ± 1.5	CDF	[13,16]	ℓ + jets/vtx b-tag
9.2 ± 4.3	CDF	[13,16]	ℓ + jets/soft ℓ b-tag
$8.4^{+4.5}_{-3.5}$	CDF	[14,16]	$\ell\ell$
$7.6^{+3.5}_{-2.7}$	CDF	[15,16]	all jets
$6.5^{+1.7}_{-1.4}$	CDF	[16]	all combined
$4.75 - 5.5$	Theory	[9–12]	$m_t = 175$ GeV/c^2

More precise measurements of the top production cross section will test current understanding of the production mechanisms [9–12]. This is important for the extrapolation to higher energies of colliders such as the LHC, where the larger expected cross section will permit more extensive studies [17]. Discrepancies in rate between theory and data, even at the Tevatron, would be quite exciting, and might indicate the presence of exotic production or decay channels, as predicted in certain models. Such new sources of top would lead to a modification of kinematic distributions such as the invariant mass of the top pair or the transverse momentum of the top quark. Studies by CDF of the former [18] and of the latter [19] distributions, show no deviation from expected QCD behavior. DØ [20] also finds these kinematic distributions consistent with Standard Model expectations.

The top mass has been measured in the lepton + jets and dilepton channels by both DØ and CDF, and in the all-jets channel by CDF. At present, the most precise measurements come from the lepton + jets channel, with four or more jets and large missing E_T. In this channel, each event is subjected to a two-constraint kinematic fit to the hypothesis $t\overline{t} \rightarrow W^+ b\, W^- \overline{b} \rightarrow \ell\, \nu_\ell\, q\, \overline{q}'\, b\, \overline{b}$, assuming that the four highest E_T jets are the quarks from $t\overline{t}$ decay. The shape of the distribution of fitted top masses from these events is compared to templates expected from a mixture of background and signal distributions for a series of assumed top masses. This comparison yields values of the likelihood as a function of top mass, from which a best value of the top mass and its uncertainty can be obtained. 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.

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. In the dilepton channel, a kinematically constrained fit is not possible because there are two missing neutrinos, so experiments must use other mass estimators than the reconstructed top mass. In principle, any quantity which is correlated with the top mass can be used as such an estimator. The DØ method uses the fact that if a value for m_t is assumed, the $t\overline{t}$ system can be reconstructed (up to a four-fold ambiguity). They compare the resulting kinematic configurations to expectations from $t\bar{t}$ production, and obtain an m_t-dependent weight curve for each event, which they histogram in five bins to obtain four shape-sensitive quantities as their multidimensional mass estimator. This method yields a significant increase in precision over one-dimensional estimators. CDF has employed a similar method, thereby reducing their previous systematic uncertainty in the $\ell\ell$ + jets channel by a factor of two. DØ and CDF obtain the top mass and uncertainty from these mass estimators using the same type of template likelihood method as for the lepton + jets channel. CDF also measures the mass in the all-jets channel using events with six or more jets, at least one of which is tagged as a b jet through the detection of a secondary vertex.

Table 2: Top mass measurements from DØ and CDF.

m_t (GeV/c^2)	Source	Ref.	Method
$173.3 \pm 5.6 \pm 5.5$	DØ	[20]	ℓ + jets
$168.4 \pm 12.3 \pm 3.6$	DØ	[21]	$\ell\ell$
$172.1 \pm 5.2 \pm 4.9$	DØ	[20]	DØ comb.
$176.1 \pm 5.1 \pm 5.3$	CDF	[22–24]	ℓ + jet
$167.4 \pm 10.3 \pm 4.8$	CDF	[22]	$\ell\ell$
$186.0 \pm 10.0 \pm 5.7$	CDF	[15,22]	all jets
176.1 ± 6.6	CDF	[22,24]	CDF comb.
$174.3 \pm 3.2 \pm 4.0$ *	DØ & CDF	[25]	PDG best

* PDG uses this Top Averaging Group result as its best value. In spite of the new ℓ+jets CDF result [24], this average, given in Ref. 25, still applies within rounding errors.

As seen in Table 2, all results are in good agreement with a unique mass for the top quark, giving further support to the hypothesis that these events are due to $t\bar{t}$ production. The Top Averaging Group, a joint CDF/DØ working group, produced the combined CDF/DØ average top mass in Table 2, taking into account correlations between systematic uncertainties in different measurements. They assume that the uncertainty in jet energy scale is completely correlated within CDF and within DØ but uncorrelated between the two experiments, and that the signal model and Monte Carlo generator uncertainties are completely correlated between all measurements. The uncertainties from uranium noise and multiple interactions relate only to DØ and are assumed completely correlated between their two measurements. The uncertainty on the background model is taken to be completely correlated between the CDF and the DØ ℓ+jets measurements, and similarly for the $\ell\ell$ measurements. The Particle Data Group uses this combined top mass, $m_t = 174.3 \pm 5.1$ GeV/c^2 (statistical and systematic uncertainties combined in quadrature), as our PDG best value.

Given the experimental technique used to extract the top mass, these mass values should be taken as representing the top *pole mass* (see our review "Note on Quark Masses" in the current edition for more information).

With a smaller uncertainty on the top mass, and with improved measurements of other electroweak parameters, it will be possible to get important constraints on the value of the Higgs mass. Current global fits performed within the Standard Model and its minimal supersymmetric extension 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).

Other properties of top decays are being studied. CDF reports a direct measurement of the $t \to Wb$ branching ratio [26]. Their result, obtained by comparing the number of events with 0, 1 and 2 tagged b jets and using the known b-tagging efficiency, is: $R = \mathrm{B}(t \to Wb)/\sum_{q=d,s,b} \mathrm{B}(t \to Wq) = 0.94^{+0.31}_{-0.24}$, or as a lower limit, $R > 0.56$ at 95% CL. Assuming that non-W decays of top can be neglected, that only three generations of fermions exist, and that the CKM matrix is unitary, they extract a CKM matrix-element $|V_{tb}| = 0.97^{+0.16}_{-0.12}$ or $|V_{tb}| > 0.75$ at 95% CL. A more direct measurement of the Wtb coupling constant will be possible when enough data are accumulated to detect the less frequent single-top production processes, such as $q\overline{q}' \to W^* \to t\overline{b}$ (a.k.a. s-channel W exchange) and $qb \to q't$ via W exchange (a.k.a. Wg fusion). The cross sections for these processes are proportional to $|V_{tb}|^2$, and there is no assumption needed on the number of families or the unitarity of the CKM matrix in the extraction of $|V_{tb}|$. CDF [27] gives 95% CL limits of 15.8 and 15.4 pb for the single-top production rates in the s-channel and Wg-fusion channels, respectively, while DØ [28] gives 17 and 22 pb, respectively. Comparison with the expected Standard Model rates of 0.73 ± 0.10 pb and 1.70 ± 0.30 pb, respectively, shows that far better statistics will be required before significant measurements can be achieved. For the prospects of these measurements at the LHC, see [17].

Both CDF and DØ have searched for non-Standard Model top decays [29,30], particularly those expected in supersymmetric models. These studies search for $t \to H^+ b$, followed by $H^+ \to \tau\nu$ or $c\bar{s}$. The $t \to H^+ b$ branching ratio is 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 the dominant decay, while $H^+ \to \tau\nu$ 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, the 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 the Higgs decays. With a significant $t \to H^+ b$ contribution, this would give rise to measured cross sections lower than the prediction from the Standard Model (assuming that non-Standard contributions to $t\bar{t}$ production are negligible). More details, and the results of these studies, 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 reports a search for flavor changing neutral current (FCNC) decays of the top quark $t \to q\gamma$ and $t \to qZ$ [31], for which the Standard Model predicts such small rates that their observation here would indicate new physics. They assume that one top decays via FCNC while the other decays via Wb. For the $t \to q\gamma$ search, they examine two signatures, 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 γ plus four or more jets, one with a secondary vertex b tag. They observe one event ($\mu\gamma$) with an expected background of less than half an event, giving an upper limit on the top branching ratio of $\mathrm{B}(t \to q\gamma) < 3.2\%$ at 95% CL.

For the $t \to qZ$ FCNC search, they look for $Z \to \mu\mu$ or ee and $W \to$ hadrons, giving a Z + four jets signature. They observe one $\mu\mu$ event with an expected background of 1.2 events, giving an upper limit on the top branching ratio of $\mathrm{B}(t \to qZ) < 33\%$ at 95% CL. Both the γ and Z limits are non-background subtracted (i.e. conservative) estimates.

Indirect constraints on FCNC couplings of the top quark can be obtained from single-top production in e^+e^- collisions, via the process $e^+e^- \to \gamma, Z^* \to t\overline{q}$ and its charge-conjugate ($q = u, c$). Limits on the cross section for this reaction have been updated by ALEPH [32] and OPAL [33]. When interpreted in terms of top decay branching ratios [17,34], these limits lead to bounds of $\mathrm{B}(t \to qZ) < 0.17$ and < 0.137, respectively, which are stronger than the direct CDF limit.

Studies of the decay angular distributions allow a direct analysis of the V–A nature of the Wtb coupling, and provide information on the relative coupling of longitudinal and transverse W bosons to the top quark. In the Standard Model, the fraction of decays to longitudinally polarized W bosons is expected to be $\mathcal{F}_0^{\mathrm{SM}} = x/(1+x)$, $x = m_t^2/2M_W^2$ ($\mathcal{F}_0^{\mathrm{SM}} \sim 70\%$ for $m_t = 175$ GeV/c^2). Deviations from this value would bring into question the validity of the Higgs mechanism of spontaneous symmetry breaking. CDF has recently measured $\mathcal{F}_0^{\mathrm{SM}} = 0.91 \pm 0.37_{\mathrm{stat}} \pm 0.13_{\mathrm{syst}}$ [35], in agreement with the expectations.

DØ has studied $t\bar{t}$ spin correlation [36]. Top quark pairs produced at the Tevatron are expected to be unpolarized but to have correlated spins. Since top quarks decay before hadronizing, their spins are transmitted to their decay daughters. 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 charged leptons or d-type quarks, in which case, the joint distribution is

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

where θ_+ and θ_- are the angles of the daughters in the top rest frames with respect to a particular quantization axis, the optimal off-diagonal basis [37]. In this basis, the Standard Model predicts maximum correlation with $\kappa = 0.88$ at the Tevatron. DØ analyzes their six dilepton events and obtains a likelihood as a function of κ which weakly favors the Standard Model ($\kappa = 0.88$) over no correlation ($\kappa = 0$) or anticorrelation ($\kappa = -1$, as would be expected for $t\bar{t}$ produced via an intermediate scalar). They quote a limit $\kappa > -0.25$ at 68% CL. With improved statistics, an observation of $t\bar{t}$ spin correlation could yield a lower limit on $|V_{tb}|$, independent of the assumption of three quark families [38].

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