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 collects a summary of its currently measured properties, in addition to a discussion of the experimental and theoretical issues involved in the determination of its parameters (mass, production cross section, decay branching ratios, *etc.*) and some comments on of the prospects for future improvements.

B. Top quark production at the Tevatron: At the Tevatron energy, 1.8 TeV, top quarks are dominantly produced in pairs from pure QCD processes: $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. The production cross section through these channels is expected to be approximately 5 pb at $m_t = 175$ GeV/c^2, with a dominant 90% contribution from the $q\overline{q}$ annihilation process. Smaller contributions come from the single-top production mechanisms, namely $q\overline{q}' \to W^* \to t\overline{b}$ and $qg \to q' t\overline{b}$, this last mediated by a t-channel virtual-W exchange. The combined rate from these processes is approximately 2.5 pb at $m_t = 175$ GeV (see Ref. 1 and references therein). The actual contribution of these channels to the detected final states is further reduced relative to the dominant pair-production mechanisms, due to the lower experimental acceptances.

With a mass above the Wb threshold, the top quark decay width is dominated by the two-body decay $t \to Wb$. Neglecting terms of order m_b^2/m_t^2 and 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 values increase with mass, going for example from 1.02 GeV at $m_t =$ 160 GeV to 1.56 GeV at $m_t =$ 180 GeV (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 $t\bar{t}$-quarkonium bound states can form.

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 0.042 and 0.013, 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. $t\overline{t} \to W\,b\,W\,\overline{b} \to q\,\overline{q}'\,b\,q''\,\overline{q}'''\,\overline{b}$,

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

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

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

The final state quarks emit radiation and 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. 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 in detail below, the top quark production and decay properties extracted from the three different decay channels above are all consistent with each other, within the present experimental sensitivity. In particular, the $t \to Wb$ decay mode has been confirmed by the reconstruction of the $W \to jj$ invariant mass in the $\ell\overline{\nu}_\ell b\bar{b}jj$ final state [3].

The extraction of the top-quark properties from the Tevatron data requires a good understanding of the production and decay mechanisms of the top itself, as well as of the large background processes. The theoretical estimates of the physics backgrounds have large uncertainties, since only leading order QCD calculations are available for most of the relevant processes (W+3 and 4 jets, or WW+2 jets). While this limitation is known to affect the estimates of the overall production rates, it is believed that the LO determination of the event kinematics and of the fraction of W plus multi-jet events containing b quarks is rather accurate. In particular, one expects the E_T spectrum of these jets to fall rather steeply, the jet direction to point preferentially at small angles from the beams, and the fraction of events with b quarks to be of the order of few percent. In the case of the top signal, *vice versa*, 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 by either requiring the presence of a b quark, or by selecting very energetic and central kinematical 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 the background estimates.

C. Measured top properties: 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. Since the first direct experimental evidence for the top quark in 1994 [4] by CDF (a 2.8 σ effect. See this review in our 1996 edition [5] for more details) and the conclusive observation by both CDF and DØ in 1995 [6,7], the integrated luminosity has increased to 109 pb^{-1} for CDF and 125 pb^{-1} for DØ, allowing significant improvements in the measurement of the top production cross section, mass, and decay properties.

DØ and CDF determine the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$ from their numbers of top candidates, their estimated background, their $t\bar{t}$ acceptance, and their integrated luminosity, assuming Standard Model decays $t \to Wb$ 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.

There is fairly good agreement between the experiments and the theoretical expectations, although the CDF values are somewhat higher than the theory values. The agreement between the determinations in the lepton + jets, dileptons, and all-jets channels supports the hypothesis that the excess of events in all of these channels is due to $t\bar{t}$ production.

Future precise determinations of the top production cross section will test the current theoretical understanding of the production mechanisms [8–11]. A precise understanding of top production at the Tevatron is important for the extrapolation to the higher energies of future colliders, like the LHC, where the expected large cross section will enable more extensive studies. Discrepancies in rate between theory and data, on the other hand, would be more exciting and might indicate the presence of exotic production channels, as predicted in some models. In this case, one should also expect a modification of kinematical distributions such as the invariant mass of the top pair or the top quark transverse momentum.

Table 1: Cross section for $t\bar{t}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV from DØ ($m_t = 173.3$ GeV/c^2), CDF ($m_t = 175$ GeV/c^2), and theory.

$t\bar{t}$ cross section	Source	Ref.	Method
4.1 ± 2.0 pb	DØ	[12]	lepton + jets
8.2 ± 3.5 pb	DØ	[12]	lepton + jets/μ
6.3 ± 3.3 pb	DØ	[12]	dileptons + $e\nu$
5.5 ± 1.8 pb	DØ	[12]	Ref. 12 combined
$5.0 - 5.8$ pb	Theory	[8–11]	at $m_t = 173.3$ GeV/c^2
$6.7^{+2.0}_{-1.7}$ pb †	CDF	[13]	lepton + jet
$8.2^{+4.4}_{-3.4}$ pb †	CDF	[14]	dileptons
$10.1^{+4.5}_{-3.6}$ pb	CDF	[15]	all jets
$7.6^{+1.8}_{-1.5}$ pb †	CDF	[13]	Refs. 13–15 combined
$4.75 - 5.5$ pb	Theory	[8–11]	at $m_t = 175$ GeV/c^2

† submitted

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 $t\overline{t}$ daughters. 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 error are obtained. The results are shown in Table 2. The systematic error, the second error shown, is comparable to the statistical error and is primarily due to uncertainties in the jet energy scale and 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. Any quantity which is correlated with top mass can be used as a mass estimator. DØ uses the fact that if 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 $t\overline{t}$ production and obtain a weight *vs* m_t curve for each event, which they coarsly histogram to obtain four shape-sensitive quantities as their multidimensional mass estimator. Their method yields a significant increase in precision over one-dimensional estimators. CDF does two analyses, one using the b quark jet energy and the other using the $\ell\, b$-jet invariant mass. Both DØ and CDF obtain the top mass and error from these mass estimators using the same 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 by the presence of a secondary vertex.

Table 2: Top mass measurements from DØ and CDF.

m_t (GeV/c^2)	Source	Ref.	Method
$173.3 \pm 5.6 \pm 6.2$	DØ	[16]	lepton + jets
$168.4 \pm 12.3 \pm 3.7$ †	DØ	[17]	dileptons
$172.0 \pm 5.1 \pm 5.5$ †	DØ	[17]	Refs. 16–17 combined
$175.9 \pm 4.8 \pm 4.9$ †	CDF	[18]	lepton + jet
$161 \pm 17 \pm 10$ †	CDF	[14]	dileptons
$186 \pm 10 \pm 12$	CDF	[15]	all jets
$174.1 \pm 3.5 \pm 4.1$	PDG		Refs. 16–18 combined

† submitted

As seen in Table 2, all top mass results are in good agreement, giving further support to the hypothesis that these events are due to $t\bar{t}$ production. The mass values in Table 2 cannot be averaged without taking into account correlations in the systematic errors. A joint CDF/DØ working group is expected to produce a combined CDF/DØ top mass in the near future, taking into account these correlations. In the meantime, the PDG obtains a combined mass value as follows. Using DØ's approach to combining their own results [17], we assume a 100% correlation between their lepton + jets and dilepton systematic errors for jet energy scale, signal model, uranium noise, and multiple interactions, and no correlation between other errors, systematic or statistical. CDF has not combined its results, but we can include their strongest result, the lepton + jets result [18], by assuming 100% correlation between CDF's signal model and those of the two DØ results, 100% correlation between the background shapes for the CDF and DØ lepton + jets results, and no other correlations between the CDF and DØ results. This gives a PDG best estimate of the top mass of $m_t = 174.1 \pm 3.5 \pm 4.1$ GeV/c^2 = 174.1 ± 5.4 GeV/c^2.

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

The extraction of the value of the top mass from the analyses described requires, in addition to an understanding of the absolute energy calibration and resolution of the detectors, also an *a priori* knowledge of the structure of the final state. Given the hardness of a $t\bar{t}$ production process, jets can in fact arise not only from the top decays, but also from the initial state gluon radiation. Furthermore, quarks from the top decays can radiate additional jets. The presence of these additional jets will affect the shape of the mass spectrum, depending on the details of how the samples used for the mass determination were defined. QCD calculations used to model top production and decay are expected to be rather reliable, but residual uncertainties remain and are accounted for in the overall systematic error on the top mass. The larger samples that will become available in the future will allow more strict selection criteria, leading to purer samples of top quarks. For example, requesting the presence of two secondary-vertex b tags in the event, in addition to two and only two central jets of high-E_T, should largely reduce the possibility of erroneously including jets not coming from the top decays into the mass reconstruction. This will significantly improve the mass resolution and will make it less sensitive to the theoretical uncertainties. With a smaller error on the top mass, and with yet improved measurements of the 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 "H^0 Indirect Mass Limits from Electroweak Analysis" in the Particle Listings of the current edition), possibly within the range of the upcoming LEP2 experiments.

Measurements of other properties of top decays are underway. CDF reports a direct measurement of the $t \to Wb$ branching ratio [19]. Their preliminary result, obtained by comparing the number of events with 0, 1 and 2 tagged b jets and using the known tagging efficiency, is: $R = \mathrm{B}(t \to Wb)/\sum_{q=d,s,b}\mathrm{B}(t \to Wq) = 0.99 \pm 0.29$ where the error includes statistical and systematic uncertainties, or as a lower limit, $R > 0.58$ at 95% CL. Assuming that non-W decays of top can be neglected, that only three generations exist, and assuming the unitarity of the CKM matrix, they extract a CKM matrix-element $|V_{tb}| = 0.99 \pm 0.15$ or $|V_{tb}| > 0.76$ at 95% CL. A more direct measurement of the Wtb coupling constant will be possible when enough data has been accumulated to detect the less frequent single-top production processes, such as $q\bar{q}' \to W^* \to t\bar{b}$ and $qb \to q't$ via W exchange. The cross-sections for these processes are proportional to $|V_{tb}|^2$, and no assumption on the number of families or the unitarity of the CKM matrix needs to be made to extract $|V_{tb}|$.

Both CDF and DØ set limits on the non-Standard Model decay of top to a charged Higgs and a b quark, excluding regions of the m_{H^+} *vs* $\tan\beta$ plane, where $\tan\beta$ is the ratio of the vacuum expectation values for the two Higgs doublets. CDF [20] considers only the region of large $\tan\beta$ where H^+ decays dominantly to $\tau\nu_\tau$. They search for events with one or two τ's decaying to hadrons. As $\tan\beta$ increases, the $t \to H^+b$ and $H^+ \to \tau\nu_\tau$ branching fractions are both expected to approach one, maximizing sensitivity to this mode. CDF sees no excess of events over the expected background, giving an exclusion region in the m_{H^+} *vs* $\tan\beta$ plane with (reading from their Fig. 3) $m_{H^+} > 146$, 140 and 44 GeV/c^2 for $\tan\beta = 500$, 200, and 100 respectively, assuming $m_t = 175$ GeV/c^2 and $\sigma_{t\bar{t}} = 5.0$ pb.

DØ [21] looks for top disappearance via $t \to H^+b$, $H^+ \to \tau\nu$ or $c\bar{s}$. These charged Higgs decays would not be detected in the DØ lepton + jets cross section analysis as efficiently as $t \to W^{\pm}b$, primarily because of the absence of energetic isolated leptons in the Higgs decays. This would give rise to a measured cross section lower than the Standard Model prediction, assuming that non-Standard Model $t\bar{t}$ production is negligible. The H^+ is expected to decay to $\tau\nu$ at high $\tan\beta$ and to $c\bar{s}$ at low $\tan\beta$, leading to disagreement with the observed cross section and giving rise to exclusion regions at both low and high $\tan\beta$. Taking $m_t = 175$ GeV/c^2 and $\sigma_{tt} = 5.53$ pb, DØ obtains the preliminary limits $m_{H+} > 168$ GeV/c^2 at 95% CL for $\tan\beta > 96$ or $\tan\beta < 0.26$. Moving toward intermediate $\tan\beta$ values, the mass limit weakens until it falls below the 44 GeV/c^2 LEP lower limit for $0.96 < \tan\beta < 35$.

More extensive searches for charged Higgs bosons in top decays, as well as for other possible new particles such as a supersymmetric scalar top quark ($\tilde{t}$) via $t \to \tilde{t}\,\widetilde{\chi}^0$, are under way both at CDF and DØ.

CDF reports a search for flavor changing neutral current (FCNC) decays of the top quark $t \to q\gamma$ and $t \to qZ$ [22], 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 search for two signatures, depending on whether the W decays leptonically or hadronically. For leptonic W decay, the signature is $\gamma\ell$ plus 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 B$(t \to q\gamma) < 3.2\%$ at 95% CL.

For the $t \to qZ$ FCNC search, the they look for $Z \to \mu\mu$ or ee and $W \to$ hadrons, giving a Z plus four jet 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 B$(t \to qZ) < 33\%$ at 95% CL. Both the γ and Z limits are non-background subtracted (i.e. conservative) estimates.

Studies of the decay angular distributions are also in progress using the current data sets. They will allow a first direct analysis of the $V - A$ nature of the Wtb coupling, as well as providing direct information on the relative coupling of longitudinal and transverse W bosons to the top. In the Standard Model, the fraction of decays to transversely polarized W bosons is expected to be $1/(1 + m_t^2/2M_W^2)$ (30% for $m_t = 175$ GeV. Deviations from this value would challenge the Higgs mechanism of spontaneous symmetry breaking.

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