**t**

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

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

# THE TOP QUARK

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***A. Introduction:*** The top quark is the $Q = 2/3$, $T_3 = +1/2$ member of the weak-isospin doublet containing the bottom quark (see 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. The first observations and studies have been performed during the so-called run I, at $\sqrt{s} = 1.8$ TeV, completed in 1996. Most of the results in this note refer to analyses of these data. A new period of data-taking, the run II, started in 2001 at $\sqrt{s} = 1.96$ TeV. All analyses from run II are still only preliminary and yet unpublished [1]. The main body of this note will therefore only quote results relative to the run I data, with some highlights of current run II results included in an Appendix.

In hadron collisions, 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 1.8 TeV (1.96 TeV), the production cross section [2] in these channels is expected to be approximately 5 pb (6.5 pb) for $m_t = 175$ GeV/$c^2$, with a 90% (85%) 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 of these processes at 1.8 TeV is approximately 2.5 pb at $m_t = 175$ GeV/$c^2$ (see Ref. 3 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 $m_b^2/m_t^2$, $\alpha_s^2$ and those of order $(\alpha_s/\pi)m_W^2/m_t^2$, this is predicted in the Standard Model to be [4]:

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

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 [5]. The order $\alpha_s^2$ QCD corrections to $\Gamma_t$ have also been calculated [6], 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 0.043 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. $t\overline{t} \to W\,b\,W\,\overline{b} \to q\,\overline{q}'\,b\,q''\,\overline{q}'''\,\overline{b}$,

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. While $\ell$ in the above processes refers to $e$, $\mu$, or $\tau$, throughout the rest of this article, the meaning of $\ell$ is restricted to an observed $e$ or $\mu$.

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 $t \to Wb$ decay mode is supported through the reconstruction of the $W \to jj$ invariant mass in the $\ell\nu_\ell b\overline{b}jj$ final state [7].

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 based on the run I data use an 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 [9] reflect the final analysis of the run I data, and are adjusted to the current DØ value of the top mass. 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 $p\bar{p}$ 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 |
|---|---|---|---|
| $2.8 \pm 2.1$ | DØ | [8,9] | $e$ + jets/topological |
| $5.6 \pm 3.7$ | DØ | [8,9] | $\mu$ + jets/topological |
| $6.0 \pm 3.6$ | DØ | [8,9] | $e$ + jets/soft $\mu$ $b$-tag |
| $11.3 \pm 6.6$ | DØ | [8,9] | $\mu$ + jets/soft $\mu$ $b$-tag |
| $5.1 \pm 1.9$ | DØ | [8,9] | all $\ell$ + jets combined |
| $6.0 \pm 3.2$ | DØ | [8,9] | $\ell\ell + e\nu$ |
| $7.3 \pm 3.2$ | DØ | [9,10] | all jets |
| $5.7 \pm 1.6$ | DØ | [9,10] | all combined |
| $5.2 - 6.2$ | Theory | [2] | $m_t = 172.1$ GeV/$c^2$ |
| $5.1 \pm 1.5$ | CDF | [11,14] | $\ell$ + jets/vtx $b$-tag |
| $9.2 \pm 4.3$ | CDF | [11,14] | $\ell$ + jets/soft $\ell$ $b$-tag |
| $8.4^{+4.5}_{-3.5}$ | CDF | [12,14] | $\ell\ell$ |
| $7.6^{+3.5}_{-2.7}$ | CDF | [13,14] | all jets |
| $6.5^{+1.7}_{-1.4}$ | CDF | [14] | all combined |
| $4.5 - 5.7$ | Theory | [2] | $m_t = 175$ GeV/$c^2$ |

More precise measurements of the top production cross section will test current understanding of the production mechanisms.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 [15]. The results of preliminary analyses of the run II data are given in the Appendix: the current statistical and systematic uncertainties are still too large to draw any conclusion. With the expected improvements once larger samples have been collected, discrepancies in rate between theory and data 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 [16] and of the latter [17] distributions, show no deviation from expected QCD behavior. DØ [18] 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 $t\bar{t}$ 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.

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

**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 | [18] | $\ell$ + jets |
| $(180.1 \pm 3.6 \pm 4.0)$ † | DØ | [19] | $\ell$ + jets |
| $168.4 \pm 12.3 \pm 3.6$ | DØ | [20] | $\ell\ell$ |
| $172.1 \pm 5.2 \pm 4.9$ | DØ | [18] | DØ comb. |
| $176.1 \pm 5.1 \pm 5.3$ | CDF | [21–23] | $\ell$ + jets |
| $167.4 \pm 10.3 \pm 4.8$ | CDF | [21] | $\ell\ell$ |
| $186.0 \pm 10.0 \pm 5.7$ | CDF | [13,21] | all jets |
| $176.1 \pm 6.6$ | CDF | [21,23] | CDF comb. |
| $174.3 \pm 3.2 \pm 4.0$ * | DØ & CDF | [24] | PDG best |

† DØ finds a significantly improved preliminary result for the mass, using the same data as for the Ref. 18 result, but analyzed using a method similar to that of their dilepton analysis. This value is not used in the "DØ combined" mass of 172.1 GeV/$c^2$, nor in the "PDG best" (DØ & CDF combined) mass.

* PDG uses this Top Averaging Group result as its best value. In spite of the new $\ell$+jets CDF result [23], this average, given in Ref. 24, still applies within rounding errors.

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 $\ell$+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 [25]. 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 [26] 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 [27] gives 17 and 22 pb, respectively. Comparison with the expected Standard Model rates of $0.73 \pm 0.10$ pb and $1.70 \pm 0.30$ 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 [15].

Both CDF and DØ have searched for non-Standard Model top decays [28,29], particularly those expected in supersymmetric models. These studies search for $t \to H^+ b$, followed by $H^+ \to \tau\nu$ or $c\overline{s}$. 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 $H^+ \to c\overline{s}$ 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 $t\overline{t}$ 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 $t \to qZ$ [30], 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 $\gamma$ 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 $\gamma$ 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 [31] and OPAL [32]. When interpreted in terms of top decay branching ratios [15,33], 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 $\mathcal{F}_0^{\rm SM} = x/(1+x)$, $x = m_t^2/2M_W^2$ ($\mathcal{F}_0^{\rm SM} \sim 70\%$ for $m_t = 175$ GeV/$c^2$). Deviations from this value would bring into question the validity of the Higgs mechanism of spontaneous symmetry breaking. CDF has recently measured $\mathcal{F}_0^{\rm SM} = 0.91 \pm 0.37_{\rm stat} \pm 0.13_{\rm syst}$ [34], in agreement with the expectations.

DØ has studied $t\bar{t}$ spin correlation [35]. 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 $\theta_+$ and $\theta_-$ are the angles of the daughters in the top rest frames with respect to a particular quantization axis, the optimal off-diagonal basis [36]. 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 $\kappa$ 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 [37].

***Appendix. First Results from run II:*** Preliminary measurements of the top properties determined from run II data

have been reported at several Conferences [1]. First results for the top mass have been shown by CDF. In the lepton plus four jets channel with at least one secondary vertex $b$-tagged jet CDF obtains a value of $m_t = 177.5^{+12.7}_{-9.4}(stat) \pm 7.1(syst)\,\mathrm{GeV/c^2}$ (22 candidate events). In the dilepton channel, CDF found a preliminary value of $m_t = 175.0^{+17.4}_{-16.9}(stat) \pm 7.9(syst)\,\mathrm{GeV/c^2}$ (6 candidate events). Results for the production cross-section have been given by both experiments, and are collected in Table Table 3. The uncertainties are still rather large when compared to those achieved in run I, and the rates are consistent both with the measurements at lower energy, and with the theoretical predictions [2].

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**Table 3:** Cross section for $t\bar{t}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV from DØ ($m_t = 172.1$ GeV/$c^2$), CDF ($m_t = 175$ GeV/$c^2$), and theory. CSIP refers to a "counted signed-impact-parameter" determination of secondary vertices. The first uncertainty is statistical, the second systematical, and the third uncertainty quoted by DØ reflects the luminosity uncertainty (included in CDF's systematics). Luminosities quoted in pb$^{-1}$.

| $\sigma_{t\bar{t}}(pb)$ | Source | Lum. | Method |
|---|---|---|---|
| $8.7\ ^{+6.4}_{-4.7}\ ^{+2.7}_{-2.0} \pm 0.9$ | DØ | 90–107 | $\ell\ell$ |
| $7.4\ ^{+4.4}_{-3.6}\ ^{+2.1}_{-1.6} \pm 0.7$ | DØ | 45 | $\ell$+jets, CSIP |
| $10.8\ ^{+4.9}_{-4.0}\ ^{+2.1}_{-2.0} \pm 1.1$ | DØ | 45 | $\ell$+jets/vtx $b$-tag |
| $4.6\ ^{+3.1}_{-2.7}\ ^{+2.1}_{-2.0} \pm 0.5$ | DØ | 92 | $\ell$+jets/topological |
| $11.4\ ^{+4.1}_{-3.5}\ ^{+2.0}_{-1.8} \pm 1.1$ | DØ | 92 | $\ell$+jets/soft $\mu$ $b$-tag |
| $8.0\ ^{+2.4}_{-2.1}\ ^{+1.7}_{-1.5} \pm 0.8$ | DØ | 92 | $\ell$+jets combined |
| $8.1\ ^{+2.2}_{-2.0}\ ^{+1.6}_{-1.4} \pm 0.8$ | DØ | 90–107 | Dilepton and $\ell$+jets combined |
| $7.6\ ^{+3.8}_{-3.1}\ ^{+1.5}_{-1.9}$ | CDF | 126 | $\ell\ell$ |
| $7.3 \pm 3.4 \pm 1.7$ | CDF | 126 | $\ell$+track |
| $5.3 \pm 1.9 \pm 0.9$ | CDF | 57 | $\ell$+jets/vtx $b$-tag |
| $5.1 \pm 1.8 \pm 2.1$ | CDF | 126 | $\ell$+jets/$H_T$ |
| $5.8 - 7.4$ | Theory [2] | | $m_t = 175$ GeV/$c^2$ |


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

The $t$ quark has been observed. Its mass is sufficiently high that decay is expected to occur before hadronization. OUR EVALUATION is an AVERAGE which incorporates correlations between systematic errors of the five different measurements. The average was done by a joint CDF/DØ working group and is reported in DEMORTIER 99, an FNAL Technical Memo. They report $174.3 \pm 3.2 \pm 4.0$ GeV, which yields "OUR EVALUATION" when statistical and systematic errors are combined. When the most recent CDF lepton + jets result is combined with the other CDF and DØ results, the combined result given as "OUR EVALUATION" is unchanged from the DEMORTIER 99 result after rounding.

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

| *VALUE* (GeV) | | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **174.3± 5.1 OUR EVALUATION** | | | | | |
| 176.1± 5.1± 5.3 | [1] | AFFOLDER | 01 | CDF | lepton + jets |
| 167.4±10.3± 4.8 | [2,3] | ABE | 99B | CDF | dilepton |
| 168.4±12.3± 3.6 | [4] | ABBOTT | 98D | D0 | dilepton |
| 173.3± 5.6± 5.5 | [4] | ABBOTT | 98F | D0 | lepton + jets |
| 186 ±10 ± 5.7 | [2,5] | ABE | 97R | CDF | 6 or more jets |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 176.1± 6.6 | [6] | AFFOLDER | 01 | CDF | lepton + jets, dileptons, all-jets |
| 172.1± 5.2± 4.9 | [7] | ABBOTT | 99G | D0 | di-lepton, lepton+jets |
| 176.0± 6.5 | [3,8] | ABE | 99B | CDF | dilepton, lepton+jets, and all jets |
| 175.9± 4.8± 5.3 | [2,9] | ABE | 98E | CDF | lepton + jets |
| 161 ±17 ±10 | [2] | ABE | 98F | CDF | dilepton |
| 172.1± 5.2± 4.9 | [10] | BHAT | 98B | RVUE | dilepton and lepton+jets |
| 173.8± 5.0 | [11] | BHAT | 98B | RVUE | dilepton, lepton+jets, and all jets |
| 173.3± 5.6± 6.2 | [4] | ABACHI | 97E | D0 | lepton + jets |
| $199 \; ^{+19}_{-21} \; \pm 22$ | | ABACHI | 95 | D0 | lepton + jets |
| 176 ± 8 ±10 | | ABE | 95F | CDF | lepton + $b$-jet |
| $174 \; \pm 10 \; ^{+13}_{-12}$ | | ABE | 94E | CDF | lepton + $b$-jet |

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

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

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

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

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

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

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

[8] ABE 99B result is obtained by combining the CDF results of $m_t$ (GeV)=$167.4 \pm 10.3 \pm 4.8$ from 8 dilepton events, $m_t$ (GeV)=$175.9 \pm 4.8 \pm 5.3$ from lepton+jet events (ABE 98E),

and $m_t$ (GeV)=186.0 ± 10.0 ± 5.7 from all-jet events (ABE 97R). The systematic errors in the latter two measurements are changed in this paper.

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

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

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

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

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

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

| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$178.1^{+10.4}_{-8.3}$ OUR EVALUATION** | | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $162 \pm 15 \; ^{+25}_{-5}$ | [12] ABBIENDI | 01A | OPAL | $Z$ parameters |
| $170.7 \pm 3.8$ | [13] FIELD | 00 | RVUE | $Z$ parameters without $b$-jet + Direct |
| $171.2^{+3.7}_{-3.8}$ | [14] FIELD | 99 | RVUE | $Z$ parameters without $b$jet + Direct |
| $172.0^{+5.8}_{-5.7}$ | [15] DEBOER | 97B | RVUE | Electroweak + Direct |
| $157 \; ^{+16}_{-12}$ | [16] ELLIS | 96C | RVUE | $Z$ parameters, $m_W$, low energy |
| $175 \pm 11 \; ^{+17}_{-19}$ | [17] ERLER | 95 | RVUE | $Z$ parameters, $m_W$, low energy |
| $180 \pm 9^{+19}_{-21} \mp 2.6 \pm 4.8$ | [18] MATSUMOTO | 95 | RVUE | |
| $157 \; ^{+36}_{-48} \; ^{+19}_{-20}$ | [19] ABREU | 94 | DLPH | $Z$ parameters |
| $158 \; ^{+32}_{-40} \pm 19$ | [20] ACCIARRI | 94 | L3 | $Z$ parameters |
| $190 \; ^{+39}_{-48} \; ^{+12}_{-14}$ | [21] ARROYO | 94 | CCFR | $\nu_\mu$ iron scattering |
| $184 \; ^{+25}_{-29} \; ^{+17}_{-18}$ | [22] BUSKULIC | 94 | ALEP | $Z$ parameters |
| $153 \pm 15$ | [23] ELLIS | 94B | RVUE | Electroweak |
| $177 \pm 9 \; ^{+16}_{-20}$ | [24] GURTU | 94 | RVUE | Electroweak |
| $174 \; ^{+11}_{-13} \; ^{+17}_{-18}$ | [25] MONTAGNA | 94 | RVUE | Electroweak |
| $171 \pm 12 \; ^{+15}_{-21}$ | [26] NOVIKOV | 94B | RVUE | Electroweak |
| $160 \; ^{+50}_{-60}$ | [27] ALITTI | 92B | UA2 | $m_W$, $m_Z$ |

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## $t$ DECAY MODES

| | Mode | | Fraction ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|---|
| $\Gamma_1$ | $W\,q(q = b, s, d)$ | | | |
| $\Gamma_2$ | $W\,b$ | | | |
| $\Gamma_3$ | $\ell\,\nu_\ell$ anything | | [a,b] $(9.4 \pm 2.4)$ % | |
| $\Gamma_4$ | $\tau\,\nu_\tau\,b$ | | | |
| $\Gamma_5$ | $\gamma\,q(q{=}u,c)$ | | [c] $< 5.9 \times 10^{-3}$ | 95% |
| | **$\Delta T = 1$ weak neutral current ($T1$) modes** | | | |
| $\Gamma_6$ | $Z\,q(q{=}u,c)$ | $T1$ | [d] $< 13.7$ % | 95% |

[a] $\ell$ means $e$ or $\mu$ decay mode, not the sum over them.

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

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

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

## $t$ BRANCHING RATIOS

### $\Gamma(W\,b)/\Gamma(W\,q(q = b, s, d))$ — $\Gamma_2/\Gamma_1$

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| $0.94^{+0.26}_{-0.21}{}^{+0.17}_{-0.12}$ | [28] AFFOLDER | 01C | CDF |

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

### $\Gamma(\ell\,\nu_\ell\,\text{anything})/\Gamma_{\text{total}}$ — $\Gamma_3/\Gamma$

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| $0.094 \pm 0.024$ | [29] ABE | 98X | CDF |

[29] $\ell$ means $e$ or $\mu$ decay mode, not the sum. Assumes lepton universality and $W$-decay acceptance.

### $\Gamma(\tau\,\nu_\tau\,b)/\Gamma_{\text{total}}$ — $\Gamma_4/\Gamma$

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [30] ABE | 97V | CDF | $\ell\tau$ + jets |

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

## $\Gamma(\gamma q(q=u,c))/\Gamma_{total}$ — $\Gamma_5/\Gamma$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<0.0059** | 95 | [31] CHEKANOV | 03 | ZEUS | $B(t \to \gamma u)$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <0.041 | 95 | [32] ACHARD | 02J | L3 | $B(t \to \gamma c$ or $\gamma u)$ |
| <0.032 | 95 | [33] ABE | 98G | CDF | $t\bar{t} \to (W b)(\gamma c$ or $\gamma u)$ |

[31] CHEKANOV 03 looked for single top production via FCNC in the reaction $e^{\pm} p \to e^{\pm}$ ($t$ or $\bar{t}$) X in 130.1 pb$^{-1}$ of data at $\sqrt{s}$=300–318 GeV. No evidence for top production and its decay into $b W$ was found. The result is obtained for $m_t$=175 GeV when $B(\gamma c)=B(Z q)=0$, where $q$ is a $u$ or $c$ quark. Bounds on the effective $t$-$u$-$\gamma$ and $t$-$u$-$Z$ couplings are found in their Fig. 4. The conversion to the constraint listed is from private communication, E. Gallo, January 2004.

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

[33] ABE 98G looked for $t\bar{t}$ events where one $t$ decays into $q\gamma$ while the other decays into $b W$. The quoted bound is for $\Gamma(\gamma q)/\Gamma(W b)$.

## $\Gamma(Z q(q=u,c))/\Gamma_{total}$ — $\Gamma_6/\Gamma$

Test for $\Delta T$=1 weak neutral current. Allowed by higher-order electroweak interaction.

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| <0.137 | 95 | [34] ACHARD | 02J | L3 | $e^+ e^- \to \bar{t} c$ or $\bar{t} u$ |
| <0.14 | 95 | [35] HEISTER | 02Q | ALEP | $e^+ e^- \to \bar{t} c$ or $\bar{t} u$ |
| **<0.137** | 95 | [36] ABBIENDI | 01T | OPAL | $e^+ e^- \to \bar{t} c$ or $\bar{t} u$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <0.17 | 95 | [37] BARATE | 00S | ALEP | $e^+ e^- \to \bar{t} c$ or $\bar{t} u$ |
| <0.33 | 95 | [38] ABE | 98G | CDF | $t\bar{t} \to (W b)(Z c$ or $Z u)$ |

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

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

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

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

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

## *t* Decay Vertices

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $0.91 \pm 0.37 \pm 0.13$ | [39] AFFOLDER | 00B | CDF | $F_0 = W_L/(W_L + W_T)$ |
| $0.11 \pm 0.15$ | [39] AFFOLDER | 00B | CDF | $B(t \rightarrow W_+ b)$ |

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

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

Direct probes of the $t\,b\,W$ coupling and possible new physics

| VALUE (pb) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <18 | 95 | [40] ACOSTA | 02 | CDF | $p\overline{p} \rightarrow t\,b + X$ |
| <13 | 95 | [41] ACOSTA | 02 | CDF | $p\overline{p} \rightarrow t\,q\,b + X$ |
| <17 | 95 | [42,43] ABAZOV | 01C | D0 | $p\overline{p} \rightarrow t\,b + X$ |
| <22 | 95 | [43,44] ABAZOV | 01C | D0 | $p\overline{p} \rightarrow t\,q\,b + X$ |
| <39 | 95 | [42] ABBOTT | 01B | D0 | $p\overline{p} \rightarrow t\,b + X$ |
| <58 | 95 | [44] ABBOTT | 01B | D0 | $p\overline{p} \rightarrow t\,q\,b + X$ |

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

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

[42] Result bounds the cross section for single top-quark production via the $s$-channel process $q'\overline{q} \rightarrow W' \rightarrow t\,b$. It is based on $\sim 90\ \mathrm{pb}^{-1}$ of data at $\sqrt{s}$= 1.8 TeV.

[43] ABAZOV 01C results updates those of ABBOTT 01B by making use of arrays of neural networks to separate signals from backgrounds.

[44] Result bounds the cross section for single top-quark production via the $t$-channel $W$-exchange process $q'g \rightarrow q\,t\,b$. It is based on $\sim 90\ \mathrm{pb}^{-1}$ of data at $\sqrt{s}$= 1.8 TeV.

## *t*-Quark REFERENCES


| | | | | |
|---|---|---|---|---|
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| ACOSTA | 02 | PR D65 091102 | D. Acosta *et al.* | (CDF Collab.) |
| HEISTER | 02Q | PL B543 173 | A. Heister *et al.* | (ALEPH Collab.) |
| ABAZOV | 01C | PL B517 282 | V.M. Abazov *et al.* | (D0 Collab.) |
| ABBIENDI | 01A | EPJ C19 587 | G. Abbiendi *et al.* | (OPAL Collab.) |
| ABBIENDI | 01T | PL B521 181 | G. Abbiendi *et al.* | (OPAL Collab.) |
| ABBOTT | 01B | PR D63 031101 | B. Abbott *et al.* | (D0 Collab.) |
| AFFOLDER | 01 | PR D63 032003 | T. Affolder *et al.* | (CDF Collab.) |
| AFFOLDER | 01C | PRL 86 3233 | T. Affolder *et al.* | (CDF Collab.) |
| AFFOLDER | 00B | PRL 84 216 | T. Affolder *et al.* | (CDF Collab.) |
| BARATE | 00S | PL B494 33 | S. Barate *et al.* | (ALEPH Collab.) |
| FIELD | 00 | PR D61 013010 | J.H. Field | |
| ABBOTT | 99G | PR D60 052001 | B. Abbott *et al.* | (D0 Collab.) |
| ABE | 99B | PRL 82 271 | F. Abe *et al.* | (CDF Collab.) |
| Also | 99G | PRL 82 2808 (erratum) | F. Abe *et al.* | (CDF Collab.) |

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|---|---|---|---|---|
| DEMORTIER | 99 | FNAL-TM-2084 | L. Demortier *et al.* | (CDF/D0 Working Group) |
| FIELD | 99 | MPL A14 1815 | J.H. Field | |
| ABBOTT | 98D | PRL 80 2063 | B. Abbott *et al.* | (D0 Collab.) |
| ABBOTT | 98F | PR D58 052001 | B. Abbott *et al.* | (D0 Collab.) |
| ABE | 98E | PRL 80 2767 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 98F | PRL 80 2779 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 98G | PRL 80 2525 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 98X | PRL 80 2773 | F. Abe *et al.* | (CDF Collab.) |
| BHAT | 98B | IJMP A13 5113 | P.C. Bhat, H.B. Prosper, S.S. Snyder | |
| ABACHI | 97E | PRL 79 1197 | S. Abachi *et al.* | (D0 Collab.) |
| ABE | 97R | PRL 79 1992 | F. Abe *et al.* | (CDF Collab.) |
| ABE | 97V | PRL 79 3585 | F. Abe *et al.* | (CDF Collab.) |
| DEBOER | 97B | ZPHY C75 627 | W. de Boer *et al.* | |
| ELLIS | 96C | PL B389 321 | J. Ellis, G.L. Fogli, E. Lisi | (CERN, BARI) |
| ABACHI | 95 | PRL 74 2632 | S. Abachi *et al.* | (D0 Collab.) |
| ABE | 95F | PRL 74 2626 | F. Abe *et al.* | (CDF Collab.) |
| ERLER | 95 | PR D52 441 | J. Erler, P. Langacker | (PENN) |
| MATSUMOTO | 95 | MPL A10 2553 | S. Matsumoto | (KEK) |
| ABE | 94E | PR D50 2966 | F. Abe *et al.* | (CDF Collab.) |
| Also | 94F | PRL 73 225 | F. Abe *et al.* | (CDF Collab.) |
| ABREU | 94 | NP B418 403 | P. Abreu *et al.* | (DELPHI Collab.) |
| ACCIARRI | 94 | ZPHY C62 551 | M. Acciarri *et al.* | (L3 Collab.) |
| ARROYO | 94 | PRL 72 3452 | C.G. Arroyo *et al.* | (COLU, CHIC, FNAL+) |
| BUSKULIC | 94 | ZPHY C62 539 | D. Buskulic *et al.* | (ALEPH Collab.) |
| ELLIS | 94B | PL B333 118 | J. Ellis, G.L. Fogli, E. Lisi | (CERN, BARI) |
| GURTU | 94 | MPL A9 3301 | A. Gurtu | (TATA) |
| MONTAGNA | 94 | PL B335 484 | G. Montagna *et al.* | (INFN, PAVI, CERN+) |
| NOVIKOV | 94B | MPL A9 2641 | V.A. Novikov *et al.* | (GUEL, CERN, ITEP) |
| PDG | 94 | PR D50 1173 | L. Montanet *et al.* | (CERN, LBL, BOST+) |
| ALITTI | 92B | PL B276 354 | J. Alitti *et al.* | (UA2 Collab.) |