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). The existence of a sixth quark has been expected since the discovery of the bottom quark itself and has become an absolute theoretical necessity within the Standard Model (SM) after the measurement of the $T_3 = -1/2$ weak isospin of the bottom quark [1]. While models with additional quarks but quantum numbers different from the top quark have been constructed, the simplest hypothesis that the weak doublet containing the bottom be completed into a family structure similar to the first two generations has always been the most appealing. This idea has finally been confirmed with the recent announcement of the top discovery by the CDF and DØ experiments at the Fermilab 1.8 TeV Tevatron proton-antiproton collider.

We start this note by presenting a brief historical survey of top searches. Then we discuss in more detail the essential features of top production and decay properties which were exploited to perform the discovery. Finally, we discuss the experimental and theoretical issues involved in the determination of its parameters (mass, production cross section, decay branching ratios, *etc.*) and conclude with the prospects for future improvements.

B. Some history: The first expectations for the value of the top mass used a naive extrapolation of the up- to down-type quark mass ratios in the first two generations, leading to values in the range of 10–20 GeV. Direct searches for $t\bar{t}$ pair production in e^+e^- collisions in this mass range were performed beginning in the late 70's at DESY and SLAC (see the compilation of limits in our 1990 edition [2]). These searches looked for a sudden increase in the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ or for anomalies in the distributions of thrust and acoplanarity in hadronic events. The lower limit on the top

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mass was increased to 30 GeV and then to approximately 46 GeV between the end of the 80's and the beginning of the 90's, when the more powerful Tristan, SLC and LEP e^+e^- colliders began operations (see the Full Listings in our 1994 edition [3] or in the 1995 WWW update).

In parallel to the searches in e^+e^- collisions, direct searches were performed during the 80's by the UA1 and UA2 experiments at the CERN $S\overline{p}pS$ proton-antiproton collider, $\sqrt{s} =$ 630 GeV. At this energy, and at the available luminosities, the CERN experiments were sensitive to top mass values not exceeding 70 GeV, the top quark being mostly produced via an intermediate on-shell W, decaying to $t\overline{b}$. A top quark with mass below the Wb threshold was then expected to undergo a 3-body weak decay to a $bf\overline{f}'$ final state, with $f\overline{f}'$ being a weak isospin doublet such as $\nu_\ell\overline{\ell}$ or $u\overline{d}$.

Because of the overwhelming QCD background to the detection of the purely hadronic final states, the experiments looked for final states including a high momentum isolated lepton, missing transverse energy ($\not\!\!E_T$), and one or more jets. No evidence for top production was obtained (see the Full Listings in our 1994 edition [3] or in the 1995 WWW update for the references): the 95% CL mass limits went from 41 GeV (UA1, 1988), to 60 GeV (UA1, 1990), to 69 GeV (UA2, 1990). The first limits from CDF at the Fermilab Tevatron also appeared in 1990: $m_t > 72$ GeV from searches in the $e\mu$ final states, and $m_t > 77$ GeV from searches in the e plus jets and missing E_T final states.

Further indications of a large top mass had come from the measurement of a significant $B^0 - \overline{B}^0$ mixing, performed in 1986 by UA1 and Argus .

Mass limits independent of the decay mode were also set in the range $m_t > 40$ GeV via the determination of the W boson width, from the measurement in hadronic collisions of the ratio $\sigma(W \to \ell\nu_\ell)/\sigma(Z \to \ell^+\ell^-)$. With the advent of high-precision electroweak data (from deep-inelastic scattering, M_W, atomic parity violation and, most importantly, from the study of the Z-boson couplings at SLC and LEP), global fits of the SM parameters have become possible, and have provided significant indirect constraints on the value of the top mass, once more indicating a large value (see our review "Standard Model of Electroweak Interactions" in this 1995 WWW update for more information).

In the 1995 WWW Particle Properties Listings, we collect a list of indirect top mass limits. This list includes superseded results to show the historical development.

C. Top quark searches at the Tevatron: The first direct limits on the top mass exceeding the threshold for the decay into real W and a bottom quark came in the early 90's from the Fermilab Tevatron collider: $m_t > 91$ GeV (CDF, 1992) and $m_t > 131$ GeV (D0, 1994).

At the Tevatron energy, 1.8 TeV, a top quark above the W mass is dominantly produced in pairs from pure QCD processes: $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. For a top mass around 100 GeV, the production cross section is expected to be of the order of 100 pb and is evenly shared between the two above channels. At 150 (175, 200) GeV the cross section is about 10 (5, 2.5) pb, with approximately 80% (90%, 95%) of it due to the light quark annihilation.

For masses above the Wb threshold, and neglecting terms of order m_b^2/m_t^2, the top quark decay width is predicted in the SM to be [4]:

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

The use of G_F in this equation accounts for the largest part of the 1-loop electroweak radiative corrections, providing an expression accurate to better than 2%. The width values increase from 302 MeV (for $m_t = 120$ GeV) to 1.04 GeV ($m_t = 160$ GeV) and 2.23 GeV ($m_t = 200$ GeV). With such a correspondingly short lifetime, the top quark is expected to decay before top-favoured hadrons or $t\bar{t}$ quarkonium bound states can form.

The top quark decay is expected to be largely dominated by the Wb final state. The Ws and Wd final states are suppressed relatively 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

0.046 and 0.014, respectively (see our review "The Cabibbo-Kobayashi-Maskawa Mixing Matrix" in this 1995 WWW update for more information).

Typical final states therefore belong to three classes:

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

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

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

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 $t\bar{t}$ production signature is by itself quite clear in all possible decay channels, due to the many kinematical constraints imposed by the sequential decay via a real W. However, the combination of the limited experimental resolution and of the large cross section for the production of 6 jets in the QCD continuum (several nb) make the search in the purely hadronic channel very difficult. Since the detection of τ leptons has small efficiency, studies have therefore mostly concentrated on final states where one (or both) W decays to either an electron or a muon. Potential physics backgrounds still exist, mainly due to associated production of one (or two) W and several jets, with the W decaying leptonically. The gain in the S/B ratio is by an approximate factor of 10 for each W which is required to decay leptonically.

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 as 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 (*e.g.*, a sample of Z plus multi-jet events), is required to provide a reliable check on the background estimates.

D. Top observation at CDF and DØ: The CDF experiment and the DØ experiment independently observed the production and decay of the top quark at the Fermilab Tevatron collider in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV.

The CDF experiment published the first direct experimental evidence for the top quark in 1994 [5]. They found 12 events consistent with top, containing 6 silicon vertex tags, 7 low-p_T lepton tags, and 3 dilepton events (these categories are discussed below in more detail) with estimated backgrounds of 2.3 ± 0.3, 3.1 ± 0.3, and $0.56^{+0.25}_{-0.13}$ respectively. The combined excess signal was inconsistent with backgrounds by 2.8 σ, not enough to firmly establish the existence of the top quark. Interpreting the excess events as top, they found a $t\overline{t}$ production cross section of $13.9^{+6.1}_{-4.8}$ pb, larger than the expected QCD cross section discussed below. A mass analysis of seven of these events yielded $m_t = 174 \pm 10^{+13}_{-12}$ GeV. A sample of events selected according to the expected kinematical properties of top provided additional support for the top interpretation [6].

The DØ experiment [7] found nine top candidates in their data taken during the same Tevatron run with an estimated background of 3.8 ± 0.9. They found a probability of 2.7% that this yield was consistent with backgrounds, corresponding to a 1.9 σ effect. If they assumed that the observed excess was top production, they obtained a $t\overline{t}$ production cross section of 8.2 ± 5.1 pb at $m_t = 180$ GeV.

After accumulating more than three times the amount of data, both CDF and DØ reported in 1995 [8,9] that they had conclusively observed the top quark.

The CDF experiment [8] observed top signals in two classes of events: $\ell\ell + jets$ events, which have two high-p_T leptons (e or μ) of opposite charge, large missing E_T, and at least two jets; and $\ell + jets/b$-tag events, which have one high-p_T lepton, large missing E_T, and at least three jets, of which at least one is tagged as a b jet. They tagged b jets by finding secondary vertices from b-quark decay with their silicon vertex detector or by finding low-p_T leptons from semileptonic b decay.

In 67 pb^{-1} integrated luminosity, CDF observed 37 $\ell + jets/b$-tag) events containing 27 secondary vertex b tags and 23 low-p_T lepton b tags with estimated backgrounds of 6.7 ± 2.1 and 15.4 ± 2.0 respectively. They also observed 6 $\ell\ell$ events with an estimated background background of 1.3 ± 0.3 events. The combined excess signal observed in these three categories is inconsistent with the background prediction by 4.8 σ.

The DØ experiment [9] observed top signals in three classes of events: $\ell\ell + jets$ events, $\ell + jets$ events, and $\ell + jets/b$-tag events. These classes differ from those of CDF in the details of their selection cuts, but the main differences are that DØ imposes topological cuts, includes $\ell + jets$ events without a b tag if they have at least four jets, and uses soft-muon b tagging only. The topological cuts, mainly H_T, which is the scalar sum of transverse energies of the jets (and, in dilepton events, the leading electron), are very effective since the top quark is heavy, and hence top events are more spherical than background events and are produced more centrally in the detector.

In an integrated luminosity of approximately 50 pb^{-1} DØ observed 3 $\ell\ell + jets$ events, 8 $\ell + jets$ events, and 6 $\ell + jets/b$-tag events, a total of 17 top candidates. The total estimated background in these events is 3.8 ± 0.6 events. The excess signal is inconsistent with the background prediction by 4.6 σ.

E. Measured top properties: CDF and DØ both measured the top mass using single lepton events with four or more jets. Each event was subjected to a two-constraint kinematic fit to the hypothesis $t\bar{t} \to W^+ b W^- \bar{b} \to \ell \nu_\ell q \overline{q}' b \bar{b}$, assuming that the four highest E_T jets were the $t\bar{t}$ daughters. All permutations of these jets were tried, with the restriction that b-tagged jets were assigned to b quarks in the fit.

CDF found that of their 37 $\ell + jets/b$-tag events, 19 events had four or more jets. Of these 19, $6.9^{+2.5}_{-1.9}$ were expected to be background. A fit to the mass distribution of the 19 events by the sum of the expected distributions for the $W + jets$ background and a top quark yielded $m_t = 176 \pm 8 \pm 10$ GeV where the second error is the estimated systematic uncertainty.

DØ found that of their 14 $\ell + jets$ (with and without b-tags) events, 11 had four or more jets and passed the fit. To increase the statistics and reduce mass biases, the H_T requirement was removed, yielding 27 $\ell + 4jets$ events, of which 24 passed the fit. A fit of the mass distribution to top and background contributions yielded $m_t = 199^{+19}_{-21} \pm 22$ GeV, where the second error is the estimated systematic error. More recently, in a preliminary mass analysis of their $\ell\ell + jets$ events, DØ obtained $m_t = 145 \pm 25 \pm 20$ GeV [10]. Because it is preliminary, this value does not enter our data listings or the average below.

The PDG 1995 WWW average of the CDF and DØ results is $m_t = 180 \pm 12$ GeV, where statistical and systematic errors have been combined in quadrature and where CDF and DØ systematic errors have been assumed to be independent.

Given the experimental technique used to extract the top mass, this value should be taken as representing the top *pole mass* (see our review "Note on Quark Masses" in this 1995 WWW update).

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.

CDF [8] and DØ [9] determined the $t\bar{t}$ cross section in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV from their numbers of top candidates, their estimated background, their $t\bar{t}$ acceptance, and their integrated luminosity. The evaluation was done under the assumption of SM decays $t \to Wb$, with unity branching ratio. Based on their number of secondary-vertex b-tagged events, CDF determined the $t\bar{t}$ cross section to be $6.8^{+3.6}_{-2.4}$ pb at $m_t = 175$ GeV. The next-to-leading-order QCD prediction [11], allowing for a variation of the renormalization and factorization scales μ in the range $0.5 < \mu/m_t < 2$ and using the MRSA set of parton densities [12], gives $4.3 < \sigma_{t\bar{t}}(\mathrm{pb}) < 5.0$ at $m_t = 175$ GeV.

Based on their 17 top candidates, DØ determined the $t\bar{t}$ cross section to be 6.4 ± 2.2 pb at their central mass value of 199 GeV or 8.2 ± 2.9 pb at 180 GeV. The QCD predictions are: $2.0 < \sigma_{t\bar{t}}(\mathrm{pb}) < 2.4$ ($m_t = 199$ GeV), and $3.6 < \sigma_{t\bar{t}}(\mathrm{pb}) < 4.3$ ($m_t = 180$ GeV).

The measurement of other properties of the top quark has just started. CDF reported the first direct measurement of the $t \to Wb$ branching ratio [13]. Their preliminary result, obtained by comparing the number of events with 1 and 2 tagged-b jets and using the known tagging efficiency, is: $R = \mathrm{B}(t \to Wb)/\sum_{q=d,s,b}\mathrm{B}(t \to Wq) = 0.87^{+0.13}_{-0.30}{}^{+0.13}_{-0.11}$.

F. The future: With the discovery of the top quark, future studies will follow two main tracks. Theoretically, it is hoped that the large top mass, and the tantalizing coincidence between its current value and the fundamental scale of the electroweak symmetry breaking, will lead to some understanding of the structure of fermion masses and of the symmetry breaking mechanism itself. Experimentally, the work will concentrate on reducing the errors on the mass and cross section determinations and on the measurement of more specific properties of the top quark, namely its decay branching ratios and its couplings. 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 SM and its minimal supersymmetric extension, provide indications for a relatively light Higgs (see the "H^0 Indirect Mass Limits from Electroweak Analysis" 1995 WWW Particle Properties Listings), possibly within the range of the upcoming LEP2 experiments.

The current Tevatron data, once fully analysed, should allow the first determination of limits on rare top decay modes, such as $t \to \gamma c$ or $t \to Zc$. Studies of the decay angular distributions 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 SM, the fraction of decays to transversely polarized W bosons is expected to be $1/(1 + m_t^2/2M_W^2)$ (29% for $m_t = 180$ GeV). Deviations from this value would challenge the Higgs mechanism of spontaneous symmetry breaking.

Over the longer term, a direct measurement of the Wtb coupling constant will be possible when enough data will be 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.

A precise determination of the top production cross section will test the current theoretical understanding of the production mechanisms. The current state of the art amounts to complete calculations at the next-to-leading order in QCD [11], as well as efforts to resum classes of potentially large logarithmic corrections coming from multiple soft gluon emission in the intial state [14]. 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.

As discussed in the previous sections, some of the current uncertainty in the determination of the top mass from the reconstruction of its final state jets arises from theoretical uncertainties in the modeling of the radiation in these very hard events. The current data, once fully analyzed, will presumably help improving our theoretical understanding. At the same time, 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.

Finally, the large mass of the top quark leaves open the possibility of top decays into yet unobserved particles beyond the SM. For example, current limits on the masses of a charged Higgs (H^+) or of a supersymmetric scalar top quark ($\tilde{t}$) and neutralino (χ^0), cannot exclude the existence of decays such as $t \to H^+ b$ or $t \to \tilde{t}\chi^0$. The first channel, in particular, has been used extensively in the past in direct top searches (see the 1995 WWW Particle Properties Listings). Both these exotic modes are currently under investigation at CDF and DØ.

References

1. W. Bartel *et al.*, Phys. Lett. **B146**, 437 (1984).
2. Particle Data Group, *Review of Particle Properties*, Phys. Lett. **B239**, P. VII. 167 (1990).
3. Particle Data Group, *Review of Particle Properties*, Phys. Rev. **D50**, 1173 (1994).
4. C.S. Li, R.J. Oakes, and T.C. Yuan, Phys. Rev. **D43**, 3759 (1991);
   A. Denner and T. Sack, Nucl. Phys. **B358**, 46 (1991).
5. F. Abe *et al.*, Phys. Rev. **D50**, 2966 (1994).
6. F. Abe *et al.*, Phys. Rev. **D51**, 4623 (1995).
7. S. Abachi *et al.*, Phys. Rev. Lett. **74**, 2422 (1995).

8. F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995).
9. S. Abachi *et al.*, Phys. Rev. Lett. **74**, 2632 (1995).
10. S. Snyder, *Measurement of the top quark mass and kinematic properties with with the DØ detector*. Presented at the International Europhysics Conference on High Energy Physics, Brussels, July 27 to August 2, 1995, Fermilab-conf-95/341-e.
11. P. Nason, S. Dawson, and R.K. Ellis, Nucl. Phys. **B303**, 607 (1988);
W. Beenakker, H. Kuijf, W.L. van Neerven, and J. Smith, Phys. Rev. **D40**, 54 (1989);
G. Altarelli, M. Diemoz, G. Martinelli, and P. Nason, Nucl. Phys. **B308**, 724 (1988);
R.K. Ellis, Phys. Lett. **B259**, 492 (1991).
12. A.D. Martin, R.G. Roberts, and W.J. Stirling, Phys. Rev. **D50**, 6723 (1994).
13. F. Abe *et al.*, FERMILAB-CONF-95-237-E, Jul 1995. 8pp. Presented at 6th International Symposium on Heavy Flavor Physics, Pisa, Italy, 6-9 Jun 1995.
14. E. Laenen, J. Smith, and W.L. van Neerven, Nucl. Phys. **B369**, 543 (1992);
E.L. Berger and H. Contopanagos, Argonne preprint ANL-HEP-PR-95-31.