TOP-OLOGY

The top quark, first seen just two years ago at the Tevatron, is uniquely heavy and short-lived. But its virtual presence is felt in more familiar realms.

Chris Quigg

The top quark is a most remarkable particle, even for a quark. A single "top," as we will casually call it here, weighs 175 GeV, about as much as an atom of gold. But unlike the gold atom, which can be disassembled into 79 protons, 79 electrons and 118 neutrons, top seems to be indivisible. With an experimental resolution approaching 10^{-16} cm, we have not discerned any structure. Top's predicted lifetime of about 0.4 yoctoseconds (0.4×10^{-24} s) makes it by far the most ephemeral of the six varieties of quarks. The compensation for this exceedingly brief life is a measure of freedom: Top decays before it suffers the confining influence of the strong interactions. In spite of its fleeting existence, the top quark nonetheless helps shape the character of the everyday world.

Sought and finally found

Ever since the existence of the 5 GeV bottom quark was inferred from the discovery of the Υ family of mesons at Fermilab in 1977, particle physicists have been on the lookout for its heavier partner, which was given the name top quark long before it was finally found. The long search, which occupied large numbers of experimenters at laboratories around the world, came to a successful conclusion in 1995 with the announcement that the top quark had been observed in the CDF (Collider Detector at Fermilab) and DØ (D Zero) experiments at Fermilab's Tevatron collider.[1] (Also see PHYSICS TODAY, May 1995, page 17.) The cover of this issue shows the CDF detector.

Top is the last of the fundamental constituents of subnuclear matter that particle physicists have been led to expect by the standard gauge theories of the strong, weak and electromagnetic interactions and a wealth of experimental information. Top's existence was required lest quantum corrections clash with the symmetries of the electroweak theory and leave it internally inconsistent. Top was signaled also by the pattern of the bottom-quark decay modes and by the characteristics of the b's neutral-weak-current interactions measured in the production of $b\bar{b}$ pairs in electron–positron collisions. (Bottom and top quarks are denoted by b and t, and the bars denote antiquarks.).

Even when the energy of an electroweak process is far too low for the actual production of top quarks, higher order Feynman diagrams involving virtual top quarks are often important terms in quantum corrections to the predictions the electroweak theory makes for many observables. A case in point is the total decay rate of the Z^0 boson, as manifested in the width of its resonance in electron–positron collisions, which has been measured to exquisite precision at the CERN and Stanford Linear Accelerator Center (SLAC) e^+e^- colliders. The comparison of experiment and theory shown in figure 1a favored a top mass in the neighborhood of 175 GeV on the eve of the actual discovery. In the mid-1970s, no one was expecting anything nearly so heavy. Figure 1b shows how the top mass predicted by simultaneous fits to many electroweak observables grew over the years preceding the discovery.

In passing, it is worth mentioning another hint that I must confess seems more suggestive to me after the fact than it did before the discovery of the top: In supersymmetric unified theories of the fundamental interactions, virtual top quarks can drive the spontaneous breakdown of electroweak symmetry, provided that top is very massive.[2]

Through the 1980s and early 1990s, direct searches continually raised the lower bound on the mass of the top, but they produced no convincing sign of its existence. The most stringent limits came from the proton–antiproton colliders at CERN and Fermilab, but these relied on the assumption that the top decays (almost) exclusively into a bottom quark and a real or virtual W boson. (The 80-GeV $W^\pm$ and the 91-GeV Z^0 are the mediators of the weak interactions.) Electron–positron colliders, on the other hand, could look for $e^+e^- \to t\bar{t}$ without having to make assumptions about the decay mechanism. But the lower energies of those machines led to rather weak bounds on the top mass, m_t.

By 1994, there was an impressive body of circumstantial evidence pointing to the existence of a top quark with a mass of 175 ± 25 GeV. Finding top and measuring its mass directly emerged as a critical test of the understanding of the weak and electromagnetic interactions built up over two decades.

The decisive experiments were carried out at Fermilab's Tevatron, in which a beam of 900 GeV protons collides with a beam of 900 GeV antiprotons. Creating top–antitop pairs in sufficient numbers to claim discovery demanded exceptional performance from the Tevatron, because only one interaction in ten billion results in a $t\bar{t}$ pair. Observing traces of the disintegration of top into a b quark and a W boson required enormously sophisticated detectors

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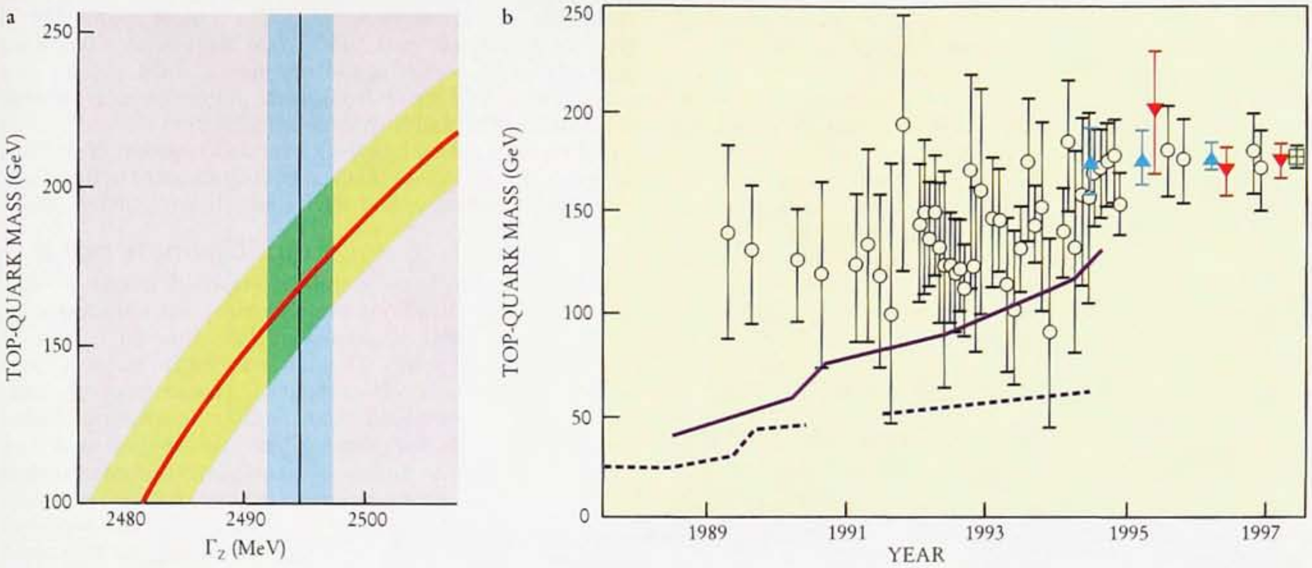


FIGURE 1. TOP-QUARK MASS. **a:** Standard-model prediction of Γ_Z, the width of the Z^0 resonance, as a function of the top-quark mass, m_t. The breadth of the green swath indicating the prediction is determined primarily by the uncertainties of the strong coupling constant and the Higgs-boson mass. The vertical line and blue bar indicate the measured value of $\Gamma_Z \pm 1$ standard deviation. **b:** Evidence for the top mass over time. Rising lower bounds on m_t inferred from direct searches are shown for $p\bar{p}$ colliders (solid line) and e^+e^- colliders (dashed lines). Open circles are indirect determinations of m_t from electroweak measurements. Colored triangles are direct measurements by CDF (blue) and DØ (red). The box indicates the world average of direct measurements.

and extraordinary attention to experimental detail. Both the b quark and the W boson are themselves unstable, each having many multibody decay modes.

The b quark's lifetime is about 1.5 picoseconds, much longer than the lifetime of the top. It's long enough for the b to "dress" itself with an ordinary quark to form a B meson, which can travel a short but discernable distance in the detector. So the B meson can be "tagged" by a decay vertex displaced by about a millimeter from the production point or, in some of its decay modes, by the appearance of a low-momentum electron or muon.

The W boson, like the top, lives for only a fraction of a yoctosecond. Two-thirds of the time, it decays into a quark–antiquark pair, which manifests itself as two narrow jets of hadrons. The remaining third of W decays are into lepton pairs—a conspicuous high-energy charged lepton accompanied by an invisible neutrino.

The characteristic channels in which top–antitop pair production can be sought are listed in the table on page 23. The so-called dilepton events ($e\mu$, ee and $\mu\mu$) are produced primarily when both W bosons decay into $e\nu$ or $\mu\nu$. Events in the lepton-plus-jets channels occur when one W decay produces an e or a μ, and the other decays into a quark–antiquark pair. Although the τ, the heaviest of the three charged leptons, occurs just as often as its lighter cousins in W decay, its subpicosecond lifetime makes it much less conspicuous than an e or a μ.

Another challenge to experimenters is the daunting complexity of events in high-energy proton–antiproton collisions. The progeny of the $t\bar{t}$ pair are typically accompanied by scores of other particles. Figure 2 shows a simulated $t\bar{t}$ event in the DØ detector. The only characteristic features evident to the eye are the high-energy muons at the top and bottom right, suggesting two $W \to \mu\nu$ decays, and the lower energy muon at the lower left. Separating the top-quark sheep from the goats is not for the faint of heart!

Each of the two detectors at the Tevatron collider is an intricate apparatus operated by an international collaboration of close to 500 physicists. With its calorimeters, tracking devices and the surrounding iron that lets muons out but keeps hadrons in, each detector weighs about 5000 tons and stands three stories high. The 16-year-old CDF, a solenoidal magnetic detector, profited from its high-resolution silicon vertex detector to tag b quarks with good efficiency. The younger DØ detector, with no central magnetic field to provide curvature measurements of charged-particle momenta, emphasizes calorimetric measurement instead.

The first evidence for top was presented in April 1994 by the CDF collaboration,[3] led by Bill Carithers (Lawrence Berkeley National Laboratory) and Mel Shochet (University of Chicago). In a data sample whose size corresponded to 19.3 events per picobarn of cross section (19.3 pb^{-1}), the CDF collaboration found 12 events consistent with either two W bosons or a W and at least one b quark. One of these candidate events, manifesting two Ws *and* two b quarks, is shown in figure 3. It illustrates the power of the silicon vertex detector, which can resolve a secondary b-decay vertex as close as 0.3 mm from the $p\bar{p}$ collision point. Although the 19.3 pb^{-1} sample lacked the statistical weight needed to claim discovery, the event characteristics were consistent with $t\bar{t}$ pair production, with a top mass near 175 GeV. A few months later, the DØ collaboration, led by Paul Grannis (State University of New York at Stony Brook) and Hugh Montgomery (Fermilab), reported[4] an excess of candidate events (9 events where a background of only 4 was expected) in a 13.5 pb^{-1} data sample.

The discovery was not far behind. By February 1995, both groups had quadrupled their data sets. The CDF collaboration reported that it had found 6 dilepton candidates where only one backgound event would have been expected, and also 37 b-tagged events containing a W and at least three jets.[5] In an adjacent paper,[6] the DØ collaboration reported 17 top candidates with an expected background of only 4 events. Taken together, the back-to-back papers provided irresistible evidence for a top quark

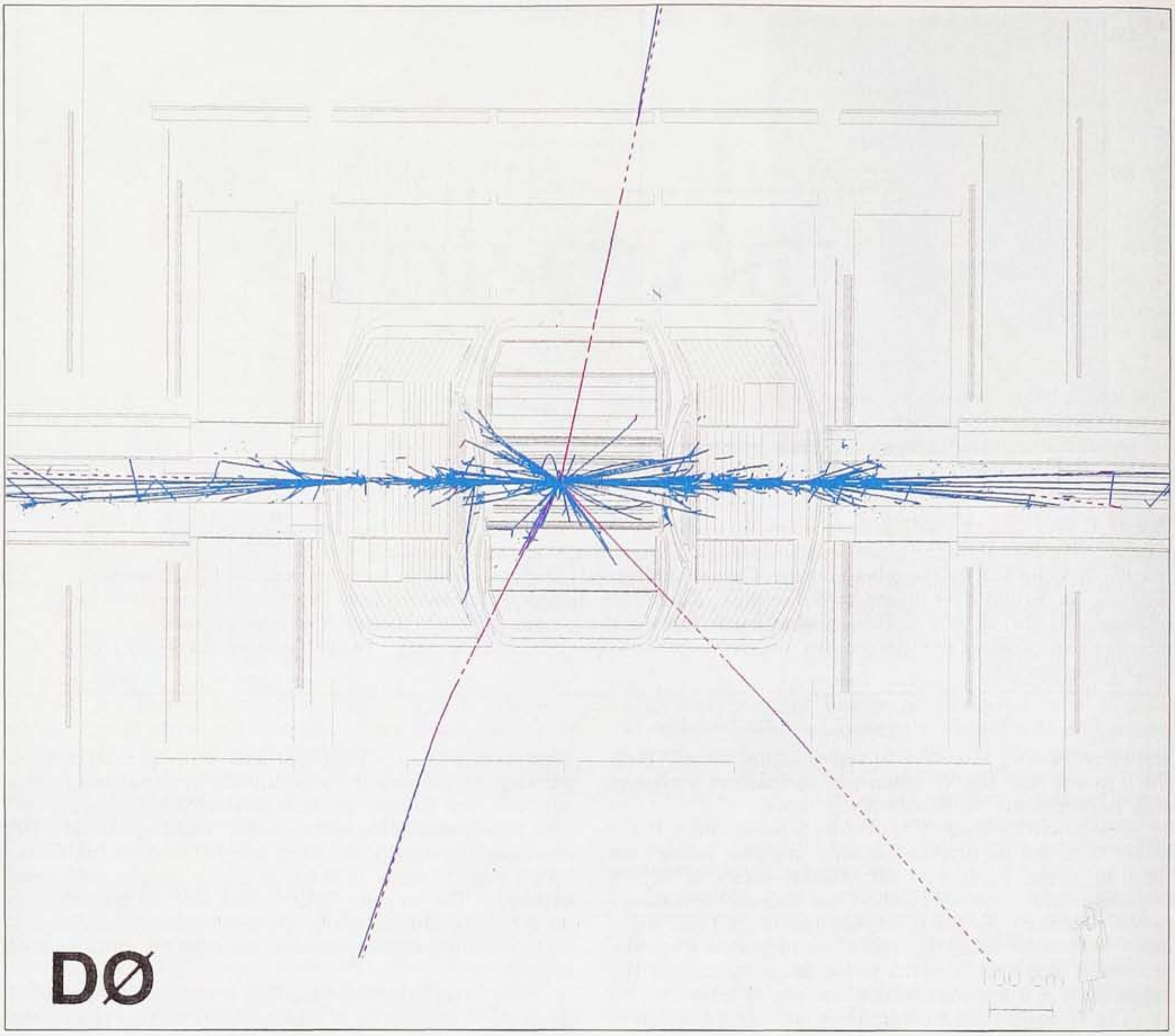


FIGURE 2. SIMULATION OF A TOP-ANTITOP PRODUCTION EVENT in a 2 TeV $p\bar{p}$ collision in the upgraded DØ detector, which will begin operating at the upgraded Tevatron in 1999. The horizontal beams meet head-on at the detector's center. The blue lines are trajectories of charged particles (except for the muons) resulting from the $p\bar{p}$ collision. The red lines represent muons, which can penetrate through considerable thicknesses of material. In this event, both Ws from the top-quark decays produce high-energy muons (going up and down right) when they, in turn, decay. A third muon (lower left), originates in the decay of a b-quark; its lower energy can be inferred from its noticeable curvature in the detector's magnetized-iron shielding.

with a mass somewhere in the anticipated region around 175 GeV. Furthermore, the observed $t\bar{t}$ production rate was in line with theoretical predictions. Today, with the event samples approximately doubled again, the world average for the top mass is 175.5 ± 5.1 GeV. See the box on page 24.

The top quark and the W boson

Now that we have the top quark, what do we do with it? The presumed influence of virtual top quarks on precision measurements of electroweak observables was the basis for our expectations for the top quark mass. As m_t becomes known more precisely from direct measurements, we will be able to compare predictions that depend sensitively on the top mass with new observations.

Among the most incisive tests of the theory will be the comparison of the W-boson mass with theoretical calculations. The W mass is related to the mass of the Z^0 boson by

$$M_W{}^2 = M_Z{}^2\,(1 - \sin^2\theta_W)\,(1 + \Delta\rho)\,,$$

where the electroweak mixing parameter $\sin^2\theta_W$ is about 0.232, and $\Delta\rho$ represents quantum corrections like the heavy-quark loops sketched at the top of figure 4. The loop correction reflects the fact that the b and t quark masses are very different, in violation of the weak-isospin symmetry approximation. The correction term is

$$\Delta\rho = 3G_F\,m_t^2/8\pi^2\sqrt{2}$$

plus higher order terms that depend logarithmically on the mass of the Higgs boson, the as-yet-undetected agent of electroweak symmetry breaking. (G_F is Fermi's weak-interaction coupling constant.)

Figure 4 shows how the prediction of the W-boson mass as a function of m_t depends on the presumed mass of the Higgs boson.[7] The measurements are consistent with the electroweak theory, but they do not yet provide any precise hints about the Higgs mass. Over the next decade, the Fermilab and CERN collider experiments should be able to reduce the uncertainties on the measured top and W masses to about 2 GeV and 20 MeV, respectively. That will set the stage for a crucial test of the electroweak theory when (and if) the Higgs boson is discovered.

Is it the 'standard' top?

The top-quark discovery channels listed in the table below all arise from the production of top-antitop pairs, and all contain a $b\bar{b}$ pair. We're assuming that any top decay modes other than the already observed $t \to bW^+$ are strongly suppressed. Decays to the lighter "strange" or "down" quarks should be extremely rare, unless the b-quark mode is unexpectedly supressed, which could occur if top were to have a large coupling to a more massive, fourth-generation cousin of the b quark. It is important to test the standard three-generation model by looking for such rare decays directly, or by measuring the b-tag rate. The CDF collaboration has used the tagging method to show that $99 \pm 29\%$ of all t decays producing a W boson also produce a b quark.[8]

In $p\bar{p}$ collisions, $t\bar{t}$ pairs are produced through the strong interaction. A single top, on the other hand, can be produced together with an antibottom quark by way of a weak light-quark interaction such as the light-quark collision process $u\bar{d} \to$ virtual $W^+ \to t\bar{b}$. Single-top production rates may in time give us an excellent measurement of the strength of the $Wt\bar{b}$ coupling.

In some supersymmetric models, the top can be produced in the decays of heavy superpartners of known particles, and it can itself decay into lighter superpartners. This possibility encourages the careful comparison of the top-bearing event rates with conventional expectations.

The ultrarapid decay of the top quark means that, unlike what we see for the other five quark varieties, there is no time for the formation of top mesons or top baryons. (See the box 2 on page 25.) This has the happy experimental consequence that the spin orientation of the top at the moment of its production is reflected, without dilution, in the angular distribution of its decay products. The correlation between the spins of the top and the antitop in a pair produces distinctive patterns that will help experimenters probe the character of the $t \to bW^+$ transition.

If the standard model is right about the weak interactions of the top, then its decay is an excellent source of longitudinally polarized W bosons. A large fraction, $1/(1 + 2M_W{}^2/m_t^2) \approx 70\%$, of the W bosons in top decay will be longitudinally polarized. That polarization is reflected in the angular distribution of the subsequent decay muons and electrons. The longitudinal Ws are interesting in their own right: As creatures of electroweak symmetry breaking, they may be particularly sensitive to new physics.

Because the top is so massive, many decay channels in addition to the signature $t \to bW^+$ mode may be open to it. Decay into a b quark and a putative spin-zero particle P^+ can occur in supersymmetric and technicolor models, and in multi-Higgs generalizations of the standard electroweak theory. The decay rate for $t \to bP^+$ would be similar to the $t \to bW^+$ rate, because both decays are semiweak. If the measured $t\bar{t}$ production rate turns out to be smaller than that predicted by quantum chromodynamics (QCD), the standard theory of the strong interactions, we would have an indication of new physics. The lifetime of putative P^+ would be about 10^{-21} s (a zeptosecond), far too short to leave an observable track. Such a P^+ might be recognized from its decays into heavy quarks or into the heavy τ^+ lepton. The general lesson is that top decays have the capacity to surprise us.

Electroweak symmetry breaking

What determines the masses of the fundamental fermions (quarks and leptons) and the gauge bosons (photon, Z^0 and $W^\pm$)? In the standard electroweak theory, the Higgs boson generates all these masses. Although they all the arise from the breaking of the electroweak symmetry, the mechanisms for the bosons and the fermions are logically distinct from each other. Whereas the Z^0 and $W^\pm$ masses are predicted in terms of the coupling constants and the weak mixing parameter, every fermion mass is set by a separate Yukawa coupling to the field of the Higgs boson. The mass of fermion f is

$$m_f = \zeta_f\,(2G_F\sqrt{2}\,)^{-1/2},$$

the product of its Yukawa coupling constant, ζ_f, and the vacuum expectation value of the Higgs field.[9] The Higgs expectation value is about 176 GeV, and the Yukawa couplings range from $\zeta_e \approx 3 \times 10^{-6}$ for the electron to $\zeta_t \approx 1$ for the top. Within the electroweak theory, we do not know the origin of these numbers, and we haven't a clue as to how we might calculate them.

Top's enormous mass suggests that it somehow stands apart from the other quarks and leptons. Does $\zeta_t \approx 1$ mean that top is special, or that it is the only fermion with a "normal" mass? We don't yet know. We expect that experiments at CERN's Large Hadron Collider (LHC), which will begin exploring 14 TeV proton–proton collisions in about 2006, will reveal the mechanism of electroweak symmetry breaking and complete our understanding of the gauge boson masses. But what of the fermion masses? My instinct is that top's large mass means that both questions will be answered by the LHC experiments as they probe the natural TeV scale of electroweak symmetry breaking.

That is speculation, but it is certain that the discovery of top opens a new window on electroweak symmetry breaking. The Higgs mechanism of the standard electroweak theory is the relativistic generalization of the Ginzburg–Landau phenomenology of the superconducting phase transition. Some attempts to im-

Channels studied in search of $p\bar{p} \to t\bar{t}$ + anything

Channel	Branching fraction
$e^+e^-\, b\bar{b}\, \not{E}_T$	1/81
$\mu^+\mu^-\, b\bar{b}\, \not{E}_T$	1/81
$(\tau^+\tau^-\, b\bar{b}\, \not{E}_T$	1/81)
$e^\pm\mu^\mp\, b\bar{b}\, \not{E}_T$	2/81
$(e^\pm\tau^\mp\, b\bar{b}\, \not{E}_T$	2/81)
$(\mu^\pm\tau^\mp\, b\bar{b}\, \not{E}_T$	2/81)
$e^\pm$ jets $b\bar{b}\, \not{E}_T$	12/81
$\mu^\pm$ jets $b\bar{b}\, \not{E}_T$	12/81
$(\tau^\pm$ jets $b\bar{b}\, \not{E}_T$	12/81)
$b\bar{b}$ 4 jets	36/81

Channels in parentheses, involving τ leptons, have not yet been exploited in experiments.
$\not{E}_T$ indicates significant missing energy transverse to the beam axis, attributed to neutrinos.

Three Generations of Fundamental Fermions.

The possibility that CP symmetry violation arises from a phase angle in the quark-mass matrix, provided that there are at least three generations of quark pairs,[14] was first raised in 1973. The following year the discovery of the J/ψ family of charmonium resonances at Brookhaven and SLAC completed the second generation of quarks and leptons. The case was clinched when charmed mesons, containing unpaired charmed quarks, were discovered[15] at SLAC in 1976. The second generation—strange and charmed quarks, together with the muon and its neutrino—repeated the pattern of the first generation: down and up quarks, together with the electron and its neutrino.

Meanwhile in 1975, the $\tau^{\pm}$, a third charged lepton 17 times as heavy as the muon, had also been discovered at SLAC.[16] (Its neutrino, however, has not yet been detected directly.) The accompanying third generation of quarks made its first appearance in 1977, with the discovery at Fermilab of the Υ family of heavy mesons, which proved to be bound states of the 5 GeV bottom quark and its antiquark.[17] Now the search for the top quark was on. Its discovery, completing the third generation, was not accomplished until 1995, because the top turned out to be much heavier than had been anticipated.

When will it end? Detailed studies of Z^0 production and decay at SLAC and CERN in recent years have demonstrated that there are precisely three species of light neutrinos. So if there were a fourth generation of quarks and leptons, it would have to have a very nonstandard heavy neutrino.

The Third Generation

Quark	Charge	Mass	Lifetime
t	+2/3	175 GeV	0.4 ys
b	−1/3	4.7 GeV	1.5 ps
Lepton	**Charge**	**Mass**	**Lifetime**
ν_τ	0	< 24 MeV	. . .
τ	−1	1.78 GeV	0.3 ps

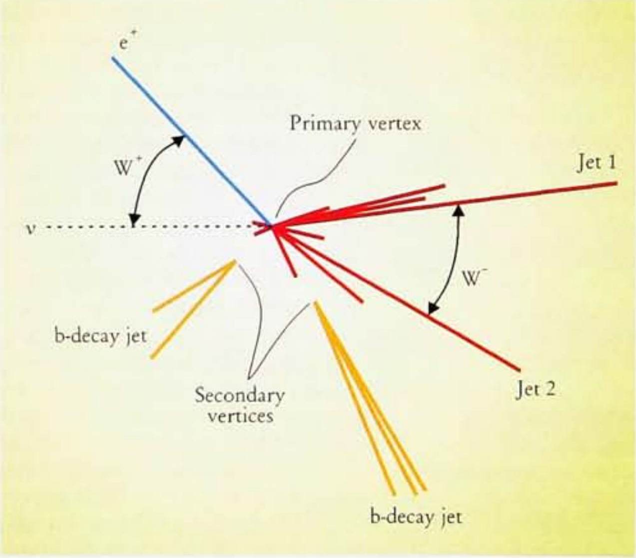


FIGURE 3. CANDIDATE EVENT for top-antitop production, as seen by CDF's silicon vertex detector at the Tevatron. Both top quarks decay at the $p\bar{p}$ collision vertex into a W boson plus a bottom quark. The W^+ decays into e^+ plus an invisible neutrino, and the W^- decays into a quark and an antiquark, which show up as two jets of hadrons. Each bottom quark becomes a neutral B meson that travels a few millimeters from the production vertex before its decay creates a hadron jet. (Many extraneous tracks are not shown.)

prove the electroweak theory and make it more predictive seek to emulate the Bardeen–Cooper–Schrieffer theory of superconductivity. Very heavy hadronic resonances that decay into $t\bar{t}$ are natural consequences of such dynamical schemes. The possibility of new sources of $t\bar{t}$ pairs makes it urgent to test how closely top production conforms to standard QCD expectations.

Technicolor and topcolor

Two classes of models have received considerable attention in the context of the heavy top quark. In the first, called technicolor, a new interaction analogous to the QCD of the familiar strong interactions becomes stronger as one comes down from ultrahigh energies and forms a technifermion condensate that gives masses to the gauge bosons. A generalization called extended technicolor allows the fermions to acquire mass through new interactions with the technifermion condensate.

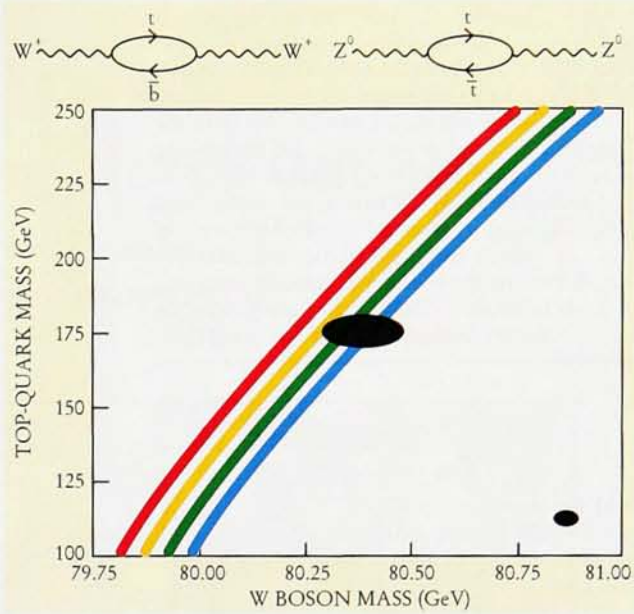
In the second class of models, called topcolor, a new interaction drives the formation of a top condensate akin to Cooper pairing. The top condensate hides the electroweak symmetry and gives masses to the ordinary fermions. Technicolor and top condensate models both imply the existence of resonances that decay into $t\bar{t}$, for which the natural mass scale is a few hundred GeV. So we are led to ask: Is there in fact a resonance in $t\bar{t}$ production? How is it made? How else does it decay?

In the technicolor picture,[10] a spin-zero color-octet resonance produced by gluon–gluon collisions can decay into $t\bar{t}$. That would be seen as a distortion of the standard-model $t\bar{t}$ and two-jet invariant-mass distributions; but its effect on the $b\bar{b}$ mass distribution would be negligible.

In the topcolor scenario,[11] a massive spin-1 "coloron" can be produced in quark–antiquark collisions. It decays with roughly equal probability into $t\bar{t}$ or $b\bar{b}$; so it would manifest itself as broad resonance peaks in both channels.

If an enhancement were seen in the $t\bar{t}$ channel, we would want to study its mass spectrum at different energies. At the Tevatron, about 90% of top pair production occurs in quark–antiquark collisions. At the much higher energy of the LHC, gluon–gluon collisions will account for about 90% of the top pairs. The LHC's large gluon

FIGURE 4. STANDARD ELECTROWEAK THEORY prediction of the correlation between the top-quark and W-boson masses is plotted here for various possible masses of the still-undiscovered Higgs boson. From left to right, the bands correspond to Higgs masses of 1000, 500, 250 and 100 GeV. The superposed ellipse indicates current measured world averages for the top and W masses, extended to 1 standard deviation. The smaller ellipse in the lower-right corner indicates the size of the error ellipse we might expect to have six or seven years from now. The Feynman diagrams above the plot indicate the principal contributions of virtual heavy-quark loop corrections to the masses of the W and Z bosons.



collision rate would dramatically increase the contribution of the technicolor resonance relative to the coloron.

Top really does matter!

It is popular to say that top quarks were produced in great numbers in the fiery cauldron of the Big Bang some 15 billion years ago, disintegrated in the merest fraction of a second and vanished from the scene until my colleagues learned to make them in the Tevatron. That would be reason enough to care about top: to learn how it helped sow the seeds for the primordial universe that evolved into our diverse world. But that's not the whole story; it invests the top with a remoteness that veils its importance for the everyday world.

The real wonder is that here and now, every minute of every day, the top quark affects the world around us. Through the uncertainty principle, tops and antitops wink in and out of an ephemeral presence in our world. Though they appear only fleetingly, on borrowed time, the virtual top quarks have real effects.

Quantum effects make the coupling strengths of the fundamental interactions vary with energy. The fine structure constant of electromagnetism itself has its familiar 1/137 value only in the low-energy limit. At 91 GeV (the mass of the Z^0) it has grown to about 1/129. To put it another way, vacuum-polarization effects increase the effective electric charge at short distances or high energies. (See PHYSICS TODAY, March, page 9.)

In unified theories of the strong, weak and electromagnetic interactions, all the coupling "constants" take on a common value, α_U, at some high "unification energy" M_U. If we adopt the point of view that α_U is fixed at the unification scale, then the mass of the top quark is encoded in the value of the strong coupling "constant" α_s we experience at low energies. Assuming three generations of quarks and leptons, we evolve α_s downward in energy E from the unification scale.[12] The leading-logarithmic energy dependence of the strong coupling is given by

$$1/\alpha_s(E) = 1/\alpha_U + \frac{21}{6\pi}\ln(E/M_U)\ ,$$

for energies from the unification scale down to twice the top mass. Thus the strong coupling becomes weaker with increasing energy. This behavior—the opposite of what happens to the effective electric charge—is the celebrated property of QCD known as asymptotic freedom.

The integer coefficient 21 in the equation is more generally $33 - 2n_f$, where n_f is the the number of *active* quark flavors at the energy in question. Below $2m_t$, the energy threshold for making top pairs, it becomes 23 until 10 GeV, twice the bottom mass, after which it becomes 25 until the 3 GeV charmed-quark threshold, $2m_c$. This progressive change in the logarithmic slope of $1/\alpha_s$ at every quark threshold is shown by the solid line in figure 5. The dotted line in the figure shows how the evolution of strong coupling changes if the top-quark mass is reduced. A smaller top mass means a weaker strong coupling.

If we neglect the tiny masses of the ordinary up and down quarks, the scale parameter Λ_{QCD} is the only mass parameter in the standard theory of the strong interactions. We can define Λ_{QCD} by

$$1/\alpha_s(2m_c) = \frac{27}{6\pi}\ln(2m_c/\Lambda_{QCD})\ .$$

Λ_{QCD} determines the scale of the confinement energy that is the dominant contribution to the proton mass, M_p. To a good first approximation, $M_p \approx C\Lambda_{QCD}$, where C is a number that can be calculated by the techniques of lattice

The Brief, Happy Life of the Top

The dominant decay of a sufficiently heavy top quark is into a bottom quark plus a W boson. Such a process is called semiweak, because its rate is proportional to only one power of G_F, the Fermi constant. Beta decay rates, by contrast, are proportional to $G_F{}^2$. If we neglect the mass of the bottom quark and small QCD corrections, the top's decay rate (expressed as an energy width) is[18]

$$\Gamma(t \to bW^+) \approx \frac{G_F m_t{}^3}{8\sqrt{2}\pi}|V_{tb}|^2\left(1 - \frac{M_W{}^4}{m_t{}^4}\right)^2\ ,$$

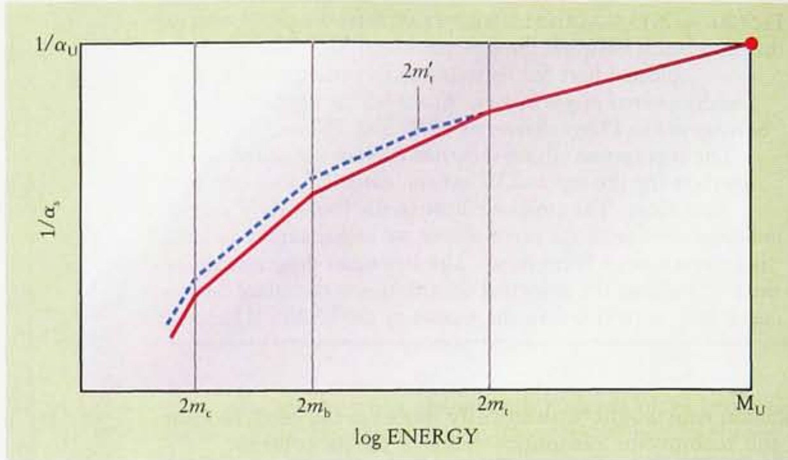
which grows rapidly with increasing top mass. The quark-mass matrix element V_{tb}, which measures the strength of the the tbW coupling, must have a magnitude close to unity if there are only three quark generations. In that case, for a top mass of 175 GeV, the decay width

$$\Gamma(t \to bW^+) \approx 1.55\ \text{GeV}\ ,$$

which corresponds to a top-quark lifetime of about 0.4×10^{-24} s, or 0.4 yoctoseconds.

The confining effects of the strong interaction act on a time scale of a few yoctoseconds, set by $1/\Lambda_{QCD}$. This means that the top quark decays long before it can be hadronized. So there is no spectroscopy of $t\bar{t}$ (toponium) bound states, nor are there any top-flavored mesons or baryons. Therefore top production should be calculable in perturbative QCD. In top decay, we are seeing the decay of an isolated quark rather than a quark bound in a hadron.

FIGURE 5. THEORETICAL ENERGY DEPENDENCE of $1/\alpha_s$, the reciprocal of the strong coupling "constant" (solid curve), exhibits kinks in the logarithmic slope at the thresholds for making pairs of charmed, bottom and top quarks. In theories unifying the strong and electroweak interactions, α_s takes on a unified value α_U at some very large unification mass M_U. Lowering the top quark mass (to some m'_t) leads to smaller values of the strong coupling constant (dashed curve) at lower energies.



field theory.

Simply by requiring that the different pieces of the curve in figure 5 match up at each quark threshold, we find that

$$\Lambda_{QCD} = \exp(-6\pi/27\alpha_U)\left(\frac{M_U}{1\,\mathrm{GeV}}\right)^{21/27} \times (2m_t\, 2m_b\, 2m_c\, / 1\,\mathrm{GeV}^3)^{2/27}\,\mathrm{GeV},$$

from which we conclude that, in a simple unified theory,

$$M_p\, / 1\, GeV \propto (m_t\, /1\, GeV)^{2/27}.$$

This is a wonderful result. Now, we can't use it to compute the mass of the top quark, because we don't know the unification parameters M_U and α_U. Nor have we yet precisely calculated C, the proportionality constant between the proton mass and the QCD scale parameter. But never mind! The important lesson—no surprise to any 20-century physicist—is that the microworld does determine the world of quotidian experience. We will fully understand the origin of one of the most important parameters in the everyday world—the proton mass—only by knowing the properties of the top quark.[13]

Top priorities

Like the end of many a scientific quest, the discovery of top marks a new opening. The first priority, already well advanced, is to continue refining the measurements of the top mass. It is now possible to begin asking just how well top fits the anticipated profile of its production and decay properties. Because of top's great mass, its decay products may include unpredicted—or at least undiscovered—new particles. A very interesting development would be the observation of resonances in $t\bar{t}$ production that would provide new clues about the breaking of electroweak symmetry. On the theoretical front, the large mass of the top encourages us to think that the two mass problems—the fundamental fermion and boson masses—may be linked at the electroweak scale.

For the moment, the direct study of the top quark belongs to the Tevatron. Early in the next century, data sets twenty times greater than the present samples should be in hand, thanks to the increased event rate made possible by Fermilab's new Main Injector and upgrades to both detector systems. Boosting the Tevatron's energy to a full TeV per beam will increase the top yield by nearly 40%. Further enhancements of Fermilab's accelerator complex are under study.

A decade from now the Large Hadron Collider at CERN will be producing tops at more than ten thousand times the rate of the discovery experiments. Electron–positron linear colliders or muon colliders may add new opportunities for the study of top-quark properties and dynamics. In the meantime the network of understanding we call the standard model of particle physics links the properties of top to many phenomena to be explored in other experiments.

According to the cockroach theory of stock market analysis ("You never see just one"), there is never a single piece of good news or bad news. In physics, one discovery usually leads to others. Top opens a new world—the domain of a very heavy fundamental fermion—in which the strange and wonderful may greet us.

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