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Chris Quigg

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Chris Quigg*

Fermi National Accelerator Laboratory, Batavia, Illinois 60510
Department of Physics, Princeton University, Princeton, New Jersey 08540

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*E-mail:quigg@fnal.gov.

Top is a most remarkable particle, even for a quark. A single top quark weighs 175 GeV/c^2, 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 indivisible, for we discern no structure at a resolution approaching 10^{-18} m. Top's expected lifetime of about 0.4 yoctosecond (0.4×10^{-24} s) makes it by far the most ephemeral of the quarks. The compensation for this exceedingly brief life is a measure of freedom: top decays before it experiences the confining influence of the strong interaction. In spite of its fleeting existence, the top quark helps shape the character of the everyday world.

Top Search and Discovery

Ever since the existence of the b-quark was inferred from the discovery of the Υ (Upsilon) family of resonances at Fermilab in 1977, particle physicists have been on the lookout for its partner, called top. The long search, which occupied 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 and DØ experiments at Fermilab [1].

Top is the last of the fundamental constituents of subnuclear matter that gauge theories of the strong, weak, and electromagnetic interactions and a wealth of experimental information have led particle physicists to expect. Top's existence was required lest quantum corrections clash with the symmetries of the electroweak theory, leaving it internally inconsistent. It was signalled too by the pattern of disintegrations of the b-quark and by the characteristics of the b-quark's neutral–weak-current interactions measured in e^+e^- annihilations into $b\bar{b}$ pairs.

Higher-order processes involving virtual top quarks are an important element in quantum corrections to the predictions the electroweak theory makes for many observables. A case in point is the total decay rate, or width, of the Z^0 boson, which has been measured to exquisite precision at the CERN and SLAC Z factories. The comparison of experiment and theory shown in the inset to Figure 1 favors a top mass in the neighborhood of 180 GeV/c^2. The top mass favored by simultaneous fits to many electroweak observables is shown as a function of time in Figure 1.

Figure 1: $m_t(t)$

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

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

By 1994, an impressive body of circumstantial evidence pointed to the existence of a top quark with a mass of 175 ± 25 GeV/c^2. Finding top and measuring its mass directly emerged as a critical test of the understanding of 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, for only one interaction in ten billion results in a top-antitop pair. Observing traces of the disintegration of top into a b-quark and a W-boson, the agent of the weak interaction, required highly capable detectors and extraordinary attention to experimental detail. Both the b-quark and the W-boson are themselves unstable, with many multibody decay modes. The b-quark's mean lifetime is about 1.5 ps. It can be identified by a decay vertex displaced by a fraction of a millimeter from the production point, or by the low-momentum electron or muon from the semileptonic decays $b \to ce\nu$, $b \to c\mu\nu$, each with branching fraction about 10%. The W boson decays after only 0.3 ys on average into $e\bar{\nu}_e$, $\mu\bar{\nu}_\mu$, $\tau\bar{\nu}_\tau$, or a quark and antiquark (observed as two jets of hadrons), with probabilities 1/9, 1/9, 1/9, and 2/3. The characteristic modes in which $t\bar{t}$ production can be sought are shown with their relative weights in Table 1.

Table 1:
Search modes

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 + jets channels ($e, \mu +$jets) occur when one W boson decays into leptons and the other decays through quarks into hadrons.

Figure 2:
DØ Simulation

Another challenge to experiment is the complexity of events in high-energy $\bar{p}p$ collisions. The top and antitop 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 penetrating muons near the top center and bottom right, which suggest two $W \to \mu\nu$ decays, and the low-momentum muon at lower left. Separating the top-quark sheep from the goats is not for the faint of heart!

Each detector is an intricate apparatus operated by an international collaboration of about 450 physicists. The tracking devices, calorimeters, and surrounding iron for muon identification occupy a volume about three stories high and weigh about 5000 tons. The Collider Detector at Fermilab (CDF), a magnetic detector with solenoidal geometry, profited from its high-resolution silicon vertex detector (SVX) to tag b-quarks with good efficiency. The DØ Detector (D-Zero) has no central magnetic field, emphasizing instead calorimetric measurement of the energies of produced particles.

Figure 3:
CDF SVX event

The first evidence for top was presented in April 1994 by the CDF Collaboration, led by Bill Carithers of Lawrence Berkeley Laboratory and Mel Shochet of the University of Chicago [5]. In a sample of 19.3 events per picobarn of cross section (19.3 pb^{-1}), CDF found 12 events consistent with either two W bosons, or a W boson and at least one b-quark. One of the $e\mu$ candidates, shown in Figure 3, shows the power of the SVX to resolve a b-decay vertex just 0.3 mm from the interaction point. Although the sample lacked the statistical weight needed to claim discovery, the event characteristics were consistent with the $t\bar{t}$ interpretation, with a top mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. A few months later, the DØ Collaboration reported an excess of candidates (9 events with an expected background of 3.8 ± 0.9) in a 13.5-pb^{-1} sample [6].

The discovery was not far behind. By February 1995, both groups had quadrupled their data sets. The CDF Collaboration, now led by Carithers and Giorgio Bellettini of the University of Pisa, found 6 dilepton candidates with an anticipated background of 1.3 ± 0.3 events, plus 37 b-tagged events containing a W-boson and at least three jets [7]. The DØ Collaboration, with Paul Grannis of Stony Brook and Hugh Montgomery of Fermilab as spokespersons, reported 17 top candidates with an expected background of 3.8 ± 0.6 [8]. Taken together, the populations and characteristics of different event classes provided irresistible evidence for a top quark with a mass in the anticipated region: $176 \pm 8 \pm 10$ GeV/c^2 for CDF, and $199^{+19}_{-21} \pm 22$ GeV/c^2 for DØ. The top-antitop production rate is in line with theoretical predictions.

Box: The Third Generation

Today, with the event samples approximately doubled again, the top mass is measured as 176.8 ± 6.5 GeV/c^2 by CDF and 173.3 ± 8.4 GeV/c^2 by DØ for a world average of 175.5 ± 5.1 GeV/c^2.

Now that we have the top quark, what do we do with it?

The Top Quark and the W Boson

The influence of virtual top quarks was the basis for the expectations for the top-quark mass from precision measurements of electroweak observables. As m_t becomes known more precisely from direct measurements, it will be possible to compare predictions that depend sensitively on m_t with new observations. Among the most incisive will be the comparison of the W-boson mass with theoretical calculations.

The W-boson mass is given as

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

where M_Z is the mass of the Z^0 boson, $\sin^2\theta_W \approx 0.232$ is the weak mixing parameter, and $\Delta\rho$ represents quantum corrections. The most important of these are shown in Figure 4. The inequality of the t- and b-quark masses violates weak-isospin symmetry and results in

$$\Delta\rho = 3G_F m_t^2/8\pi^2\sqrt{2} + \ldots, \quad (2)$$

where the unwritten terms include a logarithmic dependence upon the mass of the Higgs boson, the hitherto undetected agent of electroweak symmetry breaking.

Figure 4: $M_W(m_t)$

Predictions for M_W as a function of the top-quark mass are shown in Figure 4 for several values of the Higgs-boson mass [9]. Current measurements are consistent with the electroweak theory, but do not yet provide any precise hints about the mass of the Higgs boson. The uncertainty on the world-average M_W has now reached about 100 MeV/c^2. An uncertainty of $\delta M_W = 50$ MeV/c^2 seems a realistic possibility both at the Tevatron and at CERN's LEP200, where observations of the reaction $e^+e^- \to W^+W^-$ near threshold began in 1996. Improving δm_t below 5 GeV/c^2 will then make for a demanding test of the electroweak theory that should yield interesting clues about the Higgs-boson mass. Over the next decade, it seems possible to reduce δm_t to 2 GeV/c^2 at Fermilab and δM_W to about 20 MeV/c^2 at the Tevatron and LEP200. That will set the stage for a crucial test of the electroweak theory when (and if) the Higgs boson is discovered.

Is It Standard Top?

The top-quark discovery channels listed in Table 1 all arise from the production of top-antitop pairs, and all contain a $b\bar{b}$ pair. We expect that top decays other than the observed $t \to bW^+$ mode are strongly suppressed. Unless the $t \to bW^+$ rate is unexpectedly small, which could occur if top had a large coupling to a more massive, fourth-generation b', the decays $t \to (s \text{ or } d)W^+$ should be extremely rare. It is important to test this expectation by looking for the rare decays directly, or by comparing the number of observed (0, 1, and 2) b-tags in a $t\bar{t}$ sample with expectations derived from the measured efficiency for b-tagging. The CDF Collaboration has used the tagging method to show that $t \to bW$ accounts for $99 \pm 29\%$ of all $t \to W +$ anything decays [10].

Top pairs are produced in $\bar{p}p$ collisions through the strong interaction. A single top can be produced together with an antibottom in processes that involve the weak interaction. The elementary process $u\bar{d} \to$ virtual $W^+ \to t\bar{b}$ may in time give us an excellent measurement of the strength of the $Wt\bar{b}$ coupling.

In some supersymmetric models, top can be produced in the decays of heavy superpartners and can itself decay into lighter superpartners. This possibility encourages the careful comparison of the top-bearing events with conventional expectations, and emphasizes the importance of precision determinations of the top production cross section.

The rapid decay of the top quark means that there is no time for the formation of top mesons or top baryons. Accordingly, the spin orientation of the top quark at the moment of its production is reflected, without dilution, in the decay angular distribution of its decay products. The correlation between the spin of the top and antitop produces distinctive patterns in the structure of events that will enable us to probe the character of the $t \to bW^+$ transition.

Box: The Brief, Happy Life...

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

Because top is so massive, many decay channels may be open to it, in addition to the signature $t \to bW^+$ mode. The decay into a b-quark and a charged spin-zero particle P^+ may occur in multi-Higgs generalizations of the electroweak theory, in supersymmetric models, and in technicolor models. The decay rate for $t \to bP^+$ is similar to the $t \to bW^+$ rate, because both decays are semiweak. If the $t\bar{t}$ production rate were measured to be smaller than predicted by QCD, that would hint at nonstandard decays—and new physics. The lifetime of P^+, typically about 10^{-21} s = 1 zeptosecond, is far too short for it to be observed as a short track. P^+ might be recognized from its decays into heavy quarks or into $\tau\nu_\tau$. The general lesson is that top decays have the capacity to surprise.

Top and Electroweak Symmetry Breaking

What sets the masses of the fundamental fermions and bosons? In the standard electroweak theory, the Higgs boson gives masses to the gauge bosons

$W^{\pm}$ and Z^0, and to the quarks and leptons. The mechanisms are linked—both arise through the breaking of electroweak symmetry—but they are logically distinct. While the $W^{\pm}$ and Z^0 masses are predicted in terms of the coupling constants and the weak mixing parameter, every fermion mass is set by a separate Yukawa coupling. The mass of fermion f is

$$m_f = \zeta_f \frac{v}{\sqrt{2}}, \tag{3}$$

where $v/\sqrt{2} = (2G_F\sqrt{2})^{-1/2} \approx 176$ GeV is the vacuum expectation value of the Higgs field [13]. The Yukawa couplings range from $\zeta_e \approx 3 \times 10^{-6}$ for the electron to $\zeta_t \approx 1$ for top. Within the electroweak theory, we do not know the origin of these numbers and we haven't a clue how to calculate them.

Top's great mass suggests that top 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 the answer. We expect that experiments at CERN's Large Hadron Collider, which will explore 14-TeV proton-proton collisions beginning around the year 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 experiments that probe the natural scale of electroweak symmetry breaking.

This 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 improve the electroweak theory and make it more predictive seek to emulate the Bardeen–Cooper–Schrieffer theory of superconductivity. Resonances that decay into $t\bar{t}$ are natural consequences of these 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.

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 strong at low energies and forms a technifermion condensate that breaks chiral symmetry and gives masses to the gauge bosons. A generalization, 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 pairs. The top condensate hides the electroweak symmetry and gives masses to the ordinary fermions. Top-condensate models and technicolor both imply the existence of color-octet resonances that decay into $t\bar{t}$, for which the natural mass scale is a few hundred GeV/c^2. We are led to ask: Is there a resonance in $t\bar{t}$ production? How is it made? How else does it decay?

In the technicolor picture, which has been elaborated recently by Estia Eichten and Ken Lane [14], a color-octet analogue of the η' meson, called η_T, is produced in gluon-gluon interactions. The sequence $gg \to \eta_T \to (gg, t\bar{t})$ leads to distortions of the $t\bar{t}$ invariant-mass distribution, and of the two-jet invariant-mass distribution, but has a negligible effect on the $b\bar{b}$ invariant-mass distribution.

In the topcolor picture explored by Chris Hill and Stephen Parke [15], a massive vector "coloron" can be produced in quark-antiquark interactions. The coloron decays at comparable rates into $t\bar{t}$ and $b\bar{b}$ and can appear as a broad resonance peak in both channels. There is no particular reason to expect a distortion of the invariant-mass spectrum of two jets that do not contain heavy quarks.

If an enhancement were seen in the $t\bar{t}$ channel, we would want to study the $t\bar{t}$ 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 occur for about 90% of the top pairs. The LHC's large rate of gg collisions would dramatically increase the contribution of η_T relative to the coloron.

Top Matters!

It is popular to say that top quarks were produced in great numbers in the fiery cauldron of the Big Bang some fifteen billion years ago, disintegrated in the merest fraction of a second, and vanished from the scene until my colleagues learned to create 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 world of diversity and change. But it is not the whole story; it invests the top quark 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 of quantum mechanics, top quarks and antiquarks wink in and out of an ephemeral presence in our world. Though they appear virtually, fleetingly, on borrowed time, top quarks have real effects.

Quantum effects make the coupling strengths of the fundamental interactions—appropriately normalized analogues of the fine-structure constant α—vary with the energy scale on which the coupling is measured. The fine-structure constant itself has the familiar value $1/137$ in the low-energy (or long-wavelength) limit, but grows to about $1/129$ at the mass of the Z^0 boson, about 91 GeV/c^2. Vacuum-polarization effects make the effective electric charge increase at short distances or high energies.

In unified theories of the strong, weak, and electromagnetic interactions, all the coupling "constants" take on a common value, α_U, at some high 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 α_s that we experience at low energies [16]. Assuming three generations of quarks and leptons, we evolve α_s downwards in energy from the unification scale [17]. The leading-logarithmic behavior is given by

$$1/\alpha_s(Q) = 1/\alpha_U + \frac{21}{6\pi}\ln(Q/M_U) \ , \tag{4}$$

for $M_U > Q > 2m_t$. The positive coefficient $+21/6\pi$ means that the strong coupling constant α_s is smaller at high energies than at low energies. This behavior—opposite to the familiar behavior of the electric charge—is the celebrated property of asymptotic freedom. In the interval between $2m_t$ and $2m_b$, the slope $(33 - 2n_f)/6\pi$ (where n_f is the number of active quark flavors) steepens to $23/6\pi$, and then increases by another $2/6\pi$ at every quark threshold. At the boundary $Q = Q_n$ between effective field theories with $n-1$ and n active flavors, the coupling constants $\alpha_s^{(n-1)}(Q_n)$ and $\alpha_s^{(n)}(Q_n)$ must match. This behavior is shown by the solid line in Figure 5.

Figure 5:
$1/\alpha_s$ evolution

The dotted line in Figure 5 shows how the evolution of $1/\alpha_s$ changes if the top-quark mass is reduced. A smaller top mass means a larger low-energy value of $1/\alpha_s$, so a smaller value of α_s.

Neglecting the tiny "current-quark" masses of the up and down quarks, the scale parameter Λ_{QCD} is the only mass parameter in QCD. It determines the scale of the confinement energy that is the dominant contribution to the proton mass. To a good first approximation,

$$M_{\text{proton}} \approx C\Lambda_{\text{QCD}}, \tag{5}$$

where the constant of proportionality C is calculable using techniques of lattice field theory.

To discover the dependence of Λ_{QCD} upon the top-quark mass, we calculate $\alpha_s(2m_t)$ evolving up from low energies and down from the unification scale, and match:

$$1/\alpha_U + \frac{21}{6\pi}\ln(2m_t/M_U) = 1/\alpha_s(2m_c) - \frac{25}{6\pi}\ln(m_c/m_b) - \frac{23}{6\pi}\ln(m_b/m_t). \tag{6}$$

Identifying

$$1/\alpha_s(2m_c) \equiv \frac{27}{6\pi}\ln(2m_c/\Lambda_{\text{QCD}})\,, \tag{7}$$

we find that

$$\Lambda_{\text{QCD}} = e^{-6\pi/27\alpha_U}\left(\frac{M_U}{1\text{ GeV}}\right)^{21/27}\left(\frac{2m_t\cdot 2m_b\cdot 2m_c}{1\text{ GeV}^3}\right)^{2/27}\text{ GeV}\ . \tag{8}$$

We conclude that, in a simple unified theory,

$$\frac{M_{\text{proton}}}{1\text{ GeV}} \propto \left(\frac{m_t}{1\text{ GeV}}\right)^{2/27}\ . \tag{9}$$

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 values of M_U and α_U, and haven't yet calculated precisely the constant of proportionality between the proton mass and the QCD scale parameter. Never mind! The important lesson—no surprise to any twentieth-century physicist—is that the microworld does determine the behavior of the quotidian. We will fully understand the origin of one of the most important parameters in the everyday world—the mass of the proton—only by knowing the properties of the top quark [18].

Top Priorities

Like the end of many a scientific quest, the discovery of top marks a new opening [19]. The first priority, already well advanced, is to continue refining the measurements of the top mass. It is now possible to begin asking how precisely top fits the profile of anticipated properties in its production and decay. 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 top-antitop production that would give new clues about the breaking of electroweak symmetry. On the theoretical front, the large mass of top encourages us to think that the two problems of mass 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, samples twenty times greater than the current samples should be in hand, thanks to the increased event rate made possible by Fermilab's Main Injector and upgrades to CDF and DØ. Boosting the Tevatron's energy to 1 TeV per beam will increase the top yield by nearly 40%. Further enhancements to Fermilab's accelerator complex are under study. A decade from now, the Large Hadron Collider at CERN will produce 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 known as 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 often leads to others. Top opens a new world—the domain of a very heavy fermion—in which the strange and wonderful may greet us.

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Box: The Third Generation

The possibility that CP violation arises from complex elements of the quark mass matrix, for theories with at least three generations, was raised by M. Kobayashi and T. Maskawa, *Prog. Theoret. Phys. (Kyoto)* **49,** 652 (1973). In the following year, the discovery of the J/ψ family of resonances by Samuel C. C. Ting's team at Brookhaven National Laboratory and by Burton Richter and collaborators at the Stanford Linear Accelerator Center completed the second generation of quarks and leptons. The J/ψ states proved to be resonances of a charmed quark and charmed antiquark when mesons containing a single charmed quark were observed by the SLAC–Berkeley team [G. Goldhaber, *et al.*, *Physical Review Letters* **37**, 255 (1976); I. Peruzzi, *et al.*, *ibid.* **37**, 569 (1976)]. The new charmed quark joined the three classical quarks in two pairs (up, down; charm, strange) that matched the pattern of leptons (electron neutrino, electron; muon neutrino, muon) known since the early 1960s.

In 1975, Martin Perl and collaborators [*Physical Review Letters* **35**, 1489 (1975)] discovered the τ lepton in electron-positron annihilations in the SPEAR storage ring at the Stanford Linear Accelerator Center. In a sample of about 36,000 events, they found 64 that consisted of a muon and electron of opposite charges, plus at least two undetected particles. The existence of the tau neutrino is inferred from the undetected (or "missing") energy of tau decay, much as the continuous electron energy spectrum in beta decay led Pauli to postulate the electron (anti)neutrino. The tau neutrino has not yet been detected directly. A tau neutrino that interacts in matter and materializes into a tau lepton is the hoped-for signature in a new generation of neutrino-oscillation searches.

The discovery in 1977 new family of heavy mesons was the first indication for a fifth quark, the b (bottom, or beauty), with a mass $m_b \approx 5$ GeV/c^2 and charge $-1/3$. The $\Upsilon(9.46$ GeV/$c^2)$ and two of its excitations were first observed by Leon Lederman and his collaborators at Fermilab in the reaction $p + (\text{Cu,Pt}) \to \mu^+\mu^- +$ anything [S. W. Herb, *et al.*, *Physical Review Letters* **39**, 252 (1977)]. The Υ family was quickly identified as a set of levels of a b-quark bound to a b-antiquark. Comparison of the $b\bar{b}$ spectrum with the charmonium (J/ψ) spectrum showed that the interquark force was independent of the flavor of the quarks, as expected from quantum chromodynamics. Hadrons containing a single b-quark were identified in due course in the CLEO Detector at the Cornell Electron Storage Ring [S. Behrends, *et al.* (CLEO Collaboration), *Physical Review Letters* **50**, 881 (1983)]. The electroweak theory predicts large CP-violating effects in certain B-meson decays. The search for these effects is a primary motivation for B Factories and other high-statistics B experiments.

Studies of Z^0 production and decay in electron-positron annihilations demonstrate that there are three species of light neutrinos. The invisible decay rate of the Z^0 is determined by subtracting the measured rates for decays into quarks and charged leptons from the total Z^0 decay rate. The invisible rate is assumed to arise from decays into N_ν species of neutrino-antineutrino pairs, each contributing the rate given by the standard model. Since there are only three light neutrinos, we conclude that there are three ordinary generations of quarks and leptons.

The top quark was found in collisions of 900-GeV protons on 900-GeV antiprotons at Fermilab in 1995 by the CDF and DØ Collaborations.

Quarks and leptons of the third generation.

Quark	Charge	Mass	Mean Life
t	+2/3	$\sim$ 175 GeV/c^2	$\sim$ 0.4 ys (?)
b	−1/3	$\sim$ 4.7 GeV/c^2	$\sim$ 1.5 ps

Lepton	Charge	Mass	Mean Life
ν_τ	0	$<$ 24 MeV/c^2	$\cdots$
τ	−1	1777.0 MeV/c^2	$\sim$ 0.3 ps

Box: The Brief, Happy Life of the Top Quark

The dominant decay of a heavy top quark is into a bottom quark and a W-boson. This process is called *semiweak,* because the rate is proportional to only one power of the Fermi constant G_F, whereas familiar weak processes like β-decay occur with rates proportional to G_F^2. The top-quark decay rate is approximately [11]

$$\begin{aligned}\Gamma(t \to bW^+) &= \frac{G_F M_W^2}{8\pi\sqrt{2}} \frac{|V_{tb}|^2}{m_t^3} \left[\frac{(m_t^2 - m_b^2)^2}{M_W^2} + m_t^2 + m_b^2 - 2M_W^2 \right] \\ &\quad \times \sqrt{[m_t^2 - (M_W + m_b)^2][m_t^2 - (M_W - m_b)^2]}.\end{aligned}$$

Here m_t, m_b, and M_W are the masses of top, bottom, and the W-boson, and V_{tb} measures the strength of the $t \to bW^+$ coupling. To the extent that the b-quark mass is negligible, the decay rate can be recast in the form

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

which grows rapidly with increasing top mass.

If there are only three generations of quarks, so that V_{tb} has a magnitude close to unity, then for a top-quark mass of 175 GeV/$c^2$the partial width is

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

which corresponds to a top lifetime $\tau_t \approx 0.4 \times 10^{-24}$ s, or 0.4 yoctosecond.

The confining effects of the strong interaction act on a time scale of a few yoctoseconds set by 1/the scale energy of quantum chromodynamics, Λ_{QCD}. This means that a top quark decays long before it can be hadronized. There will be no discrete lines in toponium $(t\bar{t})$ spectroscopy, and indeed no dressed hadronic states containing top. Accordingly, the characteristics of top production and of the hadrons accompanying top in phase space should be calculable in perturbative QCD [12]. In top decay, we see the decay of an isolated quark, rather than the decay of a quark bound in a hadron.

Table 1: Channels studied in the search for the reaction $\bar{p}p \to t\bar{t}+$ anything. Those in parentheses have not been exploited in experiments. All but the 4 jets $b\bar{b}$ mode must have significant "missing" transverse energy, carried away by the neutrino(s) in the leptonic decay of the W boson(s).

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)
4 jets $b\bar{b}$	36/81

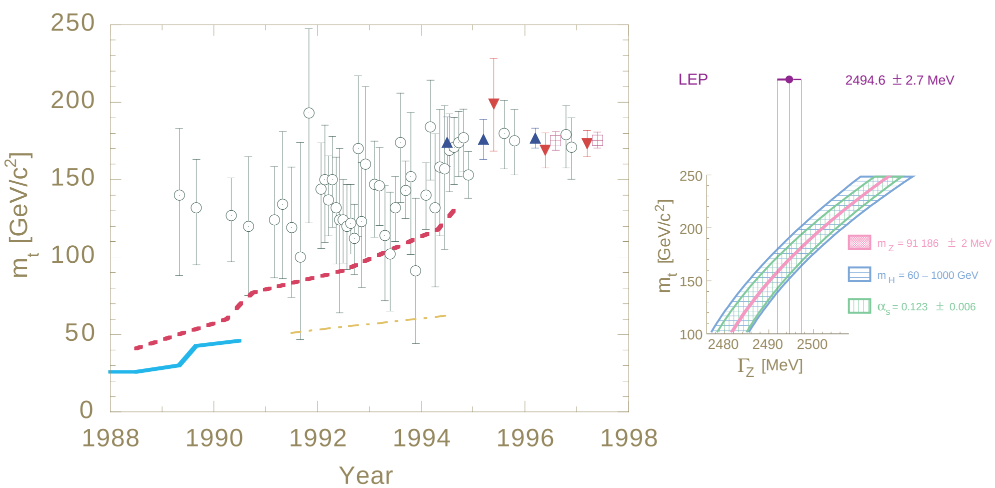

Figure 1: Indirect determinations of the top-quark mass from fits to electroweak observables (open circles) and 95% confidence-level lower bounds on the top-quark mass inferred from direct searches in e^+e^- annihilations (solid line) and in $\bar{p}p$ collisions, assuming that standard decay modes dominate (broken line). An indirect lower bound, derived from the W-boson width inferred from $\bar{p}p \to (W \text{ or } Z) +$ anything, is shown as the dot-dashed line. Direct measurements of m_t by the CDF (triangles) and DØ (inverted triangles) Collaborations are shown at the time of initial evidence, discovery claim, and today. The current world average from direct observations is shown as the crossed box. For sources of data, see Ref. [3]. *Inset:* Electroweak theory predictions for the width of the Z^0 boson as a function of the top-quark mass, compared with the width measured in LEP experiments (Ref. [4]).

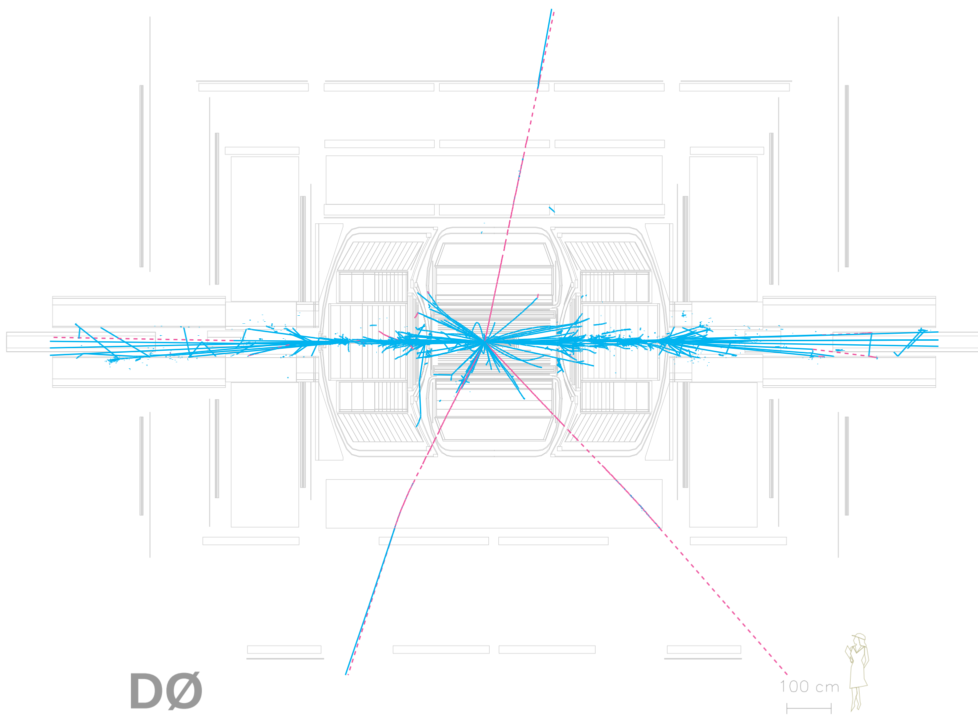

Figure 2: Simulation of a top-antitop event produced in a 2.0-TeV proton-antiproton collision in the upgraded DØ detector, which will operate at the Fermilab Tevatron starting in 1999. The beam particles entered horizontally and collided at the center of the picture. The light blue lines are the trajectories of charged hadrons, electrons and positrons produced in the collision; the pink lines represent muons. In this event, both W-bosons produced in top decays subsequently produced high energy muons (the tracks at upper center and lower right). A third muon (lower left) originated in the decay of a b-quark; its lower momentum can be inferred from the noticeable curvature of its track in the magnetized-iron section of the detector. The event was generated using the ISAJET Monte Carlo of F.E. Paige and S. Protopopescu and the detector was simulated using the GEANT package from the CERN program library. I thank John Womersley for supplying this figure.

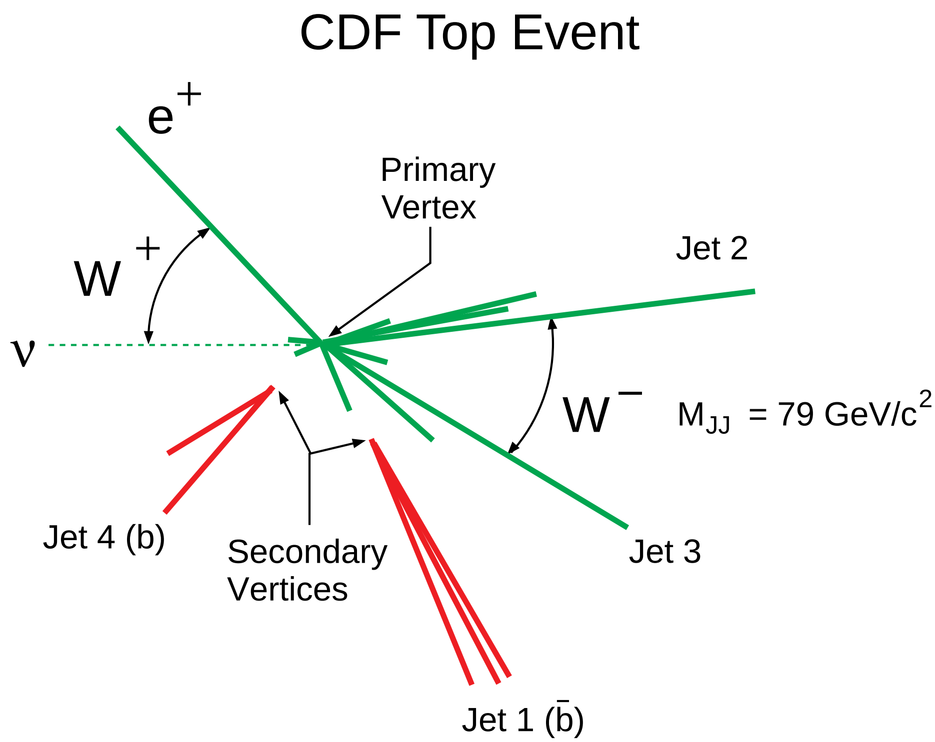

Figure 3: Candidate event for top-antitop production, as seen by CDF's silicon vertex detector at the Tevatron. Both top quarks decay at the $p\bar{p}$ collision vertex into a W-boson plus a bottom quark. The W^+ decays to e^+ plus an invisible neutrino, and the W^- decays into a quark and antiquark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

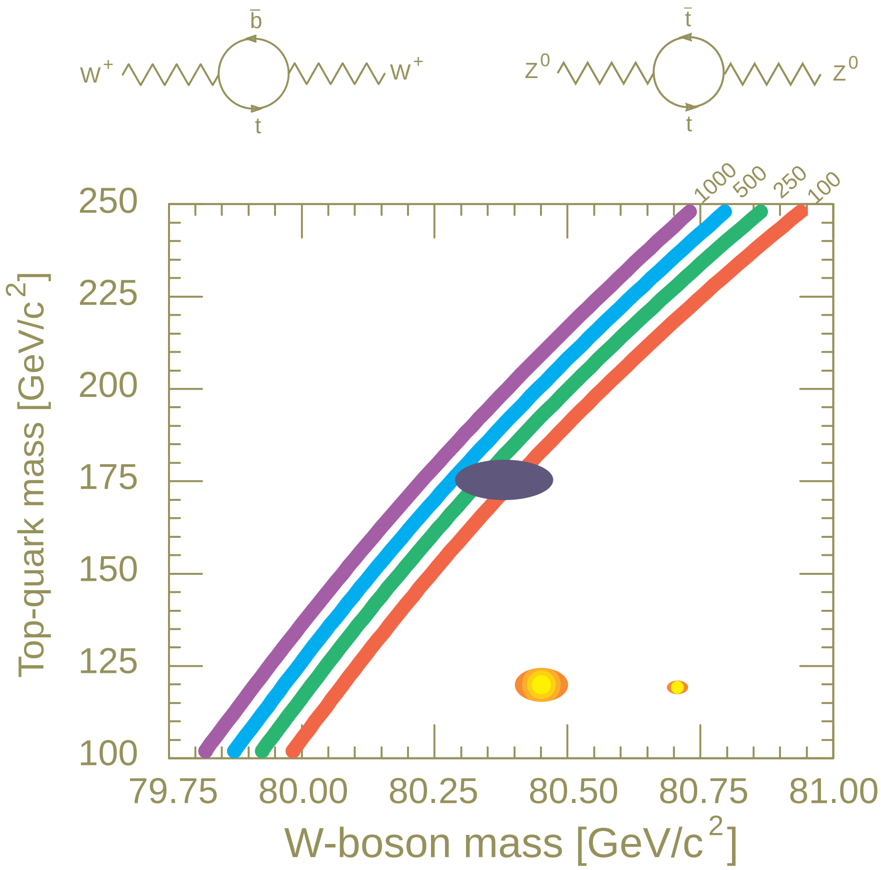

Figure 4: Correlation between the top-quark mass and the W-boson mass in the standard electroweak theory. From left to right, the bands correspond to Higgs-boson masses of 1000, 500, 250, and 100 GeV/c^2. The thickness of the bands expresses the effect of plausible variations in the value of $\alpha(M_Z)$. The dark region is the one-standard-deviation error ellipse from the current world averages, $m_t = 175.5 \pm 5.1$ GeV/c^2 and $M_W = 80.38 \pm 0.09$ GeV/c^2. Also shown are the one-standard-deviation error ellipses for precisions expected in the future: ($\delta M_W = 50$ MeV/c^2, $\delta m_t = 5$ GeV/c^2) and ($\delta M_W = 20$ MeV/c^2, $\delta m_t = 2$ GeV/c^2). Examples of the heavy-quark loops that give rise to $\Delta\rho$ are shown at the top of the figure.

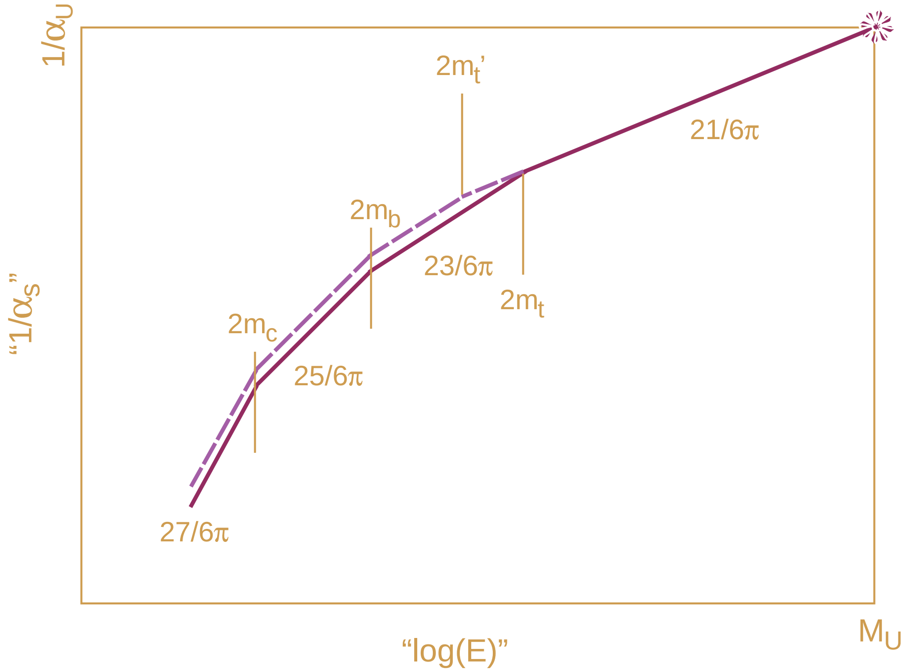

Figure 5: Two evolutions of the strong coupling constant α_s. A smaller value of the top-quark mass leads to a smaller value of α_s.