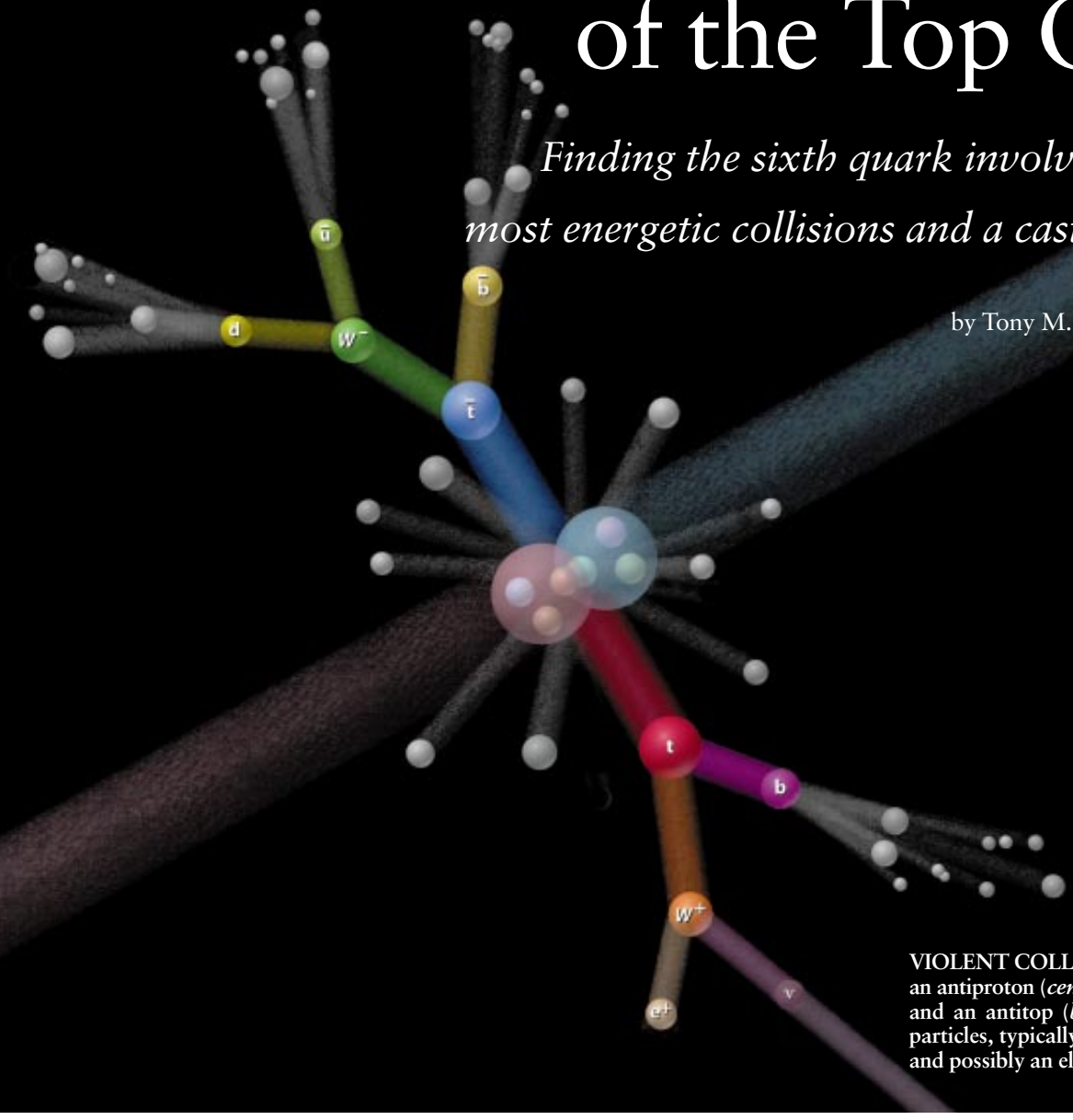
The Discovery of the Top Quark

Finding the sixth quark involved the world's most energetic collisions and a cast of thousands

by Tony M. Liss and Paul L. Tipton



VIOLENT COLLISION between a proton and an antiproton (*center*) creates a top quark (*red*) and an antitop (*blue*). These decay to other particles, typically producing a number of jets and possibly an electron or positron.

MICHAEL GOODMAN

In March 1995 scientists gathered at a hastily called meeting at Fermilab—the Fermi National Accelerator Laboratory in Batavia, Ill., near Chicago—to witness a historic event. In back-to-back seminars, physicists from rival experiments within the lab announced the discovery of a new particle, the top quark. A decades-long search for one of the last missing pieces in the Standard Model of particle physics had come to an end.

The top quark is the sixth, and quite possibly the last, quark. Along with leptons—the electron and its relatives—quarks are the building blocks of matter. The lightest quarks, designated "up" and "down," make up the familiar protons and neutrons. Along with the electrons, these make up the entire periodic table. Heavier quarks (such as the charm, strange, top and bottom quarks) and leptons, though abundant in the early moments after the big bang, are now commonly produced only in accelerators. The Standard Model describes the interactions among these building blocks. It requires that leptons and quarks each come in pairs, often called generations.

Physicists had known that the top must exist since 1977, when its partner, the bottom, was discovered. But the top proved exasperatingly hard to find. Although a fundamental particle with no discernible structure, the top quark turns out to have a mass of 175 billion electron volts (GeV)—as much as an atom of gold and far greater than most theorists had anticipated. The proton, made of two ups and one down, has a mass of just under 1 GeV. (The electron volt is a unit of energy, related to mass via $E = mc^2$.)

Creating a top quark thus required concentrating immense amounts of en-

ergy into a minute region of space. Physicists do this by accelerating two particles and having them smash into each other. Out of a few trillion collisions at least a handful, experimenters hoped, would cause a top quark to be created out of energy from the impact. What we did not know was how much energy it would take. Although many properties of the top, such as its charge and spin (intrinsic angular momentum), were predicted by the Standard Model, the mass was unconstrained.

Although particles can be created from nothing but energy, certain features, such as electrical charge, cannot—these are "conserved." A top quark cannot be born all by itself. The easiest way to make a top is along with an antitop—identical in mass but with opposite signs for other properties, so that conserved quantities cancel out.

In 1985, when the Fermilab collider was first activated, the search for the top had already been going on for eight years. Early forays at the Stanford Linear Accelerator Center in Palo Alto, Calif., and at DESY in Hamburg, Germany, turned up nothing. Over the years the hunt moved on to different accelerators as they came into operation with ever more energetic particle beams. In the early 1980s at CERN, the European laboratory for particle physics near Geneva, beams of protons and antiprotons hitting one another at energies up to 315 GeV generated two new particles, the *W* and the *Z*.

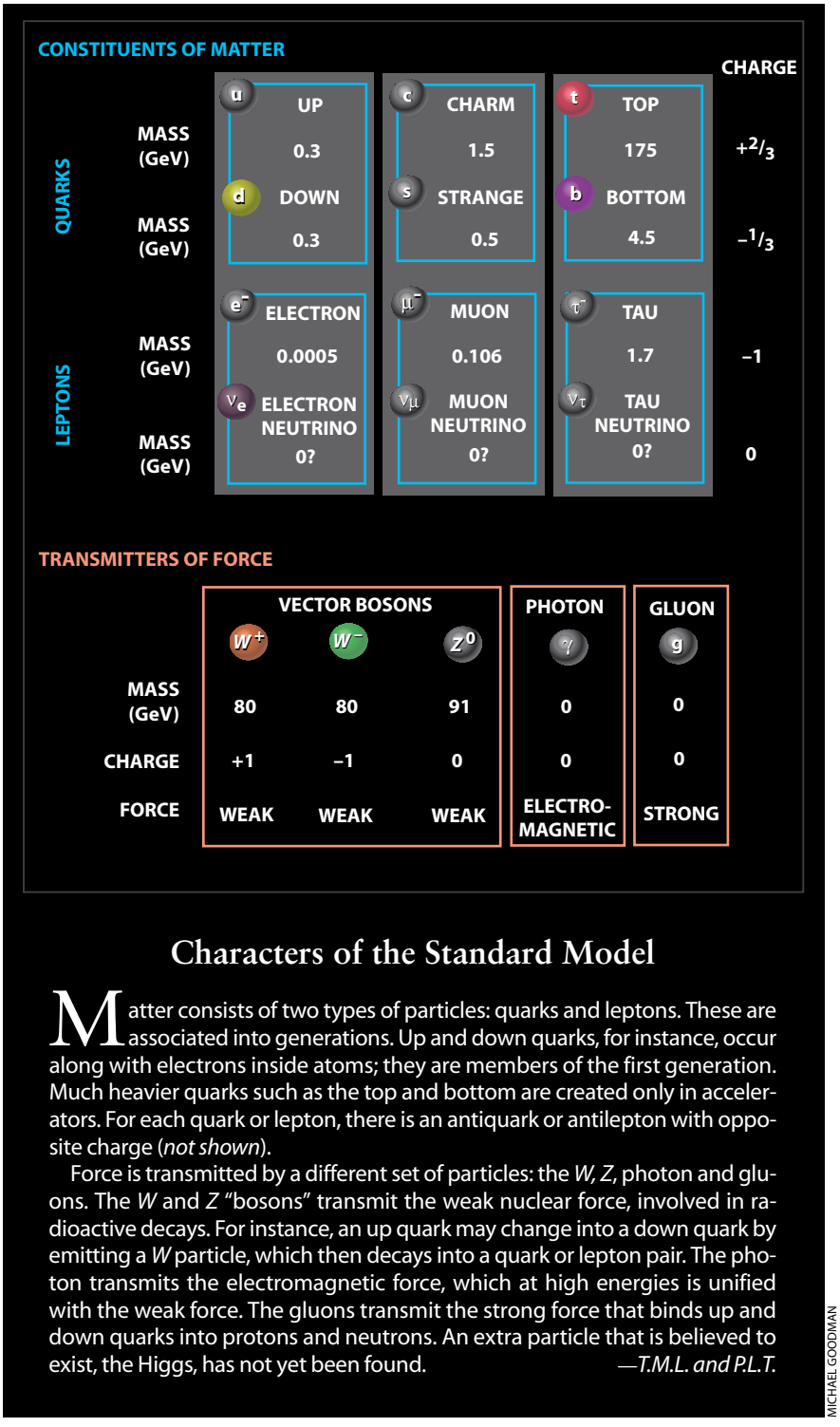
Whereas quarks and leptons constitute matter, these particles transmit force—in particular the weak force, responsible for some types of radioactive decay. Their discovery provided further confirmation of the Standard Model, which had accurately predicted their masses. It was widely believed that the discovery of the top quark at CERN was imminent.

Finding it would still be a difficult feat. When protons and antiprotons hit one another at high energies, the actual collision is between their internal quarks and gluons. Each quark or gluon carries just a modest fraction of the total energy of its host proton or antiproton, yet the collision must be energetic enough to generate top quarks. Such collisions are rare, and the higher the required energy—that is, the higher the top mass—the rarer they are.

By 1988 the top had not yet been observed at CERN; the experimenters concluded its mass must be greater than 41 GeV. Meanwhile the collider at Fermilab was just coming into its own with our young CDF (Collider Detector at Fermilab). A brief flurry of intense competition between us and a group at CERN brought the decade to a close without a top but with the knowledge that its mass could be no lower than 77 GeV.

By this time CERN had reached its limit. With its comparatively lower beam energies, its collisions would be unlikely to create top quarks heavier than 77 GeV. The competition was now between CDF and a new experiment across the accelerator ring at Fermilab, called DØ (pronounced "dee zero," after its location on the ring).

In the early 1980s Leon M. Lederman, then director of Fermilab, decided that CDF needed some local competi-

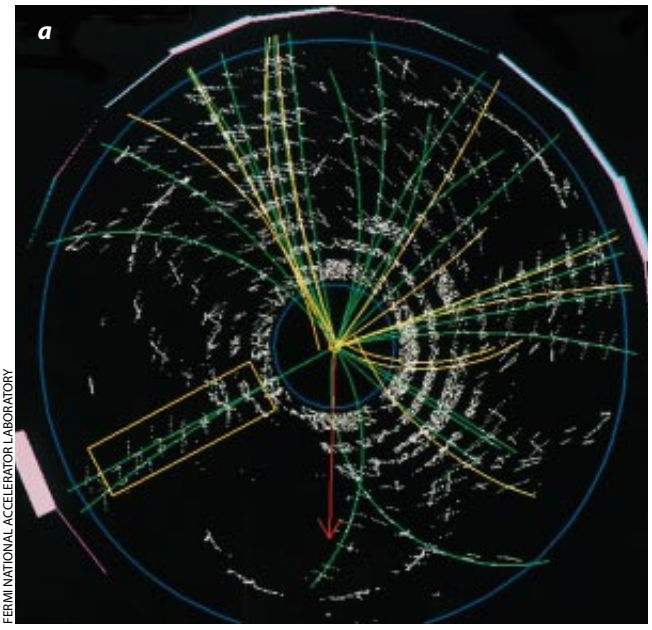


Characters of the Standard Model

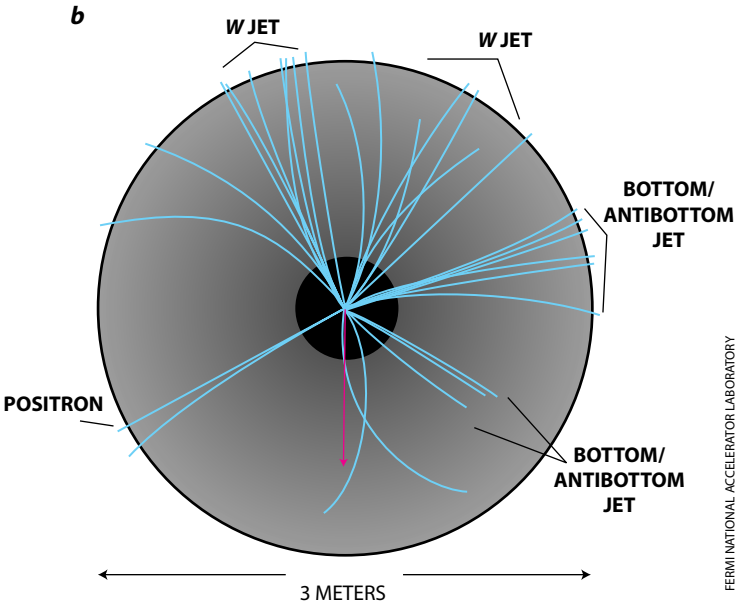
Matter consists of two types of particles: quarks and leptons. These are associated into generations. Up and down quarks, for instance, occur along with electrons inside atoms; they are members of the first generation. Much heavier quarks such as the top and bottom are created only in accelerators. For each quark or lepton, there is an antiquark or antilepton with opposite charge (*not shown*).

Force is transmitted by a different set of particles: the *W*, *Z*, photon and gluons. The *W* and *Z* "bosons" transmit the weak nuclear force, involved in radioactive decays. For instance, an up quark may change into a down quark by emitting a *W* particle, which then decays into a quark or lepton pair. The photon transmits the electromagnetic force, which at high energies is unified with the weak force. The gluons transmit the strong force that binds up and down quarks into protons and neutrons. An extra particle that is believed to exist, the Higgs, has not yet been found. *—T.M.L. and P.L.T.*

MICHAEL GOODMAN



FERMI NATIONAL ACCELERATOR LABORATORY



FERMI NATIONAL ACCELERATOR LABORATORY

tion. So we acquired in-house rivals: beginning in 1992 the DØ collaboration began to take data. In addition to spurring on our efforts, which it certainly did, having two complementary experiments studying the same physics was healthy in another way. Despite the best efforts of experimenters, spurious results can occur. Having a second experiment provides a cross-check.

Both CDF and DØ are international collaborations of more than 400 physicists. There are also numerous engineers, technicians and support personnel. The rival teams are independent of each other and never collaborate on their analyses. Each tries to beat the other to the punch. But it is friendly competition, and we regularly share tables in the cafeteria and enjoy both serious scientific conversation and a considerable amount of needling.

It is part of the unwritten code of both experiments that the results of any physics analysis are not discussed outside the collaboration until the analysis is finished. It was clear, however, that keeping any secrets in the top search was going to be tricky. Among other things, there are at least three physicists with a spouse on the rival team. To prevent the rumor mill from spinning out of control, we agreed with DØ that if one of the experimental groups was about to make a newsworthy announcement, it would give the other a week's notice.

The critical part of a high-energy experiment is the detector, which records the debris from a collision. Based on the best theoretical calculations, we expected that about one out of every 10 billion collisions would produce a top quark. The rest, though interesting for a host of other projects, would be a complicated backdrop from which the top would have to be extracted.

Over the course of a decade, both the CDF and DØ collaborations constructed enormous, complicated instruments, with hundreds of thousands of channels of electronics, in order to isolate the top's "signature"—the trace it would leave in the detectors. Whereas the CDF detector emphasizes the ability to track accurately the paths of individual particles in a magnetic field (in order to measure their momenta), the DØ device relies on an extremely precise segmented calorimeter, which measures the energy from each collision.

The top and antitop, once produced, decay almost instantly. Unlike the up and down quarks, which are stable, the top quark has a lifetime of only about 10^{-24} second. The Standard Model predicts that if heavy enough, the top quark will decay nearly all the time into a *W* and a bottom quark. So a top and antitop, if created, should generate two *W*s, a bottom and an antibottom.

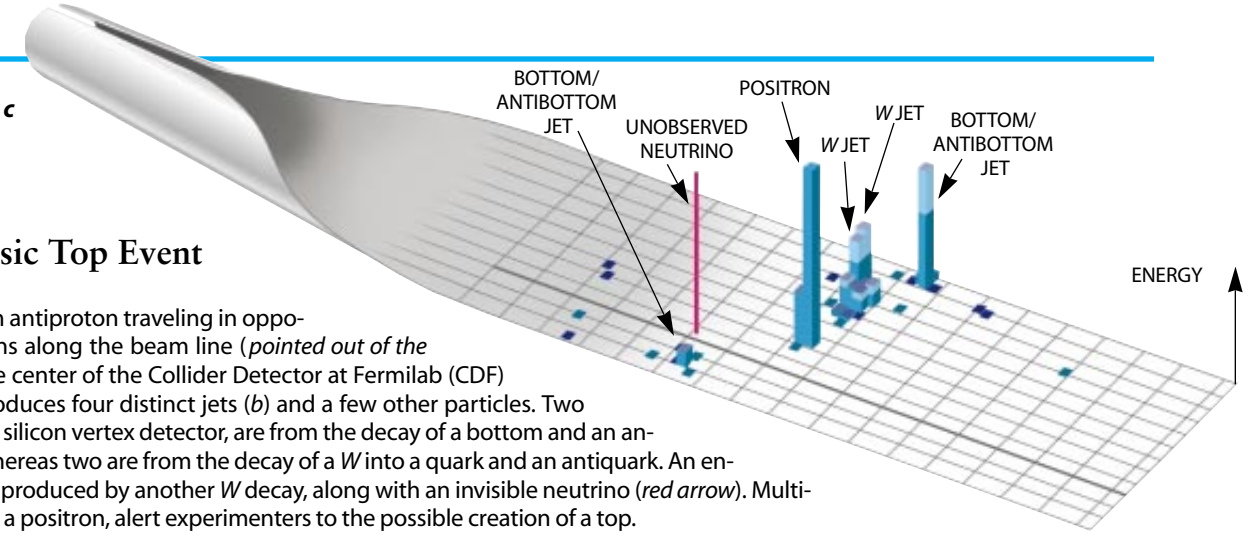
Unfortunately, neither the *W*s nor the bottom quarks can be directly observed. The *W*'s lifetime is about the same as the top's. The bottom, too, is unstable, though much longer lived than the top. Moreover, individual—or "bare"—quarks are never seen. The strong force, which binds the quarks together, ensures that quarks always appear stuck together with other quarks and antiquarks—in pairs called mesons or in triplets called baryons. (Protons and neutrons are examples of baryons.) When a quark emerges from a collision, it gets "dressed up" by a cloud of other quarks and antiquarks. What is observed is a jet, a directed beam of particles that have roughly the same direction of motion as the original quark.

A Barrage of Jets

The *W* can decay into a quark and an antiquark from the same generation, such as an up and an antidown. In this case, the quark and antiquark show up in a particle detector as two jets. But the *W* can also decay "leptonically"—into a charged and a neutral lepton from the same generation, such as an electron and a neutrino.

If the charged lepton is an electron or muon (a heavier copy of the electron), that particle can be directly observed in the detector. But if it is a tau (an even heavier copy of the electron), it decays quite rapidly, making it hard to identify. The neutrino (which has little or no mass) passes through a detector completely unobserved. Fortunately, its presence can be indirectly deduced because it carries away momentum. When the momenta of all the particles seen in the detector are added up, and a significant amount is missing, a neutrino is assumed to have carried it off.

By the time we started taking data in



JENNIFER C. CHRISTIANSEN

A Classic Top Event

A proton and an antiproton traveling in opposite directions along the beam line (*pointed out of the page*) collide at the center of the Collider Detector at Fermilab (CDF) (*a*). The impact produces four distinct jets (*b*) and a few other particles. Two jets, identified by a silicon vertex detector, are from the decay of a bottom and an antibottom quark, whereas two are from the decay of a *W* into a quark and an antiquark. An energetic positron is produced by another *W* decay, along with an invisible neutrino (*red arrow*). Multiple jets, along with a positron, alert experimenters to the possible creation of a top.

A magnetic field directed along the beam line curves the paths of the charged particles. The direction of curvature shows the sign of a particle's charge, and the extent reveals its momentum. Further, a calorimeter wraps around the beam line; it measures the energies of the emerging particles. It is shown unrolled (*c*). The height of a bar indicates the energy released by particles in the corresponding segment. The combination of devices allows experimenters to reconstruct the original event (*depicted on page 54*) with a high degree of confidence. —*T.M.L. and P.L.T.*

August 1992, we had pushed the top mass limit up to 91 GeV. This represented a milestone. The *W* mediates interactions between quarks in the same generation—and so between the top and the bottom. If the top were light enough—below about 75 GeV—a *W* might have produced a top by decaying to it, along with an antibottom. But now we knew that the only way we could find a top was by creating a top-antitop pair.

Among the most striking features of a top "event" are the jets produced by bottom quarks. The bottom quark travels in a jet as part of a meson or baryon, then decays roughly half a millimeter from where it was generated. In 1992 we started to track the particles in jets very precisely using a special instrument placed right on top of the region where the beams collide [see "The Silicon Microstrip Detector," by Alan M. Litke and Andreas S. Schwarz; SCIENTIFIC AMERICAN, May 1995]. This silicon vertex detector could locate the path of a particle to within 15 microns. By finding most of the tracks in a jet and extrapolating them backward, we hoped to find the point where the bottom quark decayed—and thereby identify it as a bottom jet.

The silicon technology was new, and we were concerned about the effects of trillions of particles passing through it. We knew that the entire detector could be fried in a fraction of a second if an accelerator glitch spilled the beams into it. We developed a special protection scheme, which would kick the beam safely away from the silicon if a problem was detected. Even as we were learning how to use the new vertex detector, the DØ collaboration was commissioning its own new detector on the opposite side of the accelerator ring.

In October 1992, just three months later, we saw our first hint of the top—an event characterized by a highly energetic muon and electron, lots of missing momentum and at least two jets. We analyzed that one event in excruciating detail, finally concluding that it was probably the real thing. DØ had also observed a similar event, the most likely interpretation of which involved a top. But a single event was not enough; we needed to observe the top in several different ways to make sure we were not being fooled by "background," events randomly mimicking the top signature. We began to analyze the data even more avidly than before, but when nothing particularly spectacular showed up, we knew we were in for a long haul.

Three groups were involved in analyzing the CDF results. Our first candidate for a top was found by a group searching among events with two leptons (from two *W* decays) and at least two jets (presumably from the bottom quarks). The two other groups were looking at events with a lepton (from one *W* decay) plus jets (from the other *W* decay and the bottom quarks). These two teams used different strategies to discern top events. One used the signals from the silicon vertex chamber, which was functioning very well, to identify bottom jets. The other looked for low-energy leptons, a telltale sign of a bottom-quark decay.

Nearly a year into the run, the mass limit was pushed to 108 GeV by CDF and later to 131 GeV by DØ, and we were still searching. Then, in July 1993, at a meeting of the entire CDF collaboration, the three groups presented the results of their ongoing analyses. Independently they were ambiguous, but together they offered persuasive evidence of a top. One of us (Tipton) was soon to go to a conference and present our latest results. After the meeting, we began to realize that if these results were presented, the audience would conclude that we had strong indications of a top. Our work was not yet ready for such intense scrutiny. So Tipton gave a talk focusing on our methods and the various difficulties in finding the top, but without the latest results. Soon rumors began to fly, some very accurate and others wildly off. We did not help matters when in the spring of 1994 we canceled a scheduled talk at a major conference.

Of the trillion or so collisions created within CDF, we had isolated 12 events that seemed to involve the creation of a top-antitop pair. Other physical processes can imitate the signature of such an event, and we had to estimate their likelihood. After months of effort, we estimated that roughly 5.7 of these background events were to be expected. The probability that background alone was responsible for these 12 events was about one in 400, leaving a small

chance that no tops had been observed.

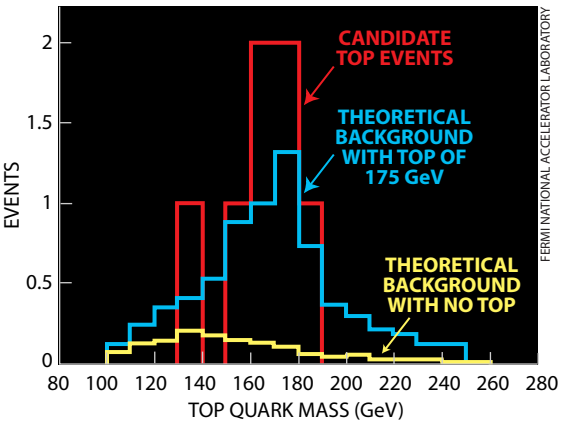
We subjected the 12 events to exhaustive analysis. One crucial study involved an attempt to "reconstruct" the top mass. By adding up the energies in the jets and leptons emitted by a (presumed) top-antitop pair, we could arrive at a value for the mass of the top. If the events were indeed from such a pair, the derived masses should fall close to some one value—the true top mass. In contrast, background events should give a much broader distribution. The mass indeed clustered in a narrow range, implying a top mass of about 175 GeV. To many of us, this was convincing evidence that we were not being fooled by background.

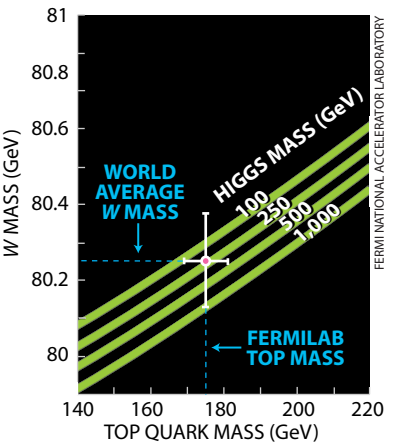
We initially planned to write four papers, one for each kind of analysis and one summarizing the results. At the next meeting of the entire collaboration, which we privately refer to as the October Massacre, the four groups writing the papers presented them to the rest of the collaboration. We were loudly and appropriately criticized because the papers were incomplete and did not paint a coherent picture. We abandoned the four-paper idea, and a small group (including the two of us) started instead to work on one.

The process was excruciating. Each person in the collaboration had a different view as to the strength of the claim we should make. It is hard to satisfy 400 editors. Moreover, as the effort finally drew to a close months later, we were even receiving corrections from physicists outside the collaboration, who were not supposed to have the drafts at all. After much debate, the collaboration decided to report the result not as a discovery but more tentatively as evidence for the existence of a top quark. On April 22, 1994, when we finally submitted the paper for publication, most of us thought it was a very good paper, the result of an excellent, democratic process we hoped never to have to repeat.

We hid all the drafts and documentation in a subdirectory of our secretary's computer, under the name of "pot." As might be expected, this feeble attempt at encryption did little to safeguard our secrets. Just before the announcement, two postdoctoral fellows posted a tongue-in-cheek theoretical paper on an electronic bulletin board. On the basis of a wild theory, they "predicted" the top mass—the CDF value to the last decimal place—and noted they were available for job offers.

A few days after the submission of the CDF paper, we held a seminar and press conference at Fermilab to announce the findings. The DØ collaboration presented its results as well. Although consistent with CDF's, the DØ data showed little compelling evidence for top quarks except for the one exceptional event recorded early in their run. The group had, however, assumed a low value for the top mass and as a consequence had not designed its search optimally.





TOP MASS reconstructed (*above*) from 12 initial events at the CDF cluster around the value of 175 GeV. But the accuracy with which the top and *W* masses are known is not enough (*below*) to predict the mass of the Higgs particle. It may vary from 100 to 1,000 GeV.

Within weeks DØ had finished its reanalysis (for a heavier top) and were observing some signs of it as well. Meanwhile both teams set to collecting more data. To confirm the finding, we would need at least twice as many top events. CDF put in a new silicon vertex detector; the old one had been damaged by radiation. Once again we had to learn its particular quirks, but in the end this device worked even better than the first. We wrote a new algorithm for using the vertex detector to detect top candidates, putting to good use our previous experience. Once we had enough data, we processed them with the completed algorithm. It was almost immediately obvious that we indeed had the top.

The final presentations, made on March 2, 1995, showed overwhelming evidence for the top quark from both CDF and DØ. Both teams reported a probability of less than one in 500,000 that their top quark candidates could be explained by background alone.

Since then, we have acquired more than 100 top events. We have also made preliminary searches for phenomena beyond the Standard Model. The extremely large mass of the top—the current value is 175.6 GeV—suggests that it may be fundamentally different from the other quarks, and therein lies the hope that it may lead us past the Standard Model. Although successful, this model leaves many questions unanswered.

Within the Standard Model the weak interaction, mediated by the *W* and *Z* particles, and the electromagnetic interaction, transmitted by photons, are unified into a single "electroweak" interaction at very high energies. Such energies existed in the very early universe. In the low-energy world in which we live, the electromagnetic and weak interactions behave very differently. The mechanism behind the "breaking" of their initial symmetry is not known, but in the simplest model it is caused by a new particle called the Higgs.

At high energies, when the symmetry exists, the *W*, *Z*, photon, leptons and quarks are all massless. At lower energies, when the symmetry breaks, the *W* and the *Z* interact with the Higgs and become massive. The quarks and leptons also acquire masses in the process. But whereas the *W* and *Z* masses can be calculated from the Standard Model, the quark and lepton masses have to be inserted by means of adjustable parameters that describe how strongly each type of quark or lepton interacts, or "couples," with the Higgs.

For an electron, which is very light, the interaction strength is 3×10^{-6}. For a top quark, it is almost exactly unity.

This relatively strong coupling with the Higgs, and to some extent the mystique associated with a value of unity, suggests that the top quark may have a special role. We do not yet know what it is. Certainly the top's great mass makes it the most influential quark, in terms of its interactions with other particles. A very precise measurement of the top's mass, for example, along with that of a *W,* would lead to a prediction for the Higgs's mass.

There are ways of breaking the symmetry of electroweak theory that do not invoke an elementary Higgs particle. In one candidate theory the Higgs is replaced by a top-antitop pair. This theory predicts the existence of new, heavy particles that decay into top-antitop pairs. Such an effect would enhance the rate of production of top quarks.

Over the Top

The sheer enormousness of the top's mass makes its decays fertile ground for new particle searches. Some theorists have speculated that a few of the events collected by CDF may contain supersymmetric particles [see "Is Nature Supersymmetric?" by Howard E. Haber and Gordon L. Kane; SCIENTIFIC AMERICAN, June 1986]. Supersymmetry is a postulated symmetry that assigns as yet undiscovered partners to every particle in the Standard Model. If such partners exist and are lighter than the top, they might show up in top events. For instance, a top may decay to its own supersymmetric partner (the "stop"). Or supersymmetry could allow a gluino (hypothetical partner to a gluon) to decay into a top-antitop pair. Such effects might even cancel each other out, leading to no net change in the observed production of tops and antitops.

Supersymmetry predicts not just one Higgs but a family of four or more. If they exist and are lighter than the top, some of these particles could be found in top decays. CDF and DØ have both mounted searches for these hypothetical particles, so far with null results.

Another critical question is whether quarks, especially the massive top, are really fundamental particles with no substructure. Recently the CDF collaboration measured the rate at which high-energy jets are produced at Fermilab's collider, finding that it is higher than expected. Very energetic scattering at wide angles (reminiscent of Rutherford scattering, which revealed that the atom has a nucleus) offers insights into the structure of the colliding objects. One possible interpretation of our results is that the excess jets are caused by collisions of even smaller objects within quarks—something not observed by any other experiment.

So radical a conclusion, which would completely change the theory of quarks, can be reached only if we can rule out all other possibilities. An "excessive" production of jets could be coming from subtle inaccuracies in the predictions. We are in the process of exploring the possibilities; the data currently favor one of these more boring explanations. For now we must conclude that the top quark, though massive, is indeed fundamental; it has no parts.

At present, the Fermilab accelerator is being revamped, and both CDF and DØ collaborations are dramatically improving their detectors. We will resume taking data in 1999. The accelerator upgrades will allow top quarks to be produced at 20 times the previous rate, and the detector upgrades will improve the efficiency of identifying top quarks. The net result is that both groups will find tops 30 times faster than before, allowing a more detailed look at the top's characteristics. By 2006 the Large Hadron Collider at CERN will begin operation. It will produce two proton beams colliding at 14 TeV (tera, or 10^{12}, electron volts)—seven times the energy at Fermilab—generating almost one top-antitop pair per second.

In a few years, physicists will start using the top to try to answer the many questions that still remain about matter and the forces that govern the physical world. What new tenets of physics may arise beyond what we now know is a matter of active speculation that will end only when measurements start to unravel the workings of nature. SA

A hyperlinked version of this article is available at http://www.sciam.com on the SCIENTIFIC AMERICAN *World Wide Web site.*

ABOUT 1,000 PHYSICISTS and uncounted technicians contributed to the CDF and DØ collaborations' efforts to find the top quark. The first pages of their respective papers reporting the discovery consist entirely of names.

The Authors

TONY M. LISS and PAUL L. TIPTON helped to build key elements of the Collider Detector at Fermilab (CDF) and have both served as conveners of the search group for the top quark. For his Ph.D. at the University of California, Berkeley, Liss participated in a search for monopoles. In 1988 he joined the faculty at the University of Illinois at Urbana-Champaign and in 1990 was awarded an Alfred P. Sloan Fellowship. Tipton received his Ph.D. from the University of Rochester in 1987 studying bottom quarks and is now on the faculty there. He is a recipient of the U.S. Department of Energy's Outstanding Junior Investigator Award and the National Science Foundation's Young Investigator Award. Tipton is an avid Chicago Bulls fan; Liss is a lifelong sufferer with the New York Knicks. The authors would like to thank Lynne Orr and Scott Willenbrock for helpful discussions as well as all their colleagues at CDF and DØ.

Further Reading

DREAMS OF A FINAL THEORY. Steven Weinberg. Pantheon Books, 1992.

OBSERVATION OF TOP QUARK PRODUCTION IN $p\bar{p}$ COLLISIONS WITH THE COLLIDER DETECTOR AT FERMILAB. F. Abe et al. in *Physical Review Letters,* Vol. 74, No. 14, pages 2626–2631; April 3, 1995.

OBSERVATION OF THE TOP QUARK. S. Abachi et al., ibid., pages 2632–2637.

TOP-OLOGY. Chris Quigg in *Physics Today,* Vol. 50, No. 5, pages 20–26; May 1997.