DISCOVERY
of the
TOP
QUARK

by BILL CARITHERS
& PAUL GRANNIS

Two leaders of
the Fermilab experiments
that isolated the top quark
tell the adventure of its discovery.

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MANKIND has sought the elementary building blocks of matter ever since the days of the Greek philosophers. Over time, the quest has been successively refined from the original notion of indivisible "atoms" as the fundamental elements to the present idea that objects called quarks lie at the heart of all matter. So the recent news from Fermilab that the sixth—and possibly the last—of these quarks has finally been found may signal the end of one of our longest searches.

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CDF Collaboration

Argonne National Laboratory
Istituto Nazionale di Fisica Nucleare, University of Bologna
Brandeis University
University of California at Los Angeles
University of Chicago
Duke University
Fermi National Accelerator Laboratory
Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare
Harvard University
Hiroshima University
University of Illinois
Institute of Particle Physics, McGill University and University of Toronto
The Johns Hopkins University
National Laboratory for High Energy Physics (KEK)
Lawrence Berkeley Laboratory
Massachusetts Institute of Technology
University of Michigan
Michigan State University
University of New Mexico
Osaka City University
Università di Padova, Instituto Nazionale di Fisica Nucleare
University of Pennsylvania
University of Pittsburgh
Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa
Purdue University
University of Rochester
Rockefeller University
Rutgers University
Academia Sinica
Texas A&M University
Texas Tech University
University of Tsukuba
Tufts University
University of Wisconsin
Yale University

But the properties of this fundamental constituent of matter are bizarre and raise new questions. In particular, the mass of the top quark is about forty times that of any other—a fact which suggests that perhaps it plays a fundamental role in the question of how the mass of any object arises.

IN 1964 Murray Gell-Mann and George Zweig proposed the quark hypothesis to account for the explosion of subatomic particles discovered in accelerator and cosmic-ray experiments during the 1950s and early 1960s. Over a hundred new particles, most of them strongly interacting and very short-lived, had been observed. These particles, called hadrons, are not elementary; they possess a definite size and internal structure, and most can be transformed from one state into another. The quark hypothesis suggested that different combinations of three quarks—the up (u), down (d), and strange (s) quarks—and their antiparticles could account for all of the hadrons then known. Each quark has an intrinsic spin of 1/2 unit and is presumed to be elementary, like the electron. So far, quarks appear to have no size or internal structure and thus represent the smallest known constituents of matter. To explain the observed spectrum of hadrons, quarks had to have electric charges that are fractions of the electron charge. The u quark has charge 2/3 while the d and s quarks have charges –1/3 (in units where the electron charge is –1).

The observed hadron spectrum agreed remarkably well with the expected states formed from combinations of three quarks or a quark-antiquark pair. Quarks also seemed to form a counterpart to the other class of elementary particles, the leptons, which then included the electron (e) and muon (μ) (both with unit charge) and their companion chargeless neutrinos, ν_e and ν_μ. The leptons do not feel the strong interaction, but they do participate in the electromagnetic interactions and the weak interaction responsible for radioactive decays. They have the same spin as the quarks and also have no discernible size or internal structure.

But most physicists were initially reluctant to believe that quarks were anything more than convenient abstractions aiding particle classification. The fractional electric charges seemed bizarre, and experiments repeatedly failed to turn up any individual free quarks. And—as became apparent from studies of fundamental theories of quarks and leptons—major conceptual problems arise if the numbers of quarks and leptons are not the same.

Two major developments established the reality of quarks during the 1970s. Fixed-target experiments directing high energy leptons at protons and neutrons showed that these hadrons contain point-like internal constituents whose charges and spins are just what the quark model had predicted. And in 1974 experiments at Brookhaven National Laboratory in New York and Stanford Linear Accelerator Center (SLAC) in California discovered a striking new hadron at the then very large mass of 3.1 GeV—over three times that of the proton. This hadron (called the J/ψ after its separate

	Electric Charge	First Family	Second Family	Third Family
QUARKS	+2/3	up (u)	charm (c)	top (t)
	-1/3	down (d)	strange (s)	bottom (b)
LEPTONS	-1	electron (e)	muon (μ)	tau (τ)
	0	electron neutrino (ν_e)	muon neutrino (ν_μ)	tau neutrino (ν_τ)

names in the two experiments) was found to be a bound state of a new kind of quark, called charm or c, with its antiquark. The c quark has a much greater mass than the first three, and its charge is 2/3. With two quarks of each possible charge, a symmetry could be established between the quarks and the leptons. Two pairs of each were then known: (u,d) and (c,s) for quarks and (e,ν_e) and (μ, ν_μ) for leptons, satisfying theoretical constraints.

But this symmetry was quickly broken by unexpected discoveries. In 1976 experiments at SLAC turned up a third charged lepton, the tau lepton or τ. A year later at Fermi National Accelerator Laboratory in Illinois a new hadron was discovered called the upsilon or Υ, at the huge mass of about 10 GeV; like the J/ψ, it was soon found to be the bound state of yet another new quark—the bottom or b quark—and its antiparticle. Experiments at DESY in Germany and Cornell in New York showed that the b quark has spin 1/2 and a charge of –1/3, just like the d and s quarks.

With these discoveries, and through the development of the Standard Model, physicists now understood that matter comes in two parallel but distinct classes—quarks and leptons. They occur in "generations" of two related pairs with differing electric charge—(+2/3, –1/3) for quarks and (–1, 0) for leptons (see chart above). Ordinary matter is composed entirely of first-generation particles, namely the u and d quarks, plus the electron and its neutrino. But the third-generation quark doublet seemed to be missing its charge +2/3 member, whose existence was inferred from the existing pattern. In advance of its sighting, physicists named it the top (t) quark. Thus began a search that lasted almost twenty years.

USING THE RATIOS of the observed quark masses, some physicists naively suggested that the t might be about three times as heavy as the b, and thus expected that the top would appear as a heavy new hadron containing a $t\bar{t}$ pair, at a mass around 30 GeV. The electron-positron colliders then under construction (PEP at SLAC and PETRA at DESY) raced to capture the prize, but they found no hint of the top quark.

In the early 1980s a new class of accelerator came into operation at CERN in Switzerland, in which counter-rotating beams of protons and antiprotons collided with an energy of about 600 GeV. The protons and antiprotons brought their constituent quarks and antiquarks into collision with typical energies of 50 to 100 GeV, so the top quark search could be extended considerably. Besides the important discovery of the W and Z bosons that act as carriers

DØ Collaboration

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University of Arizona
Brookhaven National Laboratory
Brown University
University of California, Davis
University of California, Irvine
University of California, Riverside
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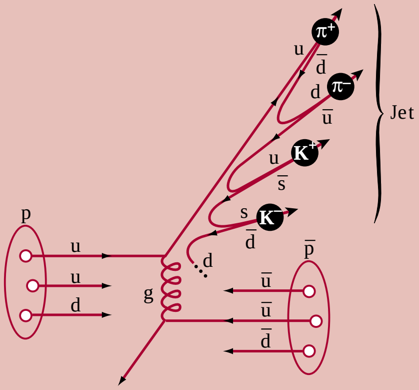
Centro de Investigacion y de Estudios Avanzados
Columbia University
Delhi University
Fermi National Accelerator Laboratory
Florida State University
University of Hawaii
University of Illinois, Chicago
Indiana University
Iowa State University
Korea University
Kyungsung University
Lawrence Berkeley Laboratory
University of Maryland
University of Michigan
Michigan State University
Moscow State University
University of Nebraska
New York University
Northeastern University
Northern Illinois University
Northwestern University
University of Notre Dame
University of Panjab
Institute for High Energy Physics, Protvino
Purdue University
Rice University
University of Rochester
Commissariat à l'Energie Atomique, Saclay
Seoul National University
State University of New York, Stony Brook
Superconducting Super Collider Laboratory
Tata Institute of Fundamental Research
University of Texas, Arlington
Texas A&M University

Jet Production



A **COLLIDING PROTON** (p) and antiproton ($\bar{p}$) bring together quarks uud and $\overline{uud}$. In this example, a u and $\bar{u}$ scatter by exchanging a gluon (g), the carrier of the strong nuclear force. Like all quarks, the scattered u quark possesses the strong interaction "charge" called *color*. The strong attraction of the u quark color to the other quark color charges prevents it from escaping freely. Energy from the collision region is converted to matter in the form of quark-antiquark pairs. The antiquark (with anti-color) joins with a quark to produce a colorless meson which is free to escape.

In this example, the primary scattered u quark is accompanied by $(d\bar{d})$, $(u\bar{u})$, $(s\bar{s})$, and $(d\bar{d})$ created pairs, leading to the formation of π^+, π^-, K^+, and K^- mesons, all traveling in similar directions and forming a "jet" of particles that may be detected in the experiment. (The remaining d quark will be joined to one of the other spectator quarks in the collision.)

of the unified electroweak force, the CERN experiments demonstrated another aspect of quarks. Though quarks had continued to elude direct detection, they can be violently scattered in high energy collisions. The high energy quarks emerging from the collision region are subject to the strong interaction as they leave the scene of the collision, creating additional quark-antiquark pairs from the available collision energy (using $E = mc^2$). The quarks and antiquarks so created combine into ordinary hadrons that the experiment can detect. These hadrons tend to cluster along the direction of the original quark, and are thus recorded as a "jet" of rather collinear particles. Such quark jets, previously sensed at SLAC and DESY, were clearly observed at CERN and became a key ingredient in the next round of top quark searches.

With the advent of the CERN collider, and in 1988 the more powerful 1800 GeV collider at Fermilab, the search for the top quark turned to new avenues. At the large masses now accessible, the $t\bar{t}$ bound state was unlikely to form and isolated top quarks were expected. For masses below that of the W boson, W decay into a t and $\bar{b}$ could predominate. Some indication of this process was reported in 1984 by the CERN UA1 experiment, but it was later ruled out by the CERN UA2 and Fermilab CDF experiments. By 1990 CDF had extended the top mass limit to 91 GeV, thus eliminating the possibility for W decay to top.

IN 1992, the DØ detector joined CDF as a long Tevatron run began. Further searches would have to rely on the production of separate t and $\bar{t}$ quarks from annihilation of incoming quarks and antiquarks in the proton and antiproton, with subsequent decays into observable particles (see box on the right). The design of DØ stressed recognition of the telltale leptons and jets over as large a solid angle as possible. Meanwhile CDF had installed a new vertex detector of silicon microstrips near the beams intended to detect short-lived particles that survive long enough to travel a millimeter or so from the interaction point. This detector was particularly good at sensing the presence of the b quarks characteristic of top decay. Another method of tagging b quarks, by detecting their decays into energetic leptons, was used by both experiments. Thus the two experiments, while searching for the same basic decay sequence, had rather complementary approaches.

With the data from this 1992–93 run, progress accelerated. First, DØ published a new lower limit of 131 GeV on the possible top mass from the absence of events with the characteristic dilepton or single lepton signatures. This paper turned out to be the end of the line in excluding top masses. Up to then, with the absence of an excess of candidate events, the analyses had tended to restrict the event sample, so as to set as high a limit on the mass as possible. But by summer of 1993, CDF noticed that the top mass limits were not improving with additional data, due to a growing handful of events that passed all preassigned criteria. Naive (in retrospect) estimates of their statistical significance triggered intense activity to review the results and prepare a draft publication with the goal of publishing the results by the October 1993 $p\bar{p}$ Workshop in Japan. As the analysis was too complex for a single journal letter, CDF planned a series of four papers in *Physical Review Letters* (PRL)—two devoted to the counting experiments in the two search topologies; one describing the kinematics of the events and giving an estimate of the top mass; and a fourth to bring it all together with the overall significance, conclusions, and top production cross section. In a heated argument at the October collaboration meeting, it became clear both that the mass and kinematics sections needed more work and that the "four PRL" format was not working well. CDF decided instead to prepare a single long *Physical Review* article, to concentrate on the remaining holes in the analysis, and to forego any public discussion of new results.

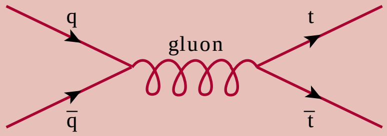
By the next CDF collaboration meeting in late January, the counting experiments were complete, the mass and kinematics analyses had made real progress, and the single long draft was in reasonable shape. The big remaining issues were the wordings of the title and conclusions section and the "between the lines" message that they sent to the community. Traditionally, scientific publications about new phenomena use certain key phrases: "Observation of" indicates a discovery when the case is unassailable; "Evidence for" means the authors believe they are seeing a signal but the case is not iron-clad; and "Search for" implies the evidence is weak or non-existent. Within every collaboration, there is a wide spectrum of comfort levels in claiming a new result. On one end of CDF, a few physicists felt that no publication should occur until the collaboration consensus was for "observation." The other end of the spectrum felt that the data were already in that category. Finally, CDF settled on a conservative interpretation and was careful to disclose even those results that contra-indicated top.

The pressure within CDF to publish increased enormously as the winter 1994 conferences approached. In addition, pirated copies of the *Physical Review D* manuscript were circulating widely and rumors (some astoundingly accurate and others comically off-base) were flying about the globe. The rumor mill churned once again when CDF withdrew its top talks at the LaThuile and Moriond Conferences. An April CDF Collaboration meeting was the watershed event, as the group hammered out the final wordings. After a virtually unanimous agreement on the final draft, the collaboration spokespersons finally notified Fermilab Director John Peoples of their intent to publish.

This CDF analysis found 12 candidate events that could not be easily explained on the basis of known backgrounds (which were predicted to be about six events). The odds for background fluctuations to yield the observed events were low—about 1 in 400—but not small enough to warrant the conclusions that the top had been found. Under the hypothesis that the data did include some $t\bar{t}$ events, the mass of the top was estimated to be 175 GeV±20 GeV. The cross section for $t\bar{t}$ production was determined to be about 13.9 picobarns, larger than the theoretical prediction of 3–7 picobarns.

Top Production and Decay

FOR TOP QUARK MASSES above $M_W + M_b$, top production proceeds mainly through annihilation of incoming quarks and antiquarks from the beam particles.



The q and $\bar{q}$ fuse briefly into a gluon, the carrier of the strong force, and then rematerialize as t and $\bar{t}$ quarks traveling in roughly opposite directions. The top quarks have a very short lifetime (about 10^{-24} seconds) and decay almost always into a W boson and a b quark ($t \rightarrow W^+ b$; $\bar{t} \rightarrow W^- \bar{b}$). The b quarks evolve into jets seen in the detectors. The W^+ and W^- have several decay possibilities:

$$\begin{aligned} W^{\pm} &\rightarrow e^{\pm}\nu && \text{(fraction = 1/9)} \\ &\rightarrow \mu^{\pm}\nu && \text{(fraction = 1/9)} \\ &\rightarrow \tau^{\pm}\nu && \text{(fraction = 1/9)} \\ &\rightarrow q\bar{q} && \text{(fraction = 2/3).} \end{aligned}$$

The q and $\bar{q}$ from W decays appear as jets. The final states containing τ's are difficult to isolate and were not sought in the experiments. The final state with both W's decaying into $q\bar{q}$, though relatively copious, are buried in huge strong interaction backgrounds. The remaining decays, studied by both CDF and DØ, can be categorized by the number leptons ($l = e$ or μ) from the W decays:

Dilepton channel:

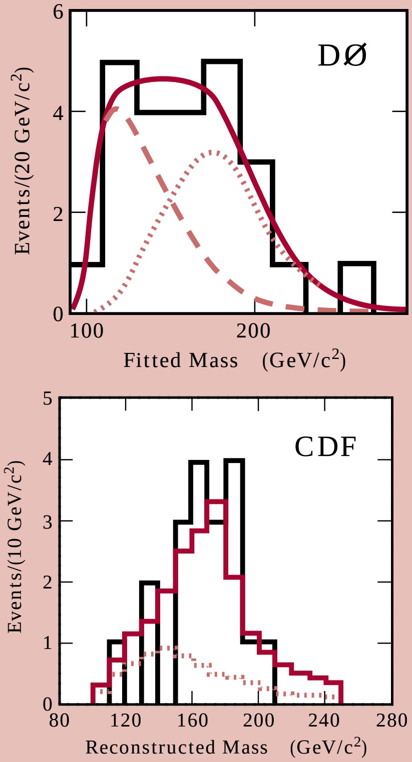
$$t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow l^+ l^- \nu\nu b\bar{b}$$

Single lepton channel:

$$t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow l^+ \nu q\bar{q} b\bar{b} \quad \text{or} \quad l^- \bar{\nu} q\bar{q} b\bar{b}$$

The dilepton channels are relatively free from background but comprise only 5 percent of all $t\bar{t}$ decays. The single lepton channels give larger yields (30 percent of all decays) but have substantial backgrounds from W + jets production processes which must be reduced.

Top Mass Distribution



The mass of the top quark can be reconstructed from the energies and directions of its decay products as measured in the detectors using the conservation laws for energy and momentum. Since the top quark has a unique mass, the data (indicated by the black histograms) should show a "peak" in the reconstructed distribution. The non-top background (the red dashed curve for DØ and the red dotted curve for CDF) has very different shapes. A simulation is required to provide the correspondence between the measured jet energies and the parent quark momenta. The red dotted curve for DØ shows the expected contribution from top for the best fit value of the top mass. The solid red curve shows what a simulated top quark mass distribution would look like when added to the background, and these curves should be compared to the actual data.

DØ used the period while CDF was preparing its publication to reoptimize its own earlier analysis, focusing on higher mass top. By April 1994, DØ was also in a position to show some of its new results, which were subsequently updated in the summer Glasgow conference and published in *Physical Review Letters*. DØ also had a small excess of top-like events but with smaller statistical significance; its analysis was based upon the dilepton and single-lepton channels with a combination of lepton tags and topological suppression techniques to reduce background. Nine events were observed, compared with an expected background of about four, giving odds for a background fluctuation of about 1 in 40. The excess events corresponded to a cross section of 8.2±5.1 picobarns. The expected yield of $t\bar{t}$ events was virtually the same for DØ and CDF. Taken together, these results from CDF and DØ were not sufficient to establish conclusively the existence of the top quark.

The final chapter in finding the top quark began with the resumption of the collider run in late summer 1994. The performance of the Tevatron was the key to the success. The Tevatron involves a collection of seven separate accelerators with a complex web of connecting beam lines. Many technical gymnastics are required to accelerate protons, produce secondary beams of antiprotons from an external target, accumulate and store the intense antiproton beams, and finally inject the counter-rotating beams of protons and antiprotons into the Tevatron for acceleration to 900 GeV. Enormous effort had been poured into understanding and tuning each of the separate elements of the process, but until summer 1994 the intensity of the collider was disappointing. During a brief mid-summer break, however, one of the Tevatron magnets was found to have been inadvertently rotated. With this problem fixed, beam intensities rose immediately by a factor of 2. With the now good understanding of the accelerator, a further doubling of the event rate was accomplished by spring 1995. In a very real sense, the final success of CDF and DØ in discovering top rested upon the superb achievements of the Fermilab Accelerator Division. The improved operations meant that the data samples accumulated by early 1995 were approximately three times larger than those used in the previous analyses, and both experiments were now poised to capitalize on the increase.

By December, both collaborations realized that the data now on tape should be enough for a discovery, if the earlier event excess had been approximately correct. In fact, the experiments do not keep daily tallies of the number of events in their samples. The physicists prefer to refine their analysis techniques and selection parameters in order to optimize the analysis on simulated events before "peeking" at the data. This reticence to check too often on the real data stems from the desire to avoid biasing the analysis by the idiosyncrasies of the few events actually found. At the beginning of January, DØ showed a partial update in the Aspen Conference using some new data but retaining previous selection criteria; these results had increased significance, with only a 1 in 150 chance of background fluctuations.

Its simulations showed that for the large-mass top now being sought, even better significance could be obtained. Recognizing that the statistics were nearly sufficient, the collaboration began working in high gear to finalize the selection criteria and obtain the last slug of data before a late-January Tevatron shutdown. In mid-January, CDF updated all of its data; with all of the pieces assembled side by side, it became clear that the collaboration had the necessary significance in hand for claiming a discovery. The CDF process was now considerably streamlined by the experience of producing the earlier top quark papers.

By February, both CDF and DØ recognized that convergence was imminent. Both worked around the clock to complete all aspects of the analyses. Even though each collaboration knew that the other was closing fast and in the process of writing its paper, there were still no formal exchanges of results, nor of intended timing. Some copies did leak out—for example, drafts left on printers in institutions with physicists on both collaborations and computer hacking from one collaboration to another. The one avenue of cross-fertilization that seems not to have operated was through couples with one person in each group!

On February 24, CDF and DØ "Observation" papers were submitted to *Physical Review Letters* (PRL); public seminars were scheduled at Fermilab for March 2. By agreement, the news of the discovery was not to be made available to the physics community or news media until the day of the seminars. In spite of all efforts, word did leak out a few days before. (*Los Angeles Times* reporter, K. C. Cole, called a distinguished Fermilab physicist to get an explanation of statistical evidence presented in the O.J. Simpson trial. The physicist used, as illustration, "the recent statistical evidence on the top quark from CDF and DØ," and Cole swiftly picked up the chase.)

In its paper, CDF reported finding six dilepton events plus 43 single-lepton events (see box on the next page for more details); it concluded that the odds were only one in a million that background fluctuations could account for these events. DØ, in its paper, observed three dilepton events plus 14 single-lepton events and concluded that the odds were two in a million that these could have been caused by backgrounds. The top quark masses reported by the two experiments were 176±13 GeV for CDF and 199±30 GeV for DØ. And both experiments gave consistent results, although somewhat below CDF's earlier value for the $t\bar{t}$ production cross section (see box on the next page for more detailed information).

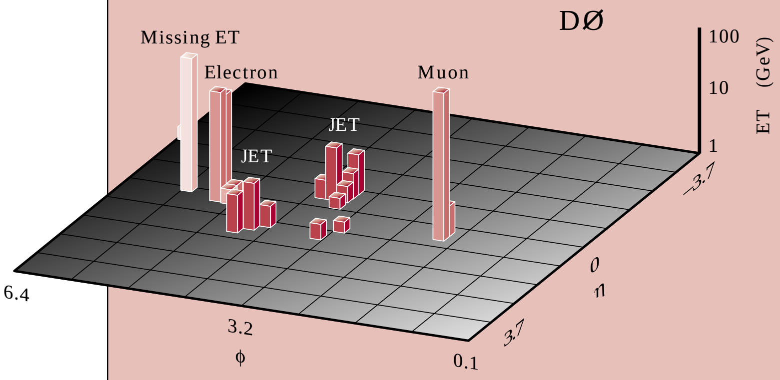
The top quark appears to be a point-like particle; it has no internal structure that we can discern. As one of the six fundamental constituents of matter, it has properties very similar to the up and charm quarks, with the exception of its remarkable massiveness and its very short lifetime. The top quark is about 200 times more massive than the proton, about forty times that of the second heaviest quark (the *b*), and roughly the same as the entire mass of the gold nucleus! Surely this striking obesity holds an important clue about how mass originates.

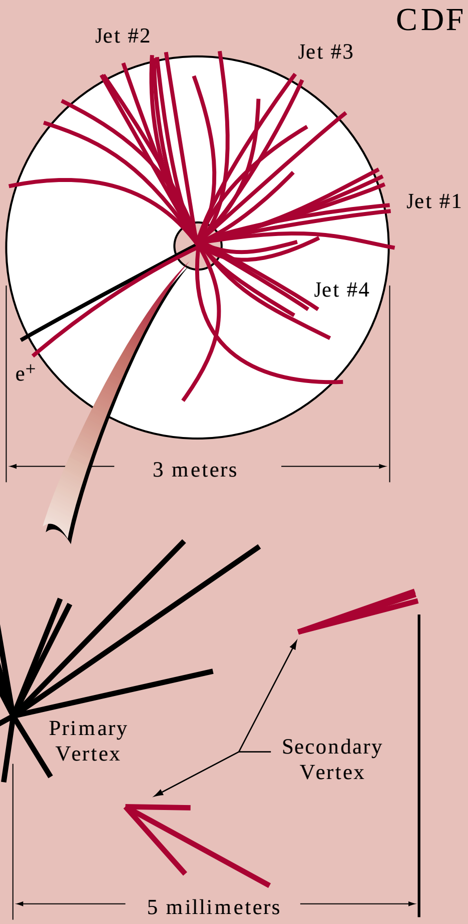
World Wide Web Statistics

BOTH THE CDF and DØ World Wide Web pages can be accessed from the Fermilab home page at http://www.fnal.gov/ (click there for top quark discovery). Since the announcement of the discovery of the top quark last March, the CDF and DØ home pages have received over 100,000 hits each. There were 2279 hits on the CDF page alone on the day after the announcement. Six months after the discovery, the Fermilab top quark page is receiving about 200 hits a day.

CDF AND DØ RESULTS

THE RESULTS FROM THE TWO COLLABORATIONS were remarkably similar. CDF found 6 dilepton events with a background of 1.3; 21 single-lepton events in which 27 cases of a *b* quark tag by the vertex detector (with 6.7 background tags expected); and 22 single-lepton events with 23 cases of a *b* tag through leptonic decay (with 15.4 background tags expected). DØ found 3 dilepton events (0.65 background events); 8 single-lepton events with topological tagging (1.9 background events); and 6 single-lepton events with *b*-to-lepton tags (1.2 background events). A particularly striking example of a dilepton event with very energetic electron, muon, and missing E_T (due to the neutrinos), plus two jets, is shown below from the DØ data. The plot shows the detector unfolded on to a plane, with the energy of the various objects indicated by the height of the bars. This event has a very low probability to be explained by any known background. The probability that background fluctuations could explain the observed signal was one-in-a-million for CDF and two-in-a-million for DØ—sufficiently solid that each experiment was able to claim the observation of the top independently.





Additional studies helped to establish that the new signal was indeed the top quark. Both experiments were able to show that the candidate events were consistent with the expected presence of *b* quarks. The single-lepton channel events should have one *W* boson that decays to a $q\bar{q}$ final state, and the data showed the expected enhancement in the di-jet mass.

Finally, both experiments made a measurement of the top quark mass, using the single-lepton events. In this study, the missing neutrino from one *W* decay must be inferred and the mass of the parent top quark deduced from a constrained-fit procedure. This mass fitting is complicated by the need to identify the correct combination of jets with parent quarks in the decay and to accommodate the tendency of the strong interaction to generate additional jets. The two experiments obtained consistent results for this mass measurement: 176±13 GeV for CDF and 199±30 GeV for DØ.

The rate for observing $t\bar{t}$ pairs is controlled by the strong-interaction production cross section. Each experiment evaluated this cross section at their mean mass value; CDF obtained $6.8^{+3.6}_{-2.4}$ picobarns, and DØ obtained 6.4±2.2 picobarns. These values are consistent with the theoretical prediction within the combined experimental and theoretical error, although the tendency for the measurements to fall above theory is interesting and if it persists could indicate that new physics is at play.

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Left to right: Giorgio Bellettini, Paul Grannis, John Peoples, Hugh Montgomery, and Bill Carithers following the seminars announcing the simultaneous discovery of the top quark at Fermilab by the DØ and CDF collaborations. Grannis and Montgomery are the co-spokesmen for the DØ Collaboration, John Peoples is the Director of Fermilab, and Carithers and Bellettini are the co-spokesmen for the CDF Collaboration. The collaborations presented their results at seminars held at Fermilab on March 2, 1995.

MODERN HIGH energy physics experiments are unique institutions; though large enough to require formal organizations and governance procedures, they remain voluntary collaborations of individual scientists who have banded together to permit achievements that a few physicists could not accomplish by themselves. But lacking the usual structures of large organizations—the ability to hire and fire, or to rigorously assign jobs to individual workers—they rely to a very large degree on the existence of a shared purpose and consensus for their constructive operation.

Although about 430 physicists participate in each collaboration, the number active in the top studies is much less—roughly 50 directly engaged at a significant level. This results from the broad scope of collider experiments; the range of tasks needing attention is very large. The physics research being done by the collaborations is widely dispersed over five major areas (top search, bottom-quark physics, strong-interaction studies, electroweak boson measurements, and searches for new phenomena). Within these physics groups there are perhaps 50 active analyses under study at any given time. Often these other analyses contributed synergistic techniques to aid the top search; for example, studies of jets by the strong-interaction group entered directly into measurements of the top mass.

A diversity of tasks occupy the members of the collaborations. In addition to running the experiment around the clock and attending to its maintenance, constant attention must be given to optimizing the event selection process (only ten interactions out of every million can be kept for analysis) and to improving the software algorithms for selecting particles in the data. Work must continue to improve the overall computing and software environment. New detector development is conducted with an eye to future upgrades, and major design and building projects are underway for future runs. The experiments are so big that reviews by the collaborations themselves, the Laboratory, and external committees continually occur. Finally, with collaborations of these sizes, group psychologists, financial analysts, and tea-leaf readers are needed!

The techniques for the top quark search and measurement of its mass developed over several years. For most important aspects (and some minor ones) several different approaches were developed by rival subgroups or individuals. This multiplicity is valuable for cross-checking results and as a tool for natural selection of the strongest methods, but such competitiveness and rivalry can also be debilitating. In some cases, the winner in these rivalries can be established on purely technical grounds—but often the basis for decision is clouded, as the alternatives have both pros and cons. Adjudicating among these contenders is a difficult and time-consuming problem. In some cases, the choice is made through a survival-of-the-fittest process—the approach first brought to full maturity, with documented error analyses and cross-checks, is chosen. Consensus plays an important role in rejecting some alternatives; experts not involved in a particular question can wield considerable influence in rejecting some weaker approaches. When the issues have sufficiently crystallized, special advisory panels drawn from the rest of the collaboration can be very useful in helping to define the direction. The last resort of turning the issue over to the "managers"—the spokespersons or physics group conveners—is successful primarily when the rivals have agreed that they are unable to resolve their differences. Fortunately, this rarely happens.

Effective communication on many levels is an essential ingredient of successful performance in the large collaborations. For the top studies, weekly meetings of a half dozen subgroups of the top analysis discuss problems and status; as many additional meetings occur on related analysis topics such as electron identification; and a more general meeting brings together all the threads. Video conferencing and electronically posted minutes of the meetings help keep those not at Fermilab involved, although most active participants travel there frequently. Informal documents prepared on sub-topics, intended only for internal use, proliferate and are disseminated electronically across the globe. Electronic mail is an essential component; colleagues working a continent apart on related problems can conduct an almost on-line dialog. Discussion and argument over fine points of interpretation can generate a flurry of productive messages among five or six experts. At the other end of the scale, there remains an essential role for formal presentations of work to the full physics group and full collaboration at regular intervals. Repetition is usually necessary to bring the non-experts to a reasonable degree of familiarity with the issues and methods, and to build acceptance of new work.

To what extent did CDF and DØ interact during the time of the top search and discovery? At a formal level, very little. New results from each collaboration were periodically shown at conferences and public presentations, so the broad outlines of each group's approach were known, but beyond that there were no direct interactions. The grapevine was of course active, with lunch-table conversations among individuals, but much of the information exchanged in this way was the anecdotal account of the day and was often outmoded by the next. There were probably several reasons for this relative isolation of two groups working toward a common goal. At one level both groups realized that the independence had real scientific value. Guarding against making a discovery by subconsciously shaping the analysis is an ever-present worry; by keeping the walls between CDF and DØ fairly high, this possibility could be minimized. Also, the two groups felt the heat of competition; for each, no doubt, the dream of being first to recognize the top was a powerful incentive to be rather closed-mouthed about innovations and progress.

The history of the top search over the final two years shows evidence of this competitiveness and friendly rivalry at work. As the more senior collaboration, CDF had developed its techniques over time to a relatively refined state. It started the race for top with the UA2 experiment in 1988 and had been denied success only by top's extraordinary massiveness. CDF would have been disappointed to lose the race to the newer DØ experiment. On the other hand, the Tevatron performance in the 1992–1994 era improved so much that the data in hand was almost all acquired after DØ's start-up, so the two experiments could work on almost equivalent data sets. DØ, with its strengths of excellent lepton identification and full solid angle coverage, was able to develop powerful tools for suppressing unwanted background; it was of course determined to make its mark as the brash newcomer by converging on the top. But the competition remained friendly and supportive throughout; it also promoted a quality of work and depth of understanding that would have been difficult otherwise. And the ultimate scientific value of two independent results was enormous.

How do hundreds of authors agree on a single paper in a timely fashion? This too is a sociological challenge! The process for writing the final papers began in late January. DØ appointed primary authors—one for a short letter paper and one for a longer paper ultimately not used. The top group designated a few individuals as its authorship committee, bringing the necessary range of expertise to the authors. The collaboration review was conducted in large part through an appointed editorial board of ten physicists including authors, drawn from widely diverse portions of the collaboration. The editorial board spent days carefully reviewing the backup documentation, probing the analysis for consistency and correctness. It also helped to revise the paper's language to make it accessible to the widest possible audience. The completed draft was distributed to the full collaboration by electronic mail, and comments were solicited from all. Well over a hundred written comments were received (plus many more verbal ones), all of which were addressed by the board. The revised paper was again circulated for concurrence of the collaboration before submission to PRL.

CDF appointed a chief author to be assisted by a group advising on the sections of their expertise. Simultaneously, a review committee (dubbed a "godparent" committee within CDF) was appointed. The draft and responses to questions were always accessible to the collaboration electronically, both on the World Wide Web (with security) and via ordinary files on the Fermilab computer.

In the final convergence to a result, it was necessary to come to grips with rather large differences of scientific style among the collaborators. Some could find in any result, no matter how thoroughly cross-checked, the need for further investigation. Some were wary of any interpretation beyond a statement of the basic experimental numbers. Others favored a more interpretative approach. Finalization of the paper itself required the resolution of these oft-conflicting outlooks on what makes good science.

In the end, the chief necessity for the convergence on the top discovery was the willingness of a collaboration to abide by a majority view. Securing this willingness requires extensive attention to the process—of being sure that all shades of opinion, reservations, and alternate viewpoints are fully heard and understood. It is more important perhaps that each point of view is carefully listened to than that it be heeded. A fine line in resolving these viewpoints must be drawn between autocracy and grass-roots democracy. The process must have the confidence of the collaboration, or its general effectiveness can diminish rapidly.

What did the physicists of CDF and DØ feel on completion of the top discovery experiments? Certainly relief that the quest was complete. Also

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Happy and relieved physicists who have completed PhD theses using the DØ experiment assemble in the DØ main control room. Students and postdoctoral candidates are the lifeblood of the experiment and have made contributions to every aspect of it. Pictured are Brad Abbott, Purdue; Jeff Bantly, Srini Rajagopalan, Northwestern; Dhiman Chakraborty, Terry Heuring, Jim Cochran, Greg Landsberg, Marc Paterno, Scott Snyder, Joey Thompson, Jaehoon Yu, Stony Brook; Regina Demina, Northeastern; Daniel Elvira, Cecilia Gerber, University of Buenos Aires; Bob Hirosky, Gordon Watts (CDF), Rochester; Jon Kotcher, New York University; Brent May, Arizona; Doug Norman, Maryland; Myungyun Pang, Iowa State.

Others who have completed theses on DØ but not pictured are Rich Astur, Bo Pi, Sal Fahey, Michigan State; Balamurali V., Notre Dame; Ties Behnke, John Jiang, Domenic Pizzuto, Paul Rubinov, Stony Brook; John Borders, Sarah Durston, Rochester; Geary Eppley, Rice; Fabrice Feinstein, Alain Pluquet, University of Paris Sud; Terry Geld, Michigan; Mark Goforth, Robert Madden, Florida State; Ray Hall, Thorsten Huehn, University of California, Riverside; Hossain Johari, Northeastern; Guilherme Lima, LAFEX/CBPF; Andrew Milder, Alex Smith, Arizona; Chris Murphy, Indiana; Haowei Xu, Brown; Qiang Zhu, New York University.

pride that such an elusive quarry had been trapped and that the two independent experiments had drawn so similar a profile of the top quark. Virtually all in both collaborations could take justifiable pride for their personal contributions to the discovery—an effective electronics controller for the high-voltage system was as essential for the discovery as devising the selection criteria for the top quark events. Despite the many strains introduced by the frenetic pace, the process of discovering the top was for most the scientific event of a lifetime. Graduate students, postdocs, junior and senior faculty, and scientists worked together on equal footing, with the contributions of the youngest as significant as those from the oldsters. Though for most scientists, solving the many small daily problems gives sufficient satisfaction to keep them hooked on physics, reaching a milestone touted as a major discovery was a special thrill not to be forgotten.

After the public announcements of the discovery, a new challenge arose in interacting with the news media, representatives of member institutions, and other scientists to explain and comment on the results. The media blitz caused strains of its own. As each physicist had contributed in some major way to the discovery, most wanted to share in the public limelight. In the unfamiliar world of public exposure, some strains and disappointments emerged, but the opportunity to explain the significance of the work to the general public was for most a rewarding and educaional experience.

How long did the euphoria of the discovery last? There were indeed celebrations, but by a week after the public announcements it was back to business, both on the top studies and on the dozens of other analyses in progress.

DOES THE DISCOVERY of the top quark close the chapter on our understanding of the fundamental building blocks of matter? Surely not—it is truly just the beginning. Though we now have found the long-awaited sixth quark, with properties as predicted, much more accurate measurements are needed. Dozens of questions about how the top is produced and how it decays are clamoring for answers. Does the extraordinarily large top quark mass hold clues to the nature of symmetry breaking or to the origin of mass? Do the regularities observed for the lighter quarks hold for the top? Are there signs of new particles that decay into the top? Or are there exotic new objects to be found in top decays? The very massive top is unique among quarks in that it does not live long enough to be bound into hadrons, so it provides a testing ground for the study of a single "bare" quark. As happens so often in physics, the latest great discovery should serve as the crucial tool for the next advance in understanding the composition of matter.

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