PHYSICS

With Quark Discovery, Truth Comes Out on Top—Twice

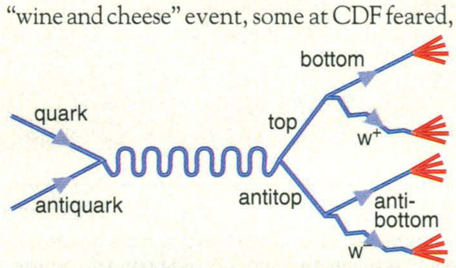
Last week's announcement by physicists at the Fermi National Accelerator Laboratory that they had finally discovered the top quark marked the end of one quest and the start of another. The 18-year search to find the sixth and final quark, a relative of the quarks that make up most of ordinary matter, was over after a last-minute sprint to the finish by groups working independently on Fermilab's mammoth accelerator, the Tevatron. In what might be called the moon shot of particle physics, two 450-person collaborations staffing detectors costing $100 million each had collided trillions of particles and sifted tens of millions of collisions to corner the elusive particle.

But the 2 March announcement, which Energy Secretary Hazel O'Leary called a "crowning moment of success," doesn't close the book on the understanding of matter. Instead it marks the start of a new era in which, like naturalists poking and prodding an exotic new specimen, experimenters will be scrutinizing the top quark for clues to new physics. "Finding the top is much more than just filling in the blank in the table of quarks," says Fermilab collaborator John Huth of Harvard University. The top, after all, stands out from the crowd: With roughly the same mass as an entire gold atom, it is far and away the heaviest elementary particle and may hold clues to a major unsolved puzzle in physics—the origin of mass.

The top had been at large since the 1977 discovery of what turned out to be the fifth quark: the bottom, or beauty, quark. Physicists' standard picture of matter demanded a sixth: Beauty must have a mate. Fittingly, it was named truth, or top, and the search to find it was on. The top, like all but two of the other quarks, does not exist as part of ordinary, observable, matter and must be created by colliding high-energy streams of particles in an accelerator. In a tiny fraction of the collisions, physicists hoped, a top quark would materialize and live for 10^{-25} seconds before decaying into a characteristic shower of particles. But for 18 years, experiments designed to create the quark failed to muster enough energy.

Indeed, even the Tevatron—the world's most powerful accelerator at 1.8 trillion electron volts—was just barely able to probe the energy range where the top was thought to hide. The first hints that the search might be ending came last April, when the CDF (Collider Detector at Fermilab) collaboration announced that their massive detector had recorded residue from 12 events that looked like top quark decays. It was "evidence" for the quark, but not enough to rule out the possibility that the events were due to background "noise" (*Science*, 29 April 1994, p. 658). Adding to the doubts, physicists at the other Tevatron detector, D0 (D-Zero), had seen no clear evidence. Since then, however, both groups continued to amass new data and reanalyze their earlier runs.

As rumors of strong results flew back and forth between the two groups in January and February, each began to fear that the other would be the first to submit a report of the discovery, and the pace of the analysis sped up. Anxiety gripped the CDF group, for example, after an early February rumor that D0 had scheduled a seminar. At this "wine and cheese" event, some at CDF feared,



	CDF	D0
Top events	43	17
Significance	4.8σ	4.6σ
Mass (billion electron volts)	176 ±13	199 ±30
Cross section (picobarns)	$6.8^{+3.6}_{-2.4}$	6.4 ± 2.2

Two views of the top quark. In a rare high-energy collision *(top)* ordinary quarks interact to produce top quarks, which decay into lighter particles.

SOURCE: FERMILAB

D0 might announce top quark results. "It was only human to imagine that," says Huth, a CDF member.

The meeting never took place, and in the end the announcement followed a protocol established 2 years ago by Fermilab Director John Peoples: If either group was ready to report significant results, it had to let the director know first and give the other collaboration a week to prepare and respond. In the end it was CDF that approached Peoples first, but at that point D0 was ready. Both groups submitted papers claiming "observation of the top quark" to *Physical Review Letters* on 24 February and agreed to preview their results in a joint seminar.

At the 2 March Fermilab seminar both collaborations reported detecting enough possible top quark events (see table) to reduce the odds that the signal arose by chance to around one in a million. The collaborations also presented data on what physicists call the "production cross section"—a measure of how, and how often, the top quark is produced—and on the quark's mass, determined from the energies of the decay products. "Everybody gets confidence from the fact that two collaborations that are pretty competitive with each other see the same result," says CDF physicist Richard Hughes.

Now experimenters are looking ahead to the work to come. As Hughes puts it, "In a couple of months no one will be asking you how sure you are the top exists; they will be asking you 'What is the mass?' " A precise mass should provide insight into a theoretical mass-giving entity called the Higgs boson. "Particles are endowed with mass in proportion to their coupling with the Higgs field," explains William Bardeen, the acting head of Fermilab's theory group. "In that sense the more massive the particle, the closer you are to a place where the Higgs might reveal itself." Right now, he adds, you can't get any closer than the top quark.

Besides its mass, physicists would like to test the new quark's spin, charge, and decay modes to see how well they match the predictions of standard theory. Serious gaps could serve as a window onto some new physics. Bardeen and his colleagues at Fermilab have theorized, for example, that certain energy states of the top quark may actually be the Higgs, or at least a part of it.

Pursuing these questions, however, will mean creating top quarks in droves, says Bardeen. "You need a lot of events of all kinds to find the few events that will tell you the hint of the new physics." Fermilab's current schedule gives CDF and D0 another year to collect top quarks. That should be enough to improve measurements of the top's mass and cross section, but it won't satisfy physicists' craving for the particles.

After that, top quark enthusiasts will have to wait for two new machines. At Fermilab, the Tevatron is scheduled for a major upgrade, known as the main injector, slated to come on line in early 1999. "We are shooting for a factor of 10 and maybe 20 in total observable top quarks," says Peoples. Then the torch will pass to Europe's Large Hadron Collider, which will take the place of the Tevatron as the world's highest energy accelerator sometime after the turn of the century.

–Antonio Regalado