Taking a Gamble on the Top Quark

Fermilab physicists think they have the long-sought particle in their sights—and they're betting the evidence is good enough to tell the world

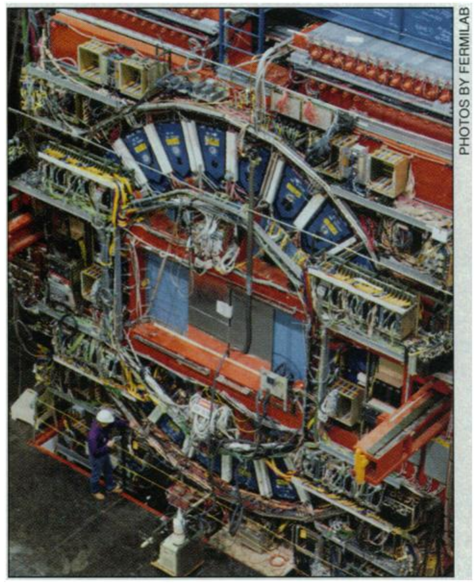
After 5 years of watching subatomic particles collide in a tunnel, researchers at Fermi National Accelerator Laboratory have decided to climb out of their subterranean experiment and into the limelight. At press time, researchers working at Fermilab's Tevatron, the most powerful accelerator in the world, were planning to announce that they may have caught the object of their quest: the elusive, short-lived particle known as the top quark, a key missing piece in physicists' current theoretical picture of matter.

Far from being exultant, however, many members of the 450-member experimental collaboration, which runs a massive particle detector at the Tevatron called the Collider Detector Facility (CDF), were ambivalent about the announcement, which was scheduled to be made in a press conference on 26 April. "We're not saying it's a discovery," says CDF co-leader Bill Carithers. "We're not there yet, but we're close."

Behind such hesitant language, say members of the collaboration, lies some strenuous soul-searching about whether to make a high-profile announcement on the basis of evidence that is good, but not airtight. So far, says Harvard physicist John Huth, a participant in the Fermilab experiment, the evidence is "like a Rorschach test. Some people see the trap door open, and some see it closed." And that leaves a lot of room for disagreement about the public announcement, says one CDF physicist: "If it were up to those of us who are close to the experiment, we wouldn't be going to the press yet."

Given the uncertainty, why is the CDF group going public? One reason, says the group's other co-leader, Melvin Shochet, is that in response to widespread rumors in the physics community, the group had already decided to lay out their latest analysis in a technical paper, which they have submitted to *Physical Review D*. And the imminent publication of that paper encouraged the group to make a public statement, says Shochet—in order to head off possible press misinterpretation of the results.

What's more, Shochet and his group say their announcement underscores the importance of keeping the Tevatron up and running. The next year of data collection, they say, should confirm the CDF findings and produce new evidence of the quark in the Tevatron's other detector, D0. But Fermilab director John Peoples notes that financial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Snare for elusive quarry. The Collider Detector Facility on Fermilab's Tevatron.

trouble has already forced months-long shutdowns, and he says that researchers are concerned that the quark search might have to be cut short.

Whatever the CDF researchers' feelings about the current announcement, none of them doubts that their quarry is within reach, if not yet in their grasp. The tried-and-true Standard Model of particles and forces insists that matter comes in three families of particles, each containing two quarks and a lepton, such as the electron. Although ordinary matter contains only the two quarks in the first family, physicists have created three of the remaining four quarks by smashing other particles together at high energies. Only the top—the heaviest quark and hence the hardest to create—has never been observed.

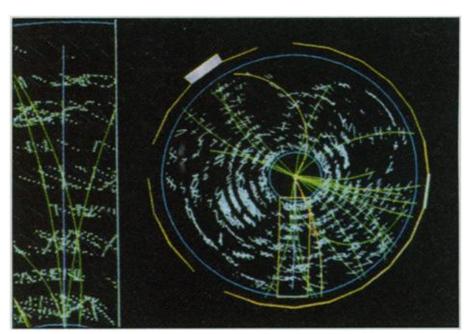
Theory predicts that if subatomic projectiles (protons and their antimatter counterparts, antiprotons) collide violently enough, even the top quark will materialize for a fraction of a second before exploding into a shower of other particles. Earlier accelerators failed to muster the energy needed to make the top quark, which indicated that the quark must carry an exceptionally large mass—174 billion electron volts, about the equivalent of an atom of gold, if the CDF group is right. But at the energies of Fermilab's Tevatron, the top quark should be making an occasional fleeting appearance.

The difficult part is recognizing it, explains Shochet. The quark is so unstable that when it does materialize, it explodes into other particles, which in turn explode into yet more particles before anything can leave a track in the detector. Since other configurations of particles might resemble this quark debris, quark-hunters can't point to any particular cluster of tracks and confidently say, "a top quark was here." But the larger the number of suspicious events, the lower the probability that they are all statistical flukes. Says Fermilab's William Foster, "The nature of the thing is that as you get more and more data, any discovery will get more and more certain, so it's a tactical question of when to publish."

In their latest experimental run, from mid-1992 to mid-1993, CDF members saw 12 events that qualified as top-quark "candidates." Analysis of the data, which the group recently completed, showed that this series deviates from the calculated background (the number of candidates they should have seen in the absence of the quark) by 2.8 standard deviations, or 2.8 sigma. That means there's only a 1-in-400 chance that these signals arose by chance rather than from top-quark decays.

In many realms of science that would be plenty. In particle physics, however, such a level of certainty is considered good—but not definitive. "In particle physics you rarely claim anything less than 5 sigma," says Drew Baden, a physicist on the D0 collaboration. Theorists who plan to use the quark's mass and other characteristics to fine-tune the Standard Model and explore other avenues in physics (see box) agree with the 5-sigma threshold. "I'm not budging until I see a 5-sigma," says Fermilab's Chris Hill.

Reaching the 5-sigma level will take another year's experimental run, says CDF's



Trace of a top? Tracks from a collision where a top quark may have briefly appeared.

Theorists Have High Hopes for the Top

While the physicists in Fermi National Accelerator Laboratory's quark-hunting groups argue over the strength of their evidence for the top quark (see main text), others in the community are looking ahead to what they can learn from the particle once its discovery has been confirmed. They acknowledge that there's some skepticism to be overcome. Theorist Bill Marciano of Brookhaven National Laboratory, for example, says he once called a talk "Top Is Not Boring" in an effort to persuade colleagues that the search for the particle, the major missing piece in the current picture of matter, is more than an exercise in scientific stamp collecting.

Marciano and some of his colleagues at Fermilab argue that the top quark is far more than just a coveted stamp. Measured precisely, they say, its properties may lead to a deeper understanding of the nature of matter. Specifically, they hope it might shed light on the question of why the fundamental building blocks of matter come in a seemingly haphazard array of different masses. Fruitless searches for the particle at less powerful accelerators have shown that, at more than 150 billion electron volts, the top quark is far more massive than theorists once thought. That heft, say Marciano and other theorists, implies that the quark may have close ties to the still-hypothetical mechanism that generates mass. By probing other properties of the quark, they say, physicists might be able to elicit clues to the sought-after mechanism.

Marciano and colleagues concede these hopes for telltale new properties may not pan out. If the top quark, when it is studied in quantity, "has all the properties it's supposed to have, you [might] say, well, it was boring," says Marciano. "But there is a possibility that there could be some surprises." Fermilab theorist Christopher Hill puts it more strongly. "I believe that in the first 100 top quarks we'll see something new."

In particular, Hill says he is hoping the first crop of quarks will yield evidence for a theory he developed with Fermilab colleague William Bardeen and others. According to current thinking, the mass of a particle isn't an independent property, but a measure of how much the particle connects, or "couples," with a hypothetical entity called the Higgs particle, which was the quarry of the defunct Superconducting Super Collider. Since the top quark is so massive, notes Hill, it must be the particle most intimately coupled with the Higgs. In fact, he, Bardeen, and their colleagues say, the top quark might actually *be* the Higgs particle, or at least one component of it. They propose that a top quark bound to its antimatter counterpart—the antitop quark—could play the mass-giving role that has been attributed to the Higgs.

Other theorists, including Marciano and Chris Quigg of Fermilab, say they consider this version of the Higgs mechanism a bit speculative—but interesting enough to test. Hill and Bardeen believe they could test it by making precision measurements of the top quark's mass and its "cross sections"—measures of how easily it is made and how readily it decays (usually into a W particle and a bottom quark). Even if those measurements don't bear out Hill and Bardeen's mechanism, they might support other new ideas in physics. If one particular version of the theory called supersymmetry is correct, for example, the top quark might decay into an electrically charged version of a Higgs particle.

Making the thousands of quarks needed to test these ideas, however, will require improvements on the Tevatron, the Fermilab accelerator conducting the current top-quark search. The Department of Energy has already approved a $230-million supplemental accelerator called the Main Injector, scheduled to be built by 1998, that will give the Tevatron a boost by whipping particles up to high speeds before they are sent into head-on collision courses inside the Tevatron ring. The Main Injector will yield a fivefold increase in luminosity (the number of particles in the colliding beams), enough to observe about a hundred top quarks per year-long run. But University of Maryland physicist Drew Baden and some of his colleagues are pushing for more. Asks Baden, "Why spend all this money to find the top quark and then stop?"

For $400 to $600 million more, spent on better magnets and other accelerator components, the Tevatron could be turned into a "top-quark factory," pumping out hundreds of thousands of the particles so Baden and his colleagues could dissect their prey's subtle properties. But even avid promoters of the top quark admit that in the current funding climate, this will be a tough sell. Extensive studies of the top quark may have to wait for Europe's Large Hadron Collider, due sometime after the turn of the century. That means Fermilab physicists, who may already be proud parents of a new quark, may be fated to watch it grow up elsewhere.

–F.F.

Shochet. And in a year D0, whose construction was slowed by funding shortages, may have corroborating evidence. At last week's American Physical Society meeting in Crystal City, Virginia, D0's Baden said his group should be able to secure evidence for top quarks by the end of the next run of particle smashing, which began early this year.

Fermilab director Peoples admits that CDF is taking a calculated risk in going to the press without the airtight case that may be available in a year. And other physicists note that, in earlier particle hunts, such gambles haven't always paid off. Ten years ago, for example, early in the search for the same elusive particle, Nobel Prize–winning physicist Carlo Rubbia had to retract a premature announcement that his experiment at CERN, the European center for particle physics, had detected signs of the top quark.

Shochet and his CDF colleagues hope to protect themselves from embarrassment by couching their announcement in caveats. Peoples is uneasy, however. He has no qualms about the decision to publish a technical paper, he says: "We thought it would be better to go forward with what we have and put it in a form that the [physics] community can use to make up their own minds." But the decision to schedule the press conference, he says, came after long and difficult negotiations; although, as director of the lab, he had to approve the decision, he still has mixed feelings. "I feel very uncomfortable about this." He adds, however, that the alternative—letting the press interpret the paper on its own—might be worse.

Contributing to the general discomfort is the fact that, so far at least, results from D0 don't support CDF. The D0 researchers are studying collisions at the same energies as CDF, says Baden, but they're not seeing the number of events that would be expected if the top quark really does have the mass and "cross section" (a measure of how easy a particle is to create or how readily it decays) implied by the CDF results. So far, D0 doesn't have enough data to refute the CDF result, but both groups regard the disagreement as a warning sign—and an additional reason to keep the Tevatron up and running.

In spite of their concerns, Baden, Peoples, and their colleagues in the high-energy physics community hope the CDF researchers won't regret their sudden emergence into the limelight. But those good wishes may not have eased the CDF physicists' jitters when they contemplated climbing out of their tunnel last week.

–Faye Flam