PHYSICS

Collisions Hint That Quarks Might Not Be Indivisible

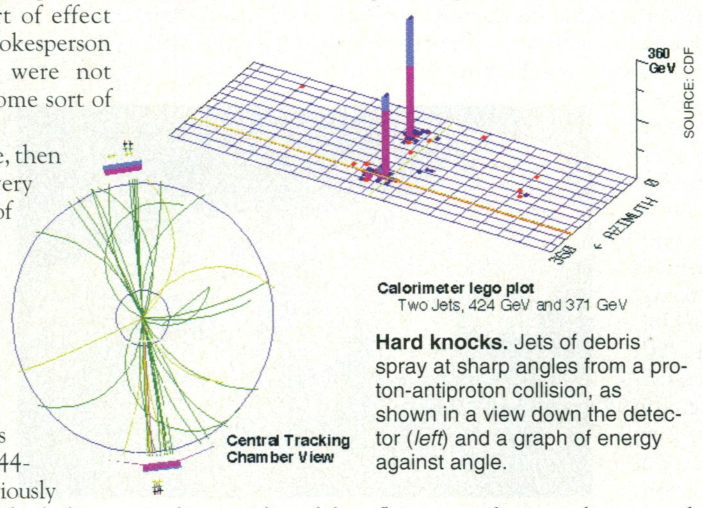
BATAVIA, ILLINOIS—When two groups of particle physicists at the Fermi National Accelerator Laboratory announced last March that they had found the top quark, they put the capstone on the current theory of the fundamental structure of matter, called the Standard Model. Now, just short of a year later, *Science* has learned that one of those groups has evidence that could challenge the model. During a yearlong run on Fermilab's Tevatron particle accelerator, the CDF collaboration—for Collider Detector at Fermilab—observed an unexpectedly large number of "hard," or violent, collisions between quarks, which the Standard Model identifies as a fundamental building block of matter. "This is just the sort of effect you would see," says CDF co-spokesperson William Carithers, "if quarks were not fundamental particles but had some sort of internal structure."

"If [quark substructure] was true, then its relevance would be very, very large," says Guido Altarelli of CERN, the European particle physics laboratory in Geneva. But he and Carithers, who is based at Lawrence Berkeley National Laboratory, quickly add that it's too soon to conclude that the Standard Model is in serious danger. Physicists both inside and outside the 444-member CDF collaboration are furiously sorting through other, less earth-shaking explanations for the data, which the CDF group describes in a paper submitted 2 weeks ago to *Physical Review Letters*. They range from the creation of an unknown particle during the collisions—the explanation Altarelli favors—to minor errors in Standard Model predictions about the behavior of quarks. Neither alternative would require a major refurbishing of theory.

But if quarks do turn out to have a substructure, the discovery would be something of a reprise of Sir Ernest Rutherford's discovery of the atomic nucleus at the turn of the century. Rutherford and his co-workers smashed positively charged alpha particles into gold foil and noticed that there were too many hard collisions—those from which the particles caromed at nearly right angles—to be explained by a structureless "plum pudding" model of the atom. Instead, Rutherford concluded, the particles must be running into a small, hard kernel he called the nucleus.

Physicists now know that the nucleus itself has structure: first the protons and neutrons making up the nucleus and, inside each of them, three quarks immersed in short-lived "virtual" quarks and their antimatter counterparts, antiquarks. The whole quantum-mechanical stew is held together by particles called gluons. Just as Rutherford tested his understanding of atomic structure by probing atoms with alpha particles, the CDF team tested its picture of this structural hierarchy by colliding protons with antiprotons in the Tevatron, the world's most powerful accelerator.

Most of the collisions were glancing. But every so often a quark from one proton collided head-on with a quark or gluon from the other, sending debris flying at a sharp angle to the beams. In the world of particle physics, the more powerful a collision, the smaller the distances it can probe. And at the energy of the Tevatron—1.8 trillion electron volts—the debris from these hard collisions gave information about the smallest distance scales ever explored.



Hard knocks. Jets of debris spray at sharp angles from a proton-antiproton collision, as shown in a view down the detector (*left*) and a graph of energy against angle.

The collaborators compared the frequency of the sideways "jets" of debris (see graphic) that spewed from the collisions with the predictions of quantum chromodynamics (QCD), the mathematical apparatus for calculating quark interactions in the Standard Model. Down to energies corresponding to scales of about a thousandth the size of the proton, says Carithers, the agreement with QCD was "right bang on." But then the frequency of high-angle jets began to diverge from theory, and at scales 10 times smaller the frequency of these jets was at least 50% higher than the prediction.

As these events began to accumulate, says CDF co-spokesperson Giorgio Bellettini of the Istituto Nazionale di Fisica Nucleare and the University of Pisa in Italy, "a fierce fight" broke out within the collaboration over how to gauge the small chance that systematic experimental errors could explain the results. The researchers made exhaustive tests of the possibility that a "conspiracy" of random or systematic errors might be fooling them, says Bellettini. Finally, he says, the collaboration reached a consensus that the excess had to be real.

Now they are left to explain it. Steve Geer, a CDF team member at Fermilab, describes the most dramatic possibility: "It might mean that, just as in Rutherford's atom, there's a hard center" lurking inside the quarks, as some speculative theories suggest.

But Geer points out that several other explanations might account for the measurements. The more mundane possibility, he says, has to do with how momentum is parceled out among the components of a speeding proton. The hardest collisions occur when two quarks that happen to carry a high fraction of each proton's momentum meet head-on. But the massless gluons can carry momentum as well. So if, say, QCD underestimates how often gluons carry a high fraction of the momentum, then the quarks they encounter could suffer an unexpected number of violent collisions, and "we could end up with more energetic jets than expected," Geer says.

A more radical suggestion by Altarelli and Pierre Chiapetta at CERN posits that the energetic quark collisions occasionally generate a new, heavy particle—a cousin of the Z^0, a known massive particle that appears briefly in high-energy collisions. The creation of the particle would give the quarks another way to interact, boosting the collision frequency. And when it decays, the particle would spray jets of debris to the side of the collisions, mimicking an excess of hard collisions. The new particle might also explain a nagging observation made at CERN: Researchers there have noted that the rate at which the Z^0 decays into bottom and charm quarks doesn't match theory. The Z^0 might "mix" with, or transform into, its heavier cousin, which would alter its lifetime and might explain the decay rates.

The CDF team is already grinding through new data to see if it can find any way to distinguish among these possibilities—for example, by studying the detailed angular distribution of the jets. But for now, the team is glad that the data are on their way to publication and a wider group of particle theorists around the world will be trying to make sense of them. Says Brenna Flaugher, a CDF team member at Fermilab, "This is where the fun begins, I guess."

–James Glanz