Beyond the Top

Now that physicists have found the top quark, what's next?

By IVARS PETERSON

The excitement has died down. The clamor has subsided. The top quark is finally in the bag.

But for more than 850 physicists working at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill., the pursuit goes on. Protons still smash into antiprotons at the Tevatron collider. Massive detectors continue to record the results of these high-energy collisions. Researchers painstakingly sift through vast quantities of data, looking for the top quark's characteristic, but exceedingly rare, signature.

The emphasis has now shifted from finding the top quark to revealing this shadowy particle's true identity—reconstructing and pinpointing its mass, lifestyle, and lifetime from the scattered remains. It's an effort aimed at exposing cracks in the standard model of particle physics, the prevailing theory of the elementary particles and forces of nature.

The top quark is a gateway to new physics, insists Fermilab theorist Christopher T. Hill.

The discovery of the top quark, reported in the April 3 PHYSICAL REVIEW LETTERS, represents a triumph for the standard model (SN: 3/11/95, p.149).

According to this theory, all matter is composed of six strongly interacting fundamental particles, or quarks, and six weakly interacting particles, or leptons. The particles in each sextet come in pairs, and these pairs can be neatly arranged in order of increasing mass.

The electron and electron neutrino, the muon and muon neutrino, and the tau and tau neutrino make up the lepton family. Only the electron is part of ordinary matter.

Two varieties of quarks—known as up and down—combine to create the protons and neutrons of atomic nuclei. Three other types of quarks—strange, charm, and bottom—have been found using particle accelerators. The newly discovered top quark is the long-sought partner of the bottom quark.

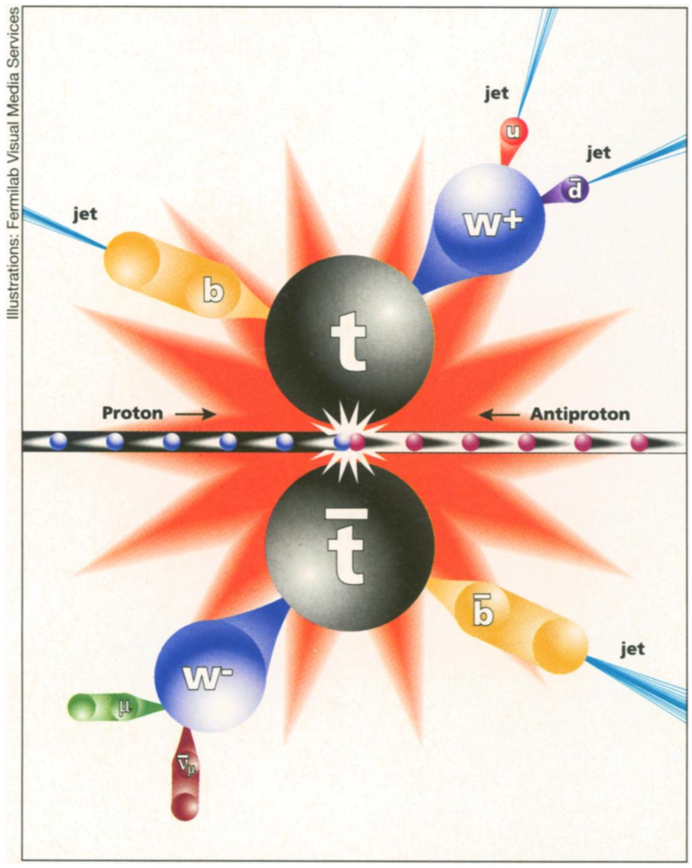
The standard model also includes a theory called quantum chromodynamics, which describes how quarks bind together via the strong force, and a unified theory of the electromagnetic force and weak interaction, which governs how leptons and quarks interact. The forces are carried by particles called bosons, which shuttle between the matter particles to create the forces between them.

But the standard model of fundamental particles and interactions says nothing directly about the masses of quarks and leptons. It enumerates the particles but fails to explain their existence or distinctive characteristics. It's like having a periodic table of chemical elements without an accompanying atomic model to show why elements belong in different groups.

In fact, the top quark has proved surprisingly heavy. Results from the Collider Detector at Fermilab (CDF) indicate that the top quark has a mass (expressed in energy units) of 176 billion electron-volts (GeV), with an uncertainty of 13 GeV. Data from the DZero detector at Fermilab provide a mass estimate of 199 GeV, with an uncertainty of 30 GeV. This makes the top quark about 40 times heavier than the bottom quark.

"The challenge and the puzzle is to explain why the top quark's mass is what it is," says Paul D. Grannis of the State University of New York at Stony Brook, a DZero team member.

Overall, quark and lepton masses cover an enormous range of values, and most particle physicists see no clear pattern in these numbers that would disclose an underlying structure.



In this artist's representation of a particle collision, a proton and an antiproton smash together at high energy to produce top and antitop quarks. These heavy quarks decay into W bosons and bottom quarks, which decay further into lighter quarks and leptons. The light quarks then disintegrate into jets of subatomic particles.

Theorists have proposed that the masses of the fundamental particles depend on how strongly each type of particle interacts with a hypothetical entity called the Higgs field, which permeates the otherwise empty vacuum of space. An electron, for example, has a tiny mass because it interacts very weakly with this pervasive field. Quarks interact more strongly and thus have significantly larger masses.

"But the Higgs mechanism is a black box," Hill remarks. "It's a theory we can use, but it doesn't really tell us what is going on."

What's intriguing about the top quark is that it has a mass close to that associated with the Higgs field and with the mechanism by which the field couples to fundamental particles. The Higgs

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In the control room, Fermilab physicist Meenaksi Narain views tracks left by a high-energy collision between a proton and an antiproton in the DZero detector.

field can also be interpreted in terms of force-carrying particles shuttling back and forth between matter particles. Physicists call this force-carrying particle the Higgs boson.

"Nature has given us something rather remarkable in the top quark," Hill says. "Many theorists are coming around to the point of view that this tells us something fundamental about the Higgs mechanism itself. Maybe we're starting to get into the dynamics of mass generation in the standard model."

In some theoretical schemes, the Higgs boson is actually a composite object made up of top quarks and their antimatter counterparts, called antitop quarks. This type of coupling suggests the existence of another type of force between top quarks. Thus, it's possible that the top quark plays a special role in the generation of the masses of all particles of matter, Grannis says.

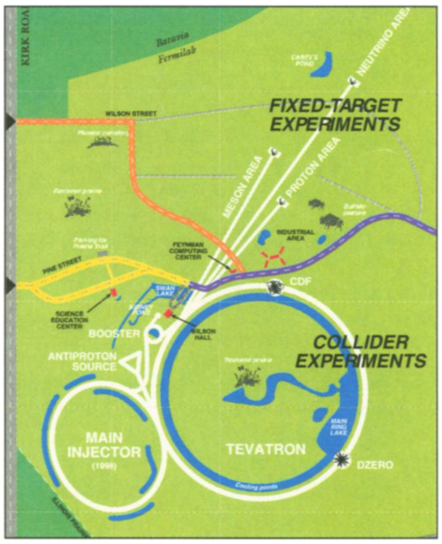
"Right now, the top quark is a laboratory in its own right," adds John Peoples Jr., Fermilab director. "It's the most massive thing we know how to produce, and generally, that has been the path of exploration in high-energy physics—to get the most energetic object and see what happens to it when it's produced."

Uncovering hints of possible new forces and exotic particles requires precise determinations of the top quark's mass, lifetime, and decay modes. That means getting a close look at lots of top and antitop quarks.

This is no simple matter. The probability of creating a top-antitop quark pair when a proton and antiproton collide and annihilate themselves in the Tevatron accelerator at Fermilab is less than 1 in 10 billion. Once generated, these massive quarks decay almost instantly into other particles.

Researchers typically look for certain types of decays that seem to characterize the top quark. In general, top and antitop quarks each decay rapidly into a W particle, which carries the weak force, and a bottom quark. The W can then decay into a lighter quark and an antiquark or into a pair of leptons (an electron and electron neutrino or a muon and muon neutrino). The bottom quark decays into a lighter quark. These lighter quarks in turn disintegrate into cascades of subatomic particles, which show up in detectors as narrow sprays, or jets.

At present, researchers at Fermilab can observe only about 50 top quark events a year. Nonetheless, with the Tevatron now delivering protons and antiprotons to its two detectors at a record-breaking pace, researchers expect to double their stock of top quark data by the end of the year.



This map of Fermilab shows the locations of the CDF and DZero detectors along the Tevatron ring and the new accelerator, called the Main Injector, which should be completed in 1999.

With this data set, "we can start to move from the observation of the top quark to studying its detailed properties," says William C. Carithers Jr. of the Lawrence Berkeley (Calif.) Laboratory and the CDF group.

One crucial element of this analysis will involve determining the combined mass of the top-antitop pair in a given event. It's possible that physicists may find evidence of the creation of a new heavy particle—a meson that decays into a top and an antitop—out of the energy of the initial proton-antiproton collision and annihilation.

"In the standard model, there is no candidate for such an object," Grannis says. "That's why this is an interesting search. It's one way we can hope to get an insight into what has to be added to our current picture."

Another important parameter is the top quark's lifetime. This lifetime is so short it can't be determined directly. Instead, researchers must study the details of how a top quark decays into a bottom quark and a W boson to deduce a value for this quantity.

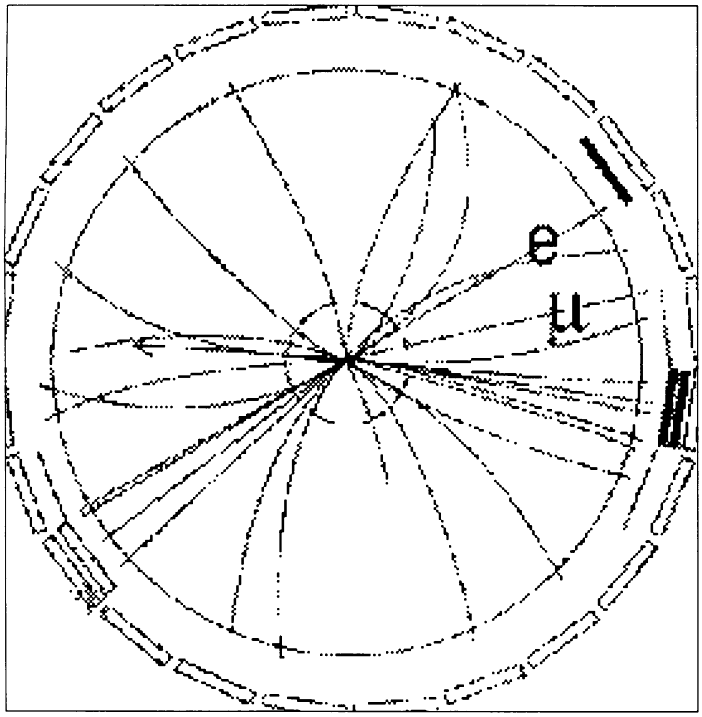
With more data, physicists can also start to look for rare types of decays. According to the standard model, a top quark should always decay into a W boson and a bottom quark, but it is also possible that a lighter quark may come out of the process.

"We're starting to look at that possibility, putting limits on it with the data that we have in hand," Carithers says. As new data come in, these limits will become tighter and presumably more interesting.

Moreover, the large mass of the top quark makes top decays a potentially bountiful hunting ground for various types of exotic particles. For example, so-called supersymmetric theories, which permit the unification of the strong and electroweak forces, posit the existence of partners for each of the matter-making fermions (leptons and quarks) and force-carrying bosons of the standard model. The fact that no one has yet discovered these additional particles in accelerators suggests that, if they exist, supersymmetric particles must be massive.

Fundamental Particles of the Standard Model

Leptons			Quarks		
Type (flavor)	Mass (GeV)	Electric Charge	Type (flavor)	Mass (GeV)	Electric Charge
Electron neutrino (ν_e)	$<7 \times 10^{-9}$	0	up (u)	0.005	2/3
Electron (e)	0.000511	-1	down (d)	0.008	-1/3
Muon neutrino (ν_μ)	<0.0003	0	charm (c)	1.5	2/3
Muon (μ)	0.1057	-1	strange (s)	0.16	-1/3
Tau neutrino (ν_τ)	<0.03	0	top (t)	176	2/3
Tau (τ)	1.7771	-1	bottom (b)	4.25	-1/3



Signature of the top quark, with distinctive electron and muon tracks.

At the end of December, the Tevatron will close down for 3 years. During this shutdown, both the facility and its two detectors will be upgraded to increase Fermilab's capability for top quark research. The construction of a new accelerator called the Main Injector forms a key part of this effort, which should be completed in 1999.

Meanwhile, researchers can perform experiments that involve firing energetic particles at fixed targets. One of their goals is to observe the tau neutrino and its interactions with matter. Physicists have obtained indirect evidence of the tau neutrino's existence but have not yet definitively characterized the particle.

However, the most dramatic and exciting findings probably lie further ahead.

"The upgrades will let us go from a few dozen events to thousands of events, allowing us to explore not only the production of the top quark but also the way in which it decays, in order to get clues as to why these constituents are so heavy," Grannis says. This research, in turn, brings physicists nearer to answering the fundamental question of why the particles that constitute the cosmos have different masses.

"We have to multiply our data sets by factors of 100 or more in order to get at such questions," he adds. "In that sense, we have really only started, and there is a long way to go."

Until the construction of the Large Hadron Collider at the European Laboratory for Particle Physics (CERN) in Geneva (SN: 1/7/95, p.4), Fermilab's Tevatron will remain the world's most powerful explorer of the particle realm and the only one capable of creating top quarks. "We have a nice monopoly for a while, and we want to exploit it," Peoples declares.

Physicists realize that the standard model of particle physics is incomplete. Future studies at Fermilab and CERN will probably point the way to a new theoretical framework for understanding matter in the universe.

"I think the standard model will become embedded in a much larger structure," Hill says. "It will take a long time before we map it out, but we will know if we are on the right track by making predictions and seeing how they match up with experiment."

He adds, "I fully expect that to start happening in the next decade."

The top quark itself may be just the tip of a new particle physics iceberg. □