Where Do You Go When You've Made it to the Top?

What a difference a year can make—especially when almost a thousand physicists spend that year in single-minded pursuit of a goal. The goal in this case was the discovery of the top quark, which one year ago sat at the threshold of statistical respectability. (See PHYSICS TODAY, June 1994, page 17.) Since then, the Collider Detector Facility group and the D0 group at Fermilab's Tevatron have steadily improved their statistics and their analyses until the question of whether they have in fact seen the top quark is no longer a subject of controversy. CDF sees 56 top candidates over a predicted background of 23.1, for a statistical significance of 4.8 standard deviations. D0 sees 17 events over a predicted background of 3.8, for a statistical significance of 4.6 standard deviations. Perhaps equally significant, all subsequent analyses of the kinematic, production and decay properties of the top samples are consistent between the two experiments and support the hypothesis that the excess events over background are indeed due to top production. The focus of debate now seems to have passed from whether the top has been discovered to how significant the discovery will be for particle physics. On the subject of significance, there seem to be two main camps.

In the first camp are those who feel that the discovery of the top quark represents just one more success, albeit a significant one, for the already successful standard model. Particle physicists have been waiting for the top quark since its partner, the bottom, or b, quark was discovered 18 years ago, or even since our first glimpse of the τ lepton indicated the existence of a third family of fundamental fermions 20 years ago. People in this camp point out that the recent measurements of the top mass—176 ± 13 GeV/c^2 for CDF and 199 ± 30 GeV/c^2 for D0—are consistent with standard-model predictions. For this group, a failure to discover the top quark would have been much more interesting.

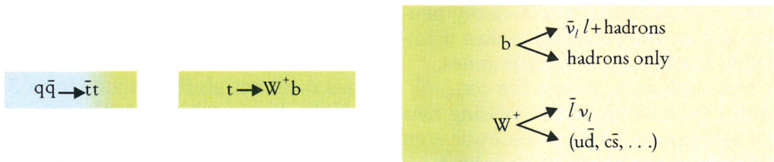
In the other camp are those who are confident that the top quark will serve as a window on the inner workings of the standard model and perhaps beyond. They point to the fact that the top mass is much heavier than was expected after the discovery of the b quark. They hope the unexpectedly large top mass can shed light on the dynamics of electroweak symmetry breaking—the process by which the fermions and weak gauge bosons acquire mass. They also hope the top's large mass, about twice that of the next heaviest fundamental particle, the Z^0, will make top decays a rich hunting ground for new and exotic particles. However, while the two camps may disagree about the significance of the discovery, they are united in the opinion that isolating a top signal from trillions of 1.8-TeV proton–antiproton collisions represents an impressive piece of physics.

> The discovery of the top quark—the first new particle in over a decade and the heaviest yet seen—has experimentalists, theorists and accelerator physicists scrambling for ways to exploit this new window onto the physics of electroweak unification.

Tracking the top

In deciding whether an event contains a possible top quark, CDF and D0 look for the top's decay products (see the figure below) and require the entire event to have its energy distributed in three dimensions and at wide angles to the beam axis—general characteristics of an event with many heavy-particle decays. One of the more important changes in D0's analysis over the past year is that an event must have a minimum transverse energy—that is, energy deposited at wide angles—if the event is to be a t-quark candidate. This requirement serves as a strong discriminant between background and signal events. Because CDF can efficiently detect the b quark from the top decay, the group can isolate a top signal without placing such a transverse-energy requirement on the entire event, although they are examining the transverse energy distribution of their signal. The other requirements imposed to isolate top quarks are based on their expected production and decay mechanisms.

The two-thirds of W bosons that decay into a quark and an antiquark are difficult to separate from the detritus from the initial $q\bar{q}$ interaction, because as the quarks from the W decay "dress" themselves into baryons and mesons, they produce jets—large numbers of particles directed in fairly narrow but ill-defined cones along the initial directions of the quarks. On the other hand, leptonic decays of the W into a high-energy lepton and its corresponding neutrino tend to have a topology that is highly uncharacteristic of hadronic background: a large energy deposited by the lepton on one side of the spectrometer at a wide angle, and a corresponding dearth of energy opposite the lepton, indicating the neutrino. For this reason CDF's and D0's present analyses require the W from either the decay of the t or the $\bar{t}$ to decay leptonically. Events where both W bosons decay leptonically are called "dilepton" events.



TOP PRODUCTION AND DECAY. Top quarks are produced at the Tevatron when a quark from a 0.9-TeV proton and an antiquark from a 0.9-TeV antiproton collide. The t decays into a W boson and a b quark. The b quark decays either hadronically or "semileptonically" into a lepton, a neutrino and hadrons. The W^+ from the top decays into either a high-energy antilepton and a corresponding neutrino or into a quark and an antiquark of different flavors. The $\bar{t}$ decays similarly, but into the corresponding antiparticles.

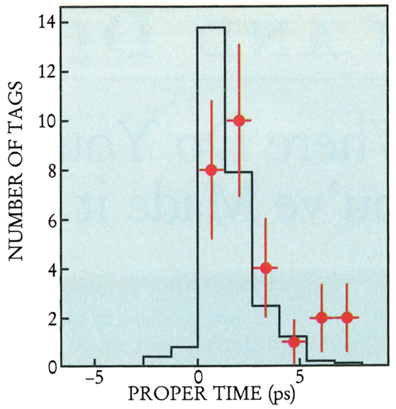
Those where one W decays leptonically and the other decays into quarks—which appear as jets in the spectrometer—are called "lepton plus jets" events.

Background can be further reduced if one identifies the b quark that is produced when the top decays. This can be done either by finding the b-decay vertex or by looking for the lepton from a "semileptonic" decay into a lepton, a neutrino and hadrons. CDF's silicon vertex detector can distinguish b-decay vertices from the main interaction vertex. (See the figure at right.) One of the main improvements in CDF's present top search was an enhanced vertex-finding algorithm. D0 cannot currently find b-decay vertices, although the group plans to install a vertex detector before the second Tevatron collider run.

Both CDF and D0 also search for the semileptonic decays of b quarks from the t or the $\bar{t}$. Those decays are indicated by a "soft" lepton with an energy less than is typical of weak-boson decay, but still greater than is typical of background events. Finding semileptonic b decays significantly reduced the background in D0's current top search.

Mass determinations

Once the top-quark events are isolated, one can begin extracting physics from them. One of the most significant analyses is the determination of the top's mass. This is not a trivial matter. Both the dilepton and the lepton-plus-jets events are plagued by missing information. As a result one must reconstruct the t and $\bar{t}$ by fitting the entire event subject to the following constraints: The momenta and energies of all the particles in the event must sum to the original $p\bar{p}$ momentum and energy—0 and 1.8 TeV, respectively. The lepton and neutrino and the quark and antiquark from the W decays must reconstruct to the W mass. Finally, the t and $\bar{t}$ are required to have the same mass. At present dilepton events cannot be reconstructed, because the information lost when the two W-decay neutrinos escape the detectors makes it impossible to calculate a reliable mass. For lepton-plus-jets events the constrained fit determines the missing neutrino momentum up to a quadratic sign ambiguity in one momentum component. Unfortunately one cannot tell *a priori* which two jets are from the hadronic W decay and which two are from the b quarks. As a result one must fit the event assuming all possible identities for each quark jet and both solutions for the neutrino momentum. Events with no b identification



Histogram of lifetimes of heavy quarks identified, or "tagged", by CDF's vertex-finding algorithm in actual top candidates (circles) is consistent with the distribution of b-quark lifetimes from simulated decays of 170-GeV/c^2 top quarks. The plot provides further support for the hypothesis that the heavy quarks from the top candidates are indeed b quarks.

have 24 possible combinations. If a b-quark jet is identified, there are 12 possible combinations.

For each combination the fit yields a t-quark mass and a χ^2 value that measures how well the combination fits the constraints. For each event CDF takes only the best fit, as indicated by the χ^2 value. D0 retains the three best combinations if they have a sufficiently good χ^2, and determines the mass as a weighted average of those combinations.

However, the main difficulties of determining the top mass stem from reconstructing jets. By examining simulated decays in a model of its spectrometer, D0 has found that jet-reconstruction difficulties systematically shift its mean top mass by an amount that ranges from about −5 GeV/c^2 for an input top-quark mass of 140 GeV/c^2 to about +20 GeV/c^2 for a 200-GeV/c^2 input top mass. The correction for this shift contributes substantially to D0's larger mass uncertainty. CDF also sees a shift (albeit a smaller one than D0) in simulated top decays, but notes that the median mass does not shift by more than 5 GeV/c^2. It is unclear whether the discrepancies arise from differences in the mass analyses, from differences in the spectrometers of the two experiments or from fundamental disagreements about how to handle jets.

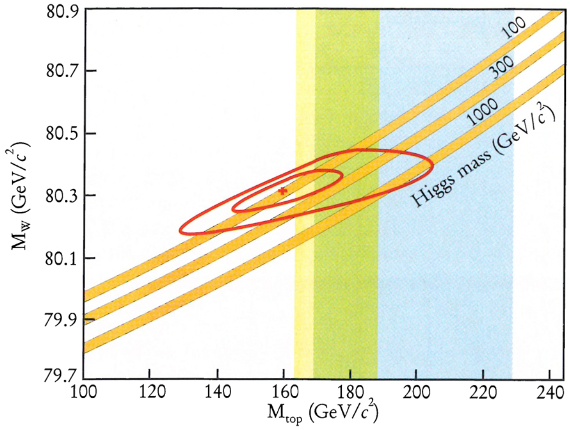
It is unlikely, however, that the differences in the mass determination will seriously affect the physics that can be done by the two experiments. The differences are viewed as cause for cooperation rather than for concern. In an April workshop the two collaborations began to resolve these differences. The workshop also initiated development of a program for the two groups to extract as much physics as possible from their top-quark samples.

Top-quark physics

The standard model is a theory of the interactions of the fundamental fermions—quarks and leptons. The model includes a theory of strong interactions—quantum chromodynamics—and a unified theory of electromagnetic and weak interactions—the Weinberg–Salam–Glashow theory. The electroweak unification is exact, however, only in the limit that the fermions and the bosons that mediate the electroweak force become massless, or equivalently, in the limit of very high energies. The symmetry of the electroweak force is hidden from us by the interaction of the electroweak bosons and the fermions with a massive, electrically neutral "Higgs field" that is thought to permeate all space. The interactions cause the neutral electroweak vector bosons to mix into the weak and electromagnetic eigenstates (a massive Z^0 and a massless photon), while the charged electroweak bosons, W^+ and W^-, remain unmixed. The interactions are also thought to give each fermion and vector boson a mass that is proportional to how strongly the particle interacts with the Higgs field. According to Fermilab theorist Chris Hill, "The top quark, because it is so massive, begs an answer to the question of what generates mass in electroweak theory."

In the simplest form of the standard model, which incorporates a single Higgs particle, the W boson and top-quark masses could be used to constrain the Higgs mass. In practice, the Higgs mass is over a hundred times as sensitive to changes in the W mass as to changes in the top mass, and so the W-mass error still dominates the Higgs-mass error. (See the figure on page 19.) Thus the differences in the CDF and D0 masses and their errors do not affect the physics the two groups can do with their top samples.

The top samples can also be used to probe the standard model in other ways. According to the standard model, the W bosons from decays of 175-GeV top quarks should be about 70% longitudinally polarized, and should be even more polarized for heavier top masses. Measuring the W polarization could serve as a probe of physics beyond the standard model. Other projects include looking



Measured properties of the Z^0 boson and the strengths of the fundamental forces constrain the top, Higgs and W masses. The bands show possible Higgs masses as a function of the top and W masses. Shaded regions are consistent with the top masses measured by CDF (blue), D0 (yellow) and both experiments (green). Top, Higgs and W masses within the inner and outer contours are consistent with results from CERN's LEP collider and the Stanford Linear Collider at the one- and two-standard-deviation levels, respectively. (Figure courtesy of the D0 group.)

for resonances in the invariant $t\bar{t}$ mass distribution to probe strong-interaction dynamics at the top-mass scale and hunting for exotic species, such as supersymmetric particles, in top decays.

However, the most interesting physics to come from the top quark could be a complete surprise. Few would have guessed when the b quark was discovered that it would be interesting enough to merit the profusion of B factories now running or proposed. Many think the physics that will come from the top quark will be every bit as unexpected and exciting as that being realized with the b quark.

A top factory?

The physics of the top is still largely unexplored. However, what we ultimately learn from the top quark may depend as much on how enthusiastically we pursue it as on what it has to teach us. During the remaining months of the first Tevatron collider run, CDF and D0 hope to double their top samples, a reasonable goal if one assumes we are still on the steep portion of the learning curve when it comes to finding top quarks. Any glaring departures from the standard model might show up in such a sample. If no departures are evident we must wait until the second Tevatron collider run, scheduled to begin in 1999 with a fivefold increase in luminosity (and top-production rate) as a result of the Tevatron main-injector upgrade. CDF and D0 also plan to make significant upgrades to their spectrometers that should increase the efficiency with which they detect top quarks. With these changes the groups hope they will be able to find between a few hundred and a thousand tops per year. Over a few years this would allow them to tighten the limits on the Higgs mass and to take a fairly sensitive look for physics beyond the standard model.

The discovery of the first fundamental particle in over a decade has fired the imaginations of theorists and experimentalists alike. It has also stimulated the creativity of Fermilab's accelerator physicists, who have already coaxed the Tevatron collider to perform consistently at 15 times its design luminosity. Several ideas for further increasing the machine's performance have flourished in the year since our first glimpse of the top quark and are now being debated within the particle physics community. (See, for example, the letter by Jay Orear in PHYSICS TODAY, January, page 73, and the response by Sidney Drell, March, page 13.) One idea in particular has progressed over the past year, namely that of beefing up the Tevatron's antiproton flux by building an inexpensive 8-GeV antiproton storage ring with permanent magnets and cold electron beams to cool the antiprotons. The project is described by Fermilab accelerator physicist William Foster as ". . . an antimatter bottle made out of refrigerator magnets." Fermilab director John Peoples is confident that the storage ring could be built in tandem with the main injector, perhaps drawing on the money Fermilab has already saved in main-injector construction costs. Ultimately the increased luminosity would require further upgrades of the CDF and D0 detectors to handle the increased interaction rate. Fermilab physicists hope the upgraded Tevatron could be producing tens of thousands of top quarks by around the beginning of the next century. A few years of running at this rate should enable the Tevatron experiments to either find or rule out the existence of several of the lightest particles predicted by supersymmetry.

In the latter half of the next decade CERN's Large Hadron Collider is scheduled to begin logging 10–14-TeV pp collisions and producing several hundred thousand top quarks per year. The LHC also gives us our best chance for directly observing the Higgs particle. Indeed, at the LHC with its five- to seven-fold increase in energy over the Tevatron, top quarks might be considered background to other, more interesting physics.

The relationship of the Tevatron to the LHC is unclear. Some contend that Tevatron upgrades would take funds away from the LHC and thereby slow the progress of particle physics. Others suggest that upgrading the Tevatron is a natural step toward the LHC. Kenneth Lane of Boston University, who strongly supports building the LHC, says, "The Tevatron is still the only training ground for the high-luminosity physics that will be done at the LHC." What CDF and D0 find during the remainder of their present run could influence the course of such arguments.

Ray Ladbury

'Asteroseismology' Offers a New Probe of Stellar Interiors

After a number of frustrated attempts, astronomers may at last be seeing seismic oscillation in nearby stars.

Just as the study of seismic waves lets us look into the bowels of the Earth, helioseismology has for more than 20 years been a rich source of information about the interior of the Sun. Apparently driven by internal convective motion, the Sun rings like a great spherical bell. Many thousands of resonant pressure-wave modes with periods on the order of 5 minutes have been painstakingly decoded from complex surface motions of dauntingly small amplitude. From the pattern of resonant frequencies one learns much about the composi-