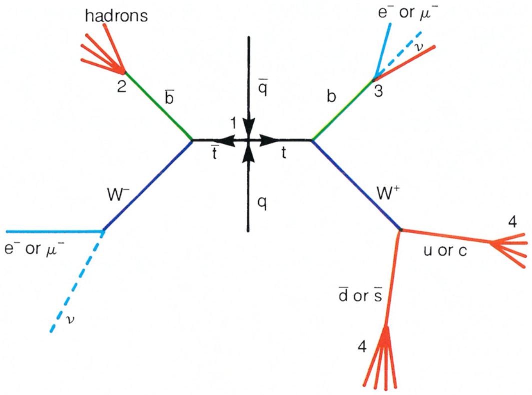
# FERMILAB TEVATRON COLLIDER GROUP GOES OVER THE TOP—CAUTIOUSLY

The evidence from Fermilab's Collider Detector Facility group for a 174-GeV/$c^2$ top quark (see PHYSICS TODAY, May, page 20) has been received with cautious enthusiasm by the particle physics community. Since most physicists still have not seen the 153-page preprint submitted on 22 April to *Physical Review D*, the demand for speakers on the result exceeds even CDF's abundant supply of experimenters. Still, it is unlikely that new developments will supplant CDF's present results before we've had time to digest them. The low top-production rate, the large backgrounds—events that mimic top decay—and the complicated topologies of t-quark decays all but ensure that the discovery of the t quark will be a protracted process rather than a single dramatic event. While awaiting new results from CDF and D0 (the other detector at Fermilab's 1.8-TeV $p\bar{p}$ collider), it is appropriate to evaluate CDF's present evidence and to anticipate possible future developments.




**Top quark signature:** $q\bar{q}$ annihilations (1) produce $t\bar{t}$ pairs. Each t quark decays into a W boson (purple) and a b quark (green). The W bosons decay hadronically (red), producing "jets" (4), or leptonically (blue). Hadronic (red) and semileptonic (blue and red) b-decays form detached vertices (2, 3).

## Top production and decay

At the Tevatron, t quarks would be produced in $t\bar{t}$ pairs when a light quark in a proton and a corresponding antiquark in an antiproton collide and annihilate. (See the figure above.) Because each proton is composed of three quarks as well as the gluons that hold the quarks together, collisions of quarks and antiquarks having a reasonable fraction of the Tevatron's 1.8-TeV center-of-mass energy are rare. If CDF's measured mass is correct, the $t\bar{t}$ pair-production threshold is high enough to put the rate of collisions capable of producing t quarks into this rare region.

According to the standard model, the t quark (or the $\bar{t}$ quark) decays almost exclusively into a $W^+$ boson and a b quark (or a $W^-$ and a $\bar{b}$ quark). Each of these W bosons decays "leptonically" one-third of the time into a neutrino and a charged lepton (one-ninth to an electron, one-ninth to a muon and one-ninth to a tau). It decays "hadronically" two-thirds of the time into a strongly interacting quark and antiquark (for example, $W^+ \to u\bar{d}$ or $c\bar{s}$, where u, d, c and s are the up, down, charm and strange quarks, respectively). The b quark "hadronizes" into a meson or baryon by "dressing" itself with quarks from the vacuum and then decays, usually after traveling a few millimeters, into a lighter quark along with other leptons and hadrons. The most easily identifiable b-quark decay is the "semileptonic" decay into an electron or muon, a neutrino and hadrons. Because the 5-GeV/$c^2$ b quark has only $\frac{1}{16}$ the mass of the W boson, the lepton from the b decay has higher energy than does the background but much lower energy than do those from the W decay. CDF's top searches seek to use the characteristics of these decays to find top candidates and eliminate as much background as possible.

## CDF's analysis

CDF's t-quark searches look for different final states of $t\bar{t}$ pairs decaying into a $W^+$ boson, a $W^-$ boson and a $b\bar{b}$ pair. Because the high-energy lepton from a W-boson decay provides excellent discrimination against background, CDF concentrates its top searches on the 35% of the $t\bar{t}$ events where at least one W boson decays into a neutrino and a muon or an electron. Decays where both W bosons decay hadronically are not considered at this time because of large hadronic backgrounds. Also because of large hadronic backgrounds, W decays producing a $\tau$ lepton are not explicitly considered, but could be found if the electron or muon from a $\tau$ satisfied the requirements of the W search. For the purposes of the CDF analysis, a lepton means an electron or a muon.

The 5% of the $t\bar{t}$ decays resulting in neutrinos and a high-energy pair of oppositely charged leptons are the goal of CDF's "dilepton" analysis. This analysis found two such events out of the $10^{12}$ $p\bar{p}$ interactions that took place during the 10-month 1992–93 data run.

The other CDF analysis looks for the 30% of the $t\bar{t}$ decays where one W decays leptonically and the other decays hadronically. Because the quark and antiquark are indicated by the presence of jets—narrow, high-transverse-momentum bunches of hadrons characteristic of high-energy quark production and hadronization—this analysis is called the "W plus jets" analysis. To further reduce backgrounds, this analysis uses two different methods to look for the b-quark decay.

The "detached vertex" method uses high-resolution tracking information to look for a b-decay vertex separated from the main event vertex. This method finds six t-quark candidates.

The "soft lepton" method looks for the soft, or relatively low-energy leptons from semileptonic b-quark decays. The soft-lepton method finds seven t-quark candidates, three of which are also found by the detached-vertex analysis. One of the dilepton events also fulfills the requirements of the detached-vertex and soft-lepton b-quark searches. While this event is surely a prime top-quark candidate, it could also result from background. This is why the argument for the t quark must be made using statistics.

## Statistical significance

The backgrounds in a particle physics experiment are random variables in the sense that a series of identical experiments may have backgrounds that differ from the expected or mean background. Because one does not know the actual background in a given experiment, one calculates the statistical significance of a result—a measure of the improbability of the mean background fluctuating up to or above the level of the observed result. The CDF collaboration uses two methods to estimate its backgrounds. While subsequent analyses indicate that the first method tends to overestimate the background, CDF uses the "method 1" backgrounds to calculate a conservative estimate of the statistical significance of its signals. The "method 2" backgrounds tend to be smaller than the method-1 backgrounds and agree well with most subsequent analyses.

Using a computer simulation, CDF finds the probabilities that the excesses above the method-1 backgrounds are due to upward fluctuations from the mean backgrounds to be 0.12 for the dilepton signal, 0.032 for the detached-vertex signal and 0.038 for the soft-lepton signal. Rather than multiplying these three probabilities together to obtain the probability that all three excesses result from background fluctuations (a risky proposition given the limited statistics and possible correlations involved), CDF sums the signals and the backgrounds and then determines the probability of a mean background of roughly 6 counts fluctuating upward to 15 counts or more. Basing the procedure on the number of counts rather than the number of events double counts the events found by both b-detection methods. Because studies show that such events are six times less likely than events found by only one b search to be background events containing no b quarks, CDF argues such double counting is justified. According to this procedure, the probability of all three results being due solely to a background fluctuation is 0.0026, corresponding to a statistical significance of 2.8 standard deviations. The method-2 background estimates give a statistical significance of 3.5 standard deviations.

Independent of statistical significance, kinematical studies also support the t-quark hypothesis, and a maximum likelihood fit to the masses of the reconstructed t candidates finds that a hypothesis that the events contain t quarks and background is 50 times more likely than a background-only hypothesis. Some of CDF's other results, however, are more difficult to interpret.

## Anomalous results?

The $13.9^{+6.1}_{-4.8}$-picobarn top-production cross section calculated by CDF is 1.5 to 3 times that predicted by the standard theory of strong interactions, quantum chromodynamics. D0's preliminary equivalent cross section is significantly lower than CDF's number, although the CDF cross section is not inconsistent with those from D0 or QCD at the 95% confidence level.

Equally intriguing and troublesome are the discrepancies between the predicted and observed numbers of events containing a W or Z boson and jets (not necessarily from top decay). CDF sees a deficit of events with a W plus four or more jets and a slight surplus of events with a Z plus three or more jets: two events compared with a theoretical prediction of 0.64. The detached-vertex analysis finds evidence that both these events have a detached vertex. At present, however, one cannot tell whether these results are simply statistical flukes, indicators of problems within CDF's detectors or analysis, or perhaps even harbingers of new physics.

Given this uncertain situation, the most important priority for CDF and D0 is to increase their data samples during the 1994–95 data run (hopefully an additional $4 \times 10^{12}$ $p\bar{p}$ interactions). This should be enough to confirm or invalidate CDF's result and any anomalies associated with it. If the large cross section is real, the new run's additional 48 to 60 top candidates would also halve the present errors on the mass to about ±8 GeV/$c^2$.

### THE QUARK QUEST

We looked up and down, high
and low,
For the quark whose strange mass
we don't know.
Oh charm please don't fail:
The bottommost tail
Of top's mass is starting to show!

BARBARA GOSS LEVI

## Top physics

If the t quark has been seen at 174 GeV/$c^2$, it is a victory for the standard model, because the existence of a heavy partner to the bottom quark is required by the standard model. Yet, as Edward Witten of the Institute for Advanced Study in Princeton, New Jersey, quickly pointed out, finding the t quark is less an end to the 17-year hunt for the b quark's partner than it is a beginning of physicists' ability to understand one of the central mysteries of modern physics—the Higgs mechanism of spontaneous symmetry breaking of the vacuum and the generation of elementary-particle masses. The Higgs mechanism is essential to a unified theory of electroweak interactions, because the symmetry of this unification is exact only for massless quarks and leptons. By breaking this symmetry, the Higgs mechanism serves as the bridge from these generic, massless particles to the physical quarks and leptons that make up the universe. As a consequence of this symmetry breaking, at least one species of massive, scalar (or spinless) Higgs boson must exist. Because the t quark is so massive and couples strongly to the W and Z bosons and the Higgs boson, precise measurements of its mass and properties can be used to determine the number and masses of the Higgs bosons.

With just over a hundred top candidates, one could distinguish between the single, heavy Higgs particle of the simplest version of the standard model and the multiple Higgs particles favored by some other models.

With thousands of t quarks, experimenters could look for exotic t-quark decay modes indicative of supersymmetric particles and other extensions of the standard model. They might also be able to measure the frequency of rare events in which a t quark is produced with a $\bar{b}$ instead of a $\bar{t}$, an indirect measure of the t-quark lifetime, which is thought to be too short to measure directly.

The difficulty of accumulating such numbers of top candidates at the present rate of 50 or fewer per year is the reason why University of Texas theorist Steven Weinberg says, "There is nothing more important to American high-energy physics right now than beefing up Fermilab's collider." As a step in this direction, the installation of the main injector at Fermilab is expected to increase the top production rate by about a factor of seven, beginning in 1998. Beyond that, one encounters many intriguing proposals for additional Tevatron upgrades, which could be operational before the end of the decade, and new accelerators, which could come on line in the first decade of the next century.

At present there are two proposals for upgrading the Tevatron, which could be implemented singly or in tandem. The Ditevatron proposal would use SSC magnet technology to double the Tevatron's energy and raise its top-production rate by another factor of seven. The Tevatron-Star proposal would build antiproton storage rings inside the main injector ring to increase the Tevatron's antiproton beam intensity and its top-production rate by a factor of 20 to 30. Both proposals pose technical challenges and are competing with other schemes for scarce funds.

According to SLAC director Burton Richter, the Next Linear Collider, a proposed 500-GeV $e^+e^-$ collider, could produce thousands of t quarks per year, with relatively low backgrounds, beginning early in the next century.

CERN's proposed Large Hadron Collider dwarfs all of these proposals, in terms of its energy (14-TeV pp collisions), its luminosity (a hundred times the Tevatron's present capability), its ability to produce t quarks (800 000 per year) and its chances of finding the Higgs boson. Still, Fermilab theorist Stephen Parke sees a role for the Tevatron-Star, saying, "Fermilab is looking primarily at $q\bar{q}$ interactions, but because the gluon–gluon cross section rises so rapidly with energy, LHC will be a gluon–gluon machine. The two machines are complementary." However, in a time of fiscal austerity, many worry that even complementary proposals like the NLC and the Tevatron-Star divide the international particle physics effort and risk slowing the progress of the field as a whole.

—Ray Ladbury

# ASTRONOMERS ARE POISED FOR THE 'CRASH OF 1994': BOOM OR BUST?

If comets are like "dirty snowballs," as Fred Whipple proposed in the early 1950s, then Jupiter is about to suffer the embarrassment of being hit by a boomerang snowball as astronomers around the world watch. Like many snowballs, Comet Shoemaker–Levy 9 broke apart in mid-flight. Comet SL9 was first seen, already in orbit around Jupiter, in March 1993, by a trio of avid comet hunters: Carolyn and Gene Shoemaker of the US Geological Survey in Flagstaff, Arizona, and David Levy, a contributing editor to *Sky & Telescope* magazine. By May of last year the comet's orbit had been determined. It was realized by Brian Marsden[1] (Smithsonian Astrophysical Observatory, Cambridge, Massachusetts) that in July 1992, SL9 had come within 95 000 km of Jupiter's center of mass, where it experienced tidal forces sufficient to rip it apart. On its next pass, SL9 will aim to come within 30 000 km of Jupiter's center of mass. Because the planet's radius is about 71 000 km, Jupiter will suffer a direct hit. Astronomers will be on hand to evaluate its injuries, if any.

This event is unprecedented—not the collision, but our advance knowledge of it. A mere glance at our Moon through a small telescope can attest to the importance of impacts in the solar system, but until now astronomers had no opportunity to tailor their observations to a particular event before it took place. Many impacts probably occur just as this event suggests: The target first captures a projectile into a bound orbit. The orbit is subsequently perturbed, and in some instances an impact occurs. SL9's highly eccentric orbit is perturbed mainly by the Sun's gravity.

The 21 known comet fragments of SL9 are inexorably moving in a lengthening train toward their separate encounters with the giant planet next month. (See the figure on page 20.) The first encounter will occur on 16 July around 20:00 universal time, and the last on 22 July around 8:00 UT. (UT is the same as Greenwich Mean Time; 20:00 UT is 4:00 pm Eastern Daylight Time.) The impacts will just miss being seen from Earth, occurring about 5–10° behind the morning limb (edge of the disk) of Jupiter. Because Jupiter rotates with a period of 9 hours 55.5 minutes, each impact site will rotate into Earth's view within 20 minutes.

Paul Chodas and Donald Yeomans of the Jet Propulsion Laboratory in Pasadena, California, did the orbital and impact-time calculations, using a dynamical model that includes perturbations due to the Sun, the planets, Jupiter's Galilean satellites and the planet's oblateness. The uncertainties in the impact times currently range from 22 minutes to 1 hour, but they will decrease to about 15 minutes as the impacts approach, according to Yeomans.

Each fragment is a comet in its own right, with a coma of dust surrounding a bright core, which many researchers believe contains a solid nucleus. The refurbished Hubble Space Telescope (see PHYSICS TODAY, March, page 42) has been following the time evolution of the fragments. According to Harold Weaver and Keith Noll of the Space Telescope Science Institute in Baltimore, at least some of the fragments appear to be breaking up, and some are essentially disappearing. So "is there a solid nucleus or not?" asks Weaver. In addition, no gas has been detected, and the dust is distributed "unlike any other comet we've ever seen," he says. "The snowballs have no ice," says Alexander Dessler of Rice University in Houston, Texas. He adds that SL9 may actually be an asteroid, not a comet, although he admits that at Jupiter's distance from the Sun of 5 astronomical units, the volatile gases might be completely frozen. (An AU is the average distance of the Earth from the Sun.)

## The world watches

According to Noll, the planned observations are driven by two main questions: What is the nature of the impacters, and what will Jupiter's response be?

Almost every observatory in the world, and many above the world, is expected to try to answer those questions during the third week of July.