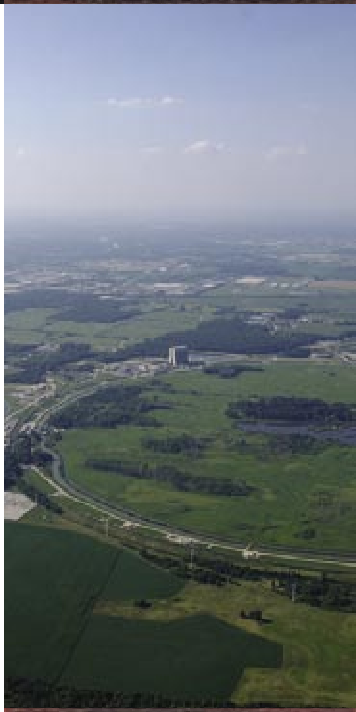
it on

Photos: Sandbox Studio

Physicist Michael Weber (right, Fermilab) and his colleagues (from left) Michael Kirby (Radboud University Nijmegen, Netherlands), Chris Neu (University of Pennsylvania), Sabine Lammers (Columbia University), Ben Kilminster (Ohio State University) as well as other experimenters at CDF and DZero are hitting upon numerous discoveries. *Photo: Sandbox Studio*

As work continues to complete the Large Hadron Collider in Europe and plans develop around the world for an International Linear Collider, one accelerator at the energy frontier is open for business right now. At Fermilab in Batavia, Illinois, the Tevatron collider is making discoveries.



Michael Weber is working late this Tuesday night in mid-November, crunching data from his desk in a cubicle in Fermilab's DZero building. He's analyzing data collected by the DZero collider experiment. He is determined to wring every drop of information from the experiment's vast and growing hoard of data. Just across the Tevatron ring, the scene is similar for Laura Sartori, working on the CDF experiment. Michael and Laura are looking for discoveries that could change particle physics forever. And the clock is ticking.

Michael and Laura are not alone—far from it. Almost 1400 scientists, members of the CDF and DZero collaborations, are pouring on the effort to make the most of the US accelerator's final run before CERN's Large Hadron Collider takes over the energy frontier later in the decade. Long after normal working hours, the lights burn in the cubicles of the CDF and DZero offices as experimenters search for the tell-tale tracks that might lead them toward a sighting of supersymmetry, extra dimensions, dark matter, exotic particles, and a host of other phenomena that no one on the planet has ever seen before.

The DZero control room
Photo: Reidar Hahn, Fermilab

Spurring them on is the fact that prospects for discovery look good for the Tevatron. The upgraded collider is producing more proton-antiproton collisions than ever before; the tuned-up CDF and DZero particle detectors track subatomic processes with unprecedented precision; and ever-sharper analysis tools tease secrets out of the floods of data with rapidly increasing sophistication.

"These kids are out there working every night," says physicist Hugh Montgomery, Fermilab associate director and former DZero spokesperson. "They see something, and they make a plot, and they're coming up with discoveries every night. Nobody else in the world will see that data and that result before breakfast the next day. That's the thrill of being an experimentalist."

All out for the final run

With all its thrills and heroic efforts, what results from the Tevatron would count as a success? To Fermilab's Montgomery, the performance of the Tevatron proton-antiproton collider during Run II has already succeeded.

"We're operating the highest-energy machine in the world, and it's producing more luminosity than ever before," he says. "All the work we've done is a platform for discovery, though we don't know what that will be. The job of the machine builder is to provide the wherewithal to perform experiments, and the job of the experimenter is to use that wherewithal to good effect."

The CDF and DZero experiments have more "wherewithal" because Tevatron upgrades over the past three years have taken the venerable accelerator to new heights of luminosity. The Tevatron can now produce in two months as many collisions as it did for the entire Run I (1992 to 1996). Every stage of the accelerator chain was improved, often with a series of 10-percent-improvements adding up to significant gains.

Since October 2003, the Tevatron peak luminosity, the maximum collision rate, has risen by a factor of five (from 4×10^{31} to 2×10^{32} cm^{-2} sec^{-1}), breaking records one after another. The total luminosity is close to 2 inverse femtobarns per experiment, ten times the luminosity of Run I. The numbers will continue to rise substantially, and each experiment may collect as many as 8 inverse femtobarns before Run II hits the finish line. With that total, Fermilab scientists expect to hit their marks in their physics goals and keep alive their chance of discovering a long-sought-after particle—the Higgs boson.

Roger Dixon, head of Fermilab's Accelerator Division, shepherded the extensive upgrade of the Fermilab accelerator complex that is producing the record-setting quantities of data.

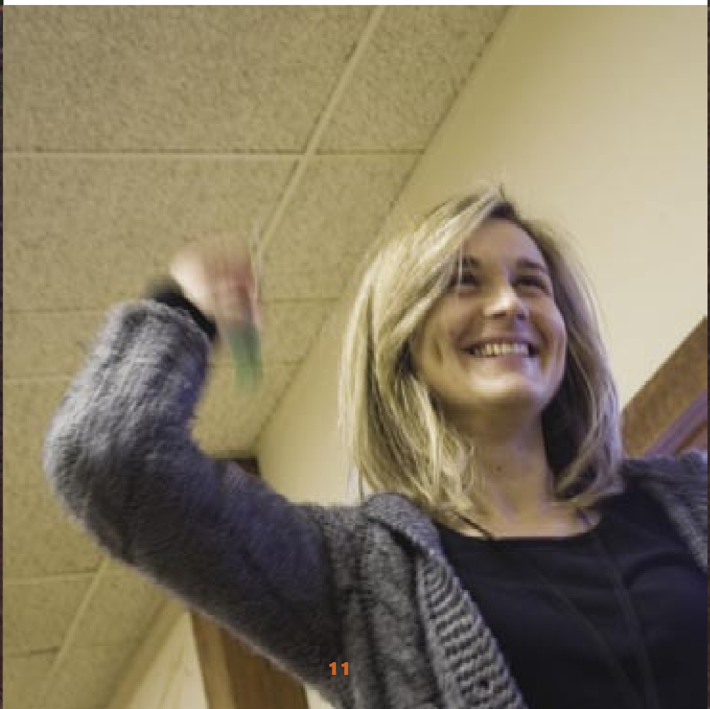
"All the hard work and dedication that we have put into building and operating the first superconducting accelerator in the world will not be validated until we have fully exploited the potential of our machine," Dixon says. "There are still the prospects for very important discoveries that we must not leave lying on the table."

The H word

There is no shortage of theoretical predictions of the discoveries that the Tevatron could produce, from the very likely (collisions producing single top quarks) to the speculative (finding

The CDF control room
Photo: Reidar Hahn, Fermilab

The Tevatron ring, four miles in circumference
Photo: Reidar Hahn, Fermilab



Laura Sartori (Fermilab) is one of about 1400 scientists working on the CDF and DZero experiments who aim to discover dark matter particles, extra dimensions and other subatomic phenomena.
Photo: Sandbox Studio

extra dimensions of space). One potential discovery, however, is on everybody's mind: the Higgs boson. Is it possible that the Fermilab experiments will at last catch sight of the particle that physicists have been tracking for more than 30 years?

The Higgs has been the ultimate quest for a generation of particle physicists. It would provide the source of mass for the other massive particles in the Standard Model of fundamental particles and forces. The Higgs is the missing keystone in the Standard Model, and discovering it would explain why some particles have mass and others don't.

CDF spokespersons Jacobo Konigsberg (left) and Robert Roser
Photo: Reidar Hahn, Fermilab

"It would be a tremendous 'wow' factor," says theorist and veteran Higgs hunter Howard Haber of the University of California, Santa Cruz. "Until 1998, no one really believed that the Tevatron had a viable shot at discovering the Higgs boson. If they could pull this off, it would be a testament to the experimental and accelerator teams achieving a result that no one initially imagined was possible."

Experimenters at CDF and DZero are considering all the possibilities for identifying rare Higgs-producing collisions among almost a million billion mundane particle collisions to be produced by the Tevatron. However, flat-out predictions of the particle's discovery are another matter.

"The Higgs is a long shot," says CDF cospokesperson Jacobo Konigsberg, of the University of Florida. "But we intend to give it our very best shot, and we hope that Nature cooperates. As we collect more and more data, we are discovering increasingly rare phenomena. You must learn how to find what is rare, before you can find what is very rare."

The sweet vs. the mundane

High luminosity takes physicists only as far as the ability of their detectors to track, record, and analyze the increasing numbers of collisions and results. Microchips and software tools are crucial to sort out background from useful events. Ever-expanding grid computing resources provide the computing power to sift through petabytes of data. Physicists' analytical skills combined with creativity are the ultimate tools to "differentiate the sweet physics from the mundane physics," as Montgomery describes it.

With all these tools in place, the ever-climbing luminosity grows in significance.

"More and more luminosity produces more and more data where you can look for increasingly rare phenomena," says Konigsberg. "What you find depends not only on how much data you collect but also on how you evolve your tools and analysis. You can get more mileage out of the same amount of data. You need to get as clever as possible as you go along."

Range of goals, solid achievements

The research program for Run II has always been about more than "just" the search for the Higgs boson; it includes searches for and measurements of many other rare phenomena:

- Signs of supersymmetry and the particles it predicts
- Signs of extra dimensions, exotic matter, and "the unexpected"
- Ultrafast matter-antimatter oscillations
- The detailed properties of the top quark
- Rare decays of particles containing bottom and charm quarks
- The strength of the electroweak force
- The interactions of quarks and gluons in protons and other hadrons

In the past year, both CDF and DZero have announced significant scientific results. In March 2006, the DZero collaboration announced that it had set limits on the astonishing behavior of the B_s meson, a quark-antiquark particle that switches between matter and antimatter trillions of times each second. In April, CDF pegged the number of B_s identity switches at three trillion per second. Within five months, CDF scientists improved their precision measurements and elevated their B_s oscillation result to the status of a formal discovery. Among its implications, the result reinforces Standard Model predictions and has key implications for supersymmetry. Fermilab Director Pier Oddone called the discovery "one of the signature measurements for Run II." In a press release, Raymond Orbach, Under Secretary for Science in the US Department of Energy, described the discovery as a "tour de force," and "a triumph for Fermilab."

Scientists think that B_s osillations could shine light on why the universe is made of matter while antimatter has all but disappeared. "With B_s oscillations firmly established, the focus of attention has now switched to searching for evidence of CP violation in the B_s system," says DZero cospokesperson Terry Wyatt of the University of Manchester, United Kingdom. "DZero has pioneered measurements that are directly sensitive to these matter-antimatter differences. An observation here would be clear evidence for new physics beyond the Standard Model."

In October, the CDF collaboration announced the discovery of new particles that are exotic relatives of the proton. In contrast to the proton, which is made of two up quarks and a down quark, CDF discovered three-quark particles containing a bottom quark. "This discovery fills another open spot in the 'periodic table' of Standard Model quark combinations, shedding light on the 'chemistry' that binds quarks together," says Fermilab's Rob Roser, cospokesperson of the CDF experiment. "We are confident that we will find more of these exotic particles. We continue to get smarter as the data pours in, and we are getting more results than we expected with the data we have so far."

In July, DZero scientists found evidence of proton-antiproton collisions that produced both a *W* boson and a *Z* boson. The bosons, carriers of the weak nuclear force, are responsible for decays of atomic nuclei. By November, CDF experimenters found enough collisions with *WZ* pairs to erase any doubts about the observation of this rare state. Measuring the *WZ* cross section—a quantity related to the probability for the process to occur—has caused excitement at CDF and DZero—both for the results themselves, and for future possibilities such as finding the Higgs particle.

"This is the lowest-cross-section state ever observed at a hadron collider. It was a coup for us," says Fermilab's Dmitri Denisov, cospokesperson of the DZero experiment. "It means we are sharpening our tools. The combination of luminosity at the Tevatron and precision at the detectors enables us to see rare events and very unlikely processes, like the *WZ* production. The Higgs has an even smaller rate of production, but our ability to see *WZ* pairs shows we are pushing in that direction."

DZero spokespersons Dmitri Denisov (left) and Terry Wyatt
Photo: Reidar Hahn, Fermilab

A rich vein

The Tevatron's most famous discovery to date is the top quark, discovered by CDF and DZero scientists in 1995. The particle is by far the most massive quark in the Standard Model, and the last of the six quarks that are the building blocks of matter. Over the course of Run I, the Tevatron produced about one thousand top quarks per experiment. Scientists "caught" enough of them to claim a discovery and measure the particle's mass, but not enough to explore the top quark in detail. Run II, so far, has delivered more than fifteen thousand top quarks, giving scientists enough data for a detailed study of the particle's properties, such as its electric charge.

The top quark provides a rich vein for researchers in several ways: making ever-more-precise mass measurements to test the consistency of the Standard Model; continuing the search for new production mechanisms, such as collisions producing a single top; and providing, perhaps, the gateway to something unexpected: new physics phenomena beyond the Standard Model.

"Is the top quark a window to new physics? Who knows?" asks Denisov. "The top is very important in itself because it is the heaviest elementary particle we know. A whole industry has grown around studying the top quark. Our mass measurements are accurate beyond those for all the lighter quarks. We need to verify whether the top does, or does not, behave as theory predicts. Studying the top also definitely helps our Higgs hunting."

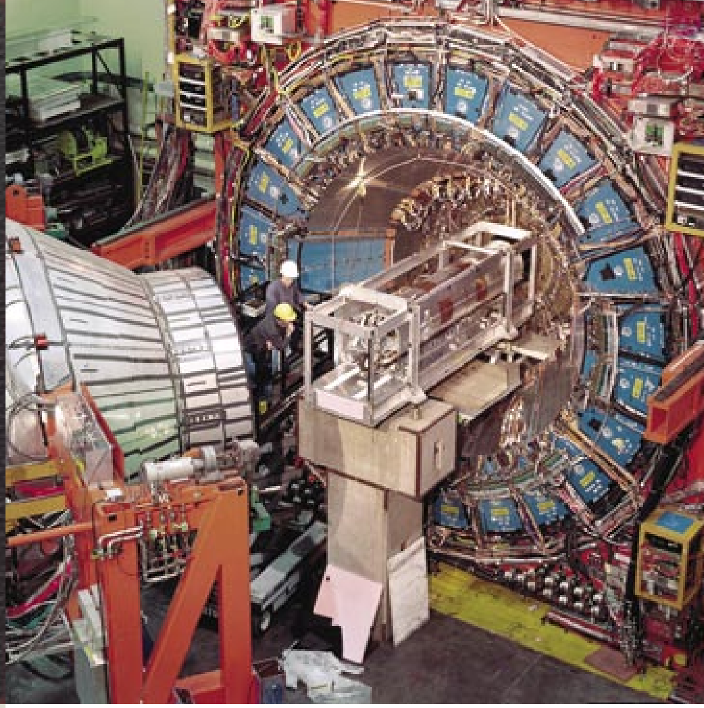
Getting close?

With or without the Higgs, the results of the Tevatron's final run will have a direct and significant impact on the future of US particle physics, the searches at LHC experiments, and, by extension, on particle physics research around the world. Still, in any consideration of Tevatron Run II, the talk inevitably circles back to the Higgs. Fermilab would like nothing better than to have the Tevatron's storied career culminate in results pointing directly to the whereabouts of this last missing piece of the Standard Model. With the rising Tevatron luminosity, and leaps in analysis techniques, scientists can't help feeling that the Higgs is waiting to be found.

In the fall of 2000, experimenters at the Large Electron Positron collider at CERN delivered a cliffhanger. Their results, obtained as LEP was shutting down to make room for the construction of the Large Hadron Collider, produced speculations whether LEP experiments had seen the first hints of Higgs boson signals.

In the end, the LEP experiments set a lower limit for the mass of the Higgs boson of 114 GeV/c^2. To see the first hints of a slightly heavier Higgs, Fermilab experiments need a few

The DZero detector weighs about 6000 tons and is the size of a three-story house. *Photo: Fermilab*



In 2001, the CDF detector received a new silicon vertex detector, which records particle tracks with high precision.
Photo: Fermilab

inverse femtobarns of data. Even for a Higgs particle as heavy as 160 GeV/c^2, Fermilab experimenters believe the Tevatron might have a chance at spotting it before time runs out.

"There is real excitement, with many more people becoming heavily involved in Higgs searches," says DZero's Denisov. Wyatt adds, "We're within spitting distance, and there's a real chance we might actually be able to get there."

Scientists at CDF and DZero are definitely ready for the challenge.

"We're ready for all sorts of surprises," says Konigsberg. "We have a whole program of searches for exotic physics, such as extra dimensions, plus we always have the unknown. We are preparing the trail for the Higgs."

Even if they do catch sight of the Higgs, however, Fermilab physicists readily acknowledge it will fall to the LHC experiments to confirm the discovery and to explore the boson's properties.

"Particle physics at the energy frontier is like a relay race, and we want to go as far as we can before we hand off the baton to our colleagues at the LHC," says Roser. "Many physicists working on CDF and DZero are also members of the LHC collaborations."

Meanwhile, the CDF and DZero collaborations keep their eyes on the grand prize. Their day-to-day—and night-to-night—work is the groundwork for a possible Higgs sighting.

"We will not be able to explore the continent," says Director Oddone of the Tevatron's prospects. "But we might be able to land on the beach."

For scientists at Fermilab, like Michael and Laura, this is enough incentive to work day and night. After all, as a senior CERN official has pointed out, it's Columbus, not Lewis and Clark, who gets remembered.