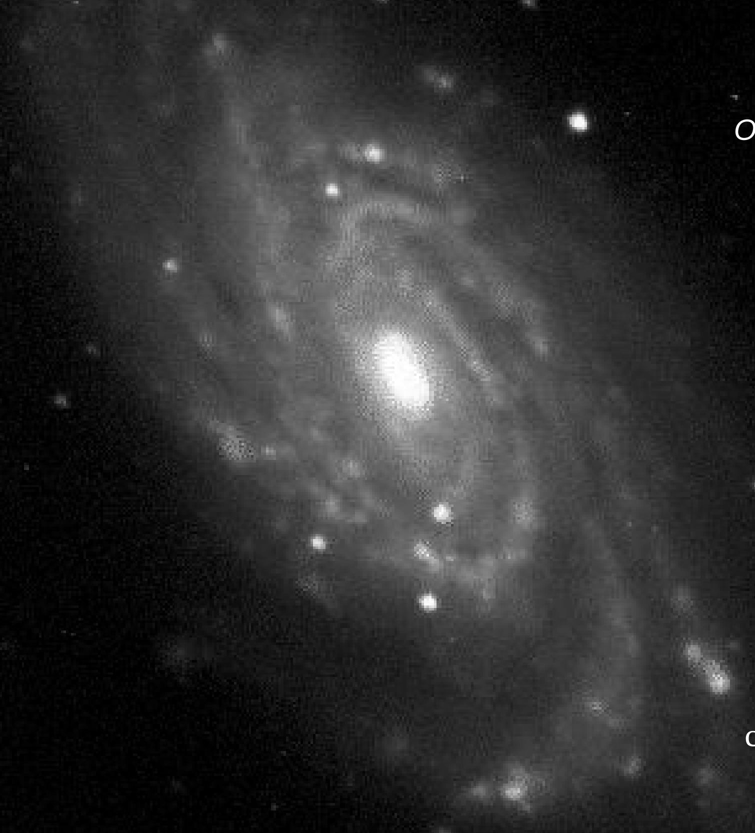
What's Next in the Search for the Higgs?

by JOHN WOMERSLEY



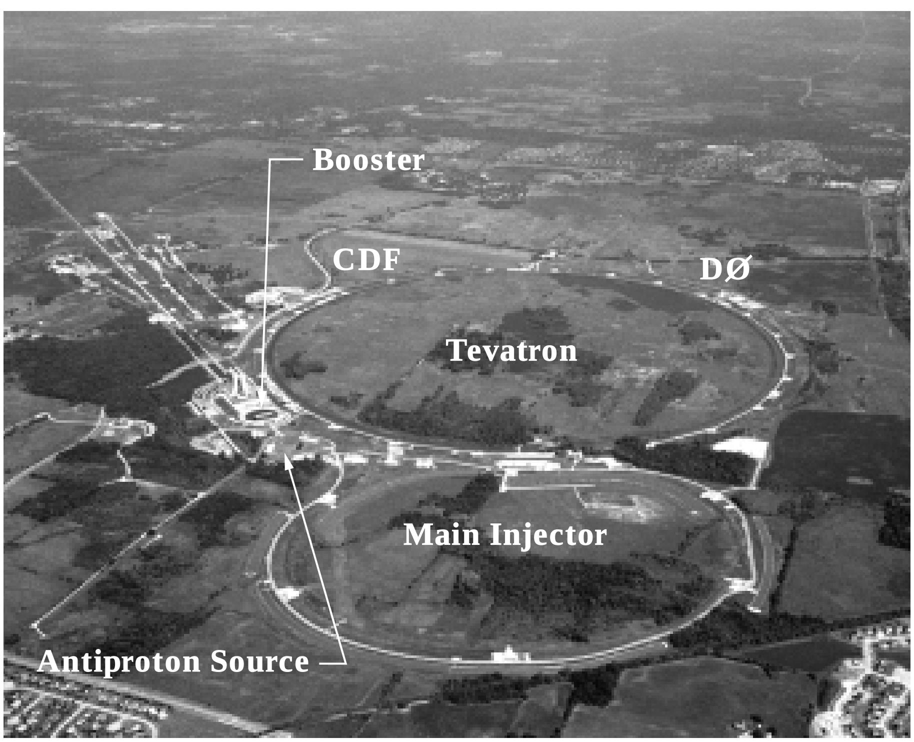
On March 1, 2001, Run II of the Tevatron Collider at Fermilab officially began. One of the primary goals of this project is to continue the search for the Higgs particle. What is this Higgs, why is it so important, and how will the Fermilab researchers try to ensnare it?

THROUGHOUT NOVEMBER and December 2000, the front pages of newspapers around the world were covered with stories about the American presidential election and the disputed vote count in Florida. While lawyers and judges argued about hanging chads and absentee ballots, an analogous story was unfolding in the science pages. Scientists and administrators at the European Laboratory for Particle Physics (CERN) were hotly debating whether experiments at the Large Electron Positron collider (LEP) had seen evidence of something called the Higgs boson. Normally sober scientific arguments turned heated, and petitions were even organized. In the end, the Director General of CERN decided to terminate operation of LEP in order to move ahead with construction of a new accelerator, the Large Hadron Collider (LHC). The LHC will certainly be capable of finding the Higgs, but it will not start doing physics until around 2007. Now that LEP is turned off, the focus of the action switches to Fermilab, just outside Chicago. Here the world's highest energy accelerator resumed data taking on March 1 and stands a good chance of clinching the discovery of the Higgs before the new European collider can start serious operations.

The Higgs boson has to do with mass. Mass is a fundamental property of matter. Through gravity—which is the only force important over astronomical distances—mass shapes the Universe. Mass is why you remain stuck to the face of the Earth and don't float off into space, and it's why the stars and planets and galaxies are the way they are. Despite Einstein's successes with general relativity, we still do not understand gravity in a quantum framework. But we believe we are getting closer to understanding the origin of mass itself.

In the cosmos, mass is present in (at least) two ways. There are atoms, the normal stuff that we (and the stars) are made of. In addition, there appears to be a lot of other stuff whose presence is felt through its gravitational pull but which cannot be accounted for through visible stars and galaxies. This is called dark matter. For reasons to do with the amount of deuterium and helium that was produced in the very early Universe, physicists are pretty sure that most of this dark matter cannot be normal atoms. It has to be new particles of some kind. (This is the first of several connections that are going to appear between particle physics and the origin and structure of the Universe.) In contrast, the masses of the atoms arise largely through physics that is understood. A proton has a mass of 938 MeV, but is composed of three quarks that together weigh no more than 5 to 15 MeV (estimates vary). That means that more than 99 percent of the mass of a proton is due to the energy captured by the force holding it together (the so-called binding energy). This force, the strong force that acts on quarks, is called quantum chromodynamics (QCD), and it is a gauge theory, like electromagnetism. But unlike electromagnetism, the force carriers of the theory (called gluons) carry the QCD charge themselves, as if photons were electrically charged. This means that gluons interact with each other, that the QCD force becomes extremely strong for small momentum transfers, and that quarks therefore end up strongly confined into particles like the proton. Precise testable QCD calculations are available for high momentum transfer processes at particle accelerators and agree well with data. For soft processes like the binding of quarks into a proton, QCD can be calculated only numerically on a computer in what is called lattice gauge theory. Recent advances in computing

Aerial view of the Fermilab site. (Courtesy Fermilab Visual Media Services)

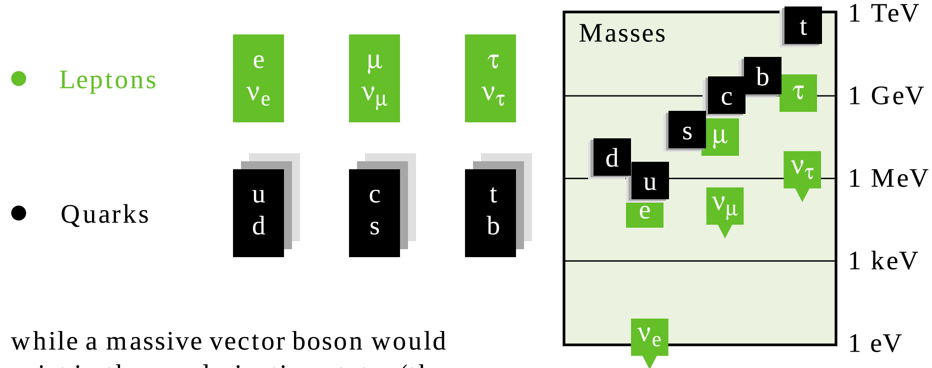


technology and calculational techniques have led to good predictions for the masses of bound states like protons.

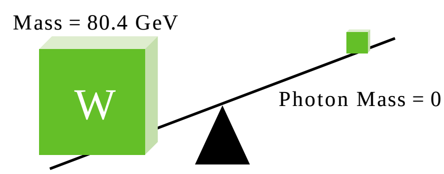
So does this mean we understand mass? Yes and no. While 99 percent of the mass of the (visible) Universe is QCD, and we understand QCD, there is more going on. We should also aim to understand the masses of the elementary particles, like the electron, the neutrino, and the quarks. These particles come in three repeating generations, each one more massive than the last (while the up quarks in a proton have a mass of around 5 MeV, the charm quark mass is 1.35 GeV, and the top quark is a whopping 175 GeV). These patterns are not understood at all. Also, we should aim to explain the masses of the vector bosons which carry forces. While the familiar photon is exactly massless, the *W* and *Z* particles register 80 and 91 GeV; but all of them couple to matter in the same way. The large mass of the *W* and *Z* is what makes the weak force weak, and without it there would be no atoms and no you and me.

What does mass really mean, for an elementary particle? Leaving aside gravity for now, if a particle has mass, it travels through space more slowly than the speed of light. In fact, a simple way to think of it is that the particle interacts with the vacuum of space. The strength with which it couples to the vacuum is what we call its mass: it's a kind of stickiness. The top quark is just much stickier than the up quark. For force-carrying particles (vector bosons) like the photon there is an extra wrinkle. This is because the massless photon exists in two distinct polarization states, while a massive vector boson would exist in three polarization states (the extra longitudinal state only makes sense if the particle travels slower than the speed of light). So the transition from zero mass to an infinitesimally small mass is not a continuous one. This extra degree of freedom has to come from somewhere. One natural way to think of this is that the mass results from the two massless states somehow mixing with some other "thing," and the three massive states that we see are the result.

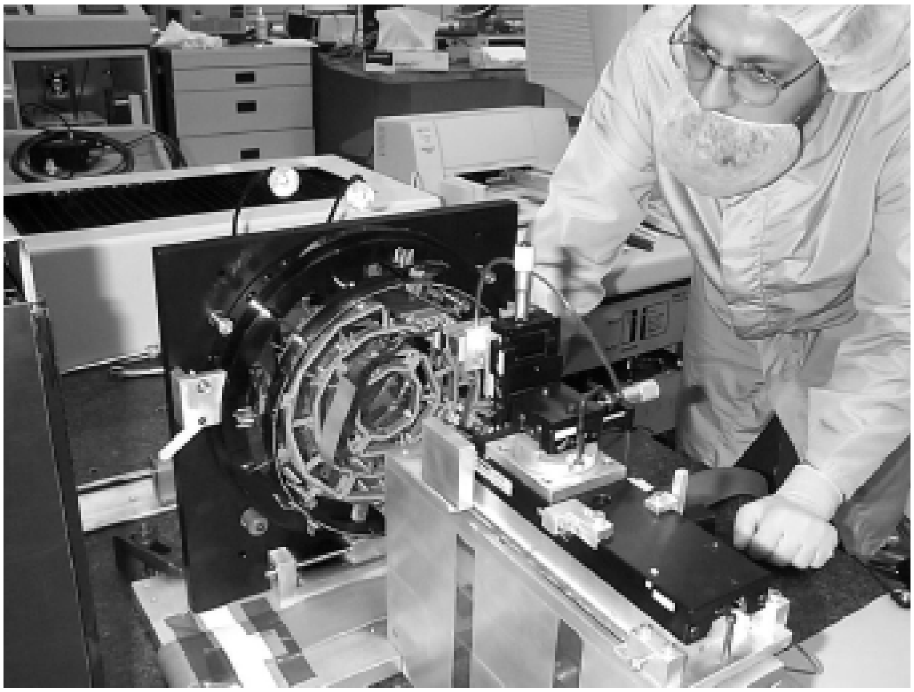
This is exactly what is done in the Standard Model of elementary particle physics. The *W* and *Z* get their masses because they mix in this way with a field, called the "Higgs field," that fills the Universe with a finite energy density. This can precisely account for the masses and coupling strengths of the *W* and *Z* and also the massless photon. If we additionally postulate that the same field interacts with all the electrons, neutrinos, quarks, and so on, then their couplings to it can account for their masses as well. This is a reasonably appealing picture, because it invokes just one new feature, the Higgs field, to explain the masses of both vector bosons and particles of matter. And it takes a rather metaphysical quantity like mass and casts it in



The three generations of fundamental particles, showing the patterns among their masses (Courtesy Particle Data Group)



The W *boson is very massive, while the photon is massless. In the Standard Model, this occurs because the* W *interacts with a Higgs field that fills the Universe.*



The silicon detector for the DØ experiment under assembly at Fermilab's Silicon Detector Facility. (Courtesy Fermilab Visual Media Services)

terms of something that physicists can understand and calculate: interactions between particles. Appealing, but is it correct? Well, it makes one clear and testable prediction: that there exists a neutral particle with zero spin (internal angular momentum) that is an excitation of the Higgs field. All its properties (production and decay rates, coupling strengths, etc.) are fixed, except its own mass. This predicted particle is the Higgs boson, and the highest priority of the worldwide high-energy physics program is to find it.

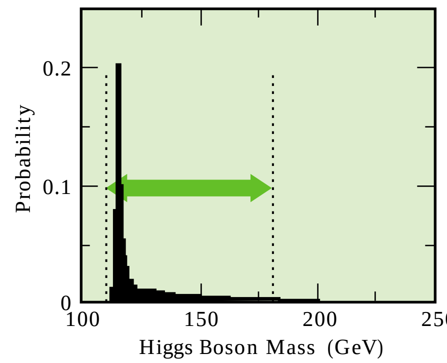
OVER THE LAST decade, the focus has been on experiments at the LEP electron-positron collider at CERN. Precision measurements of the properties of the *W* and *Z* bosons, together with Fermilab's top quark mass measurements, have set an upper limit on the Higgs mass of around 200 GeV. At the same time, direct searches have excluded masses below 113 GeV. Over the summer and fall, data from LEP started to show some hints of a Higgs around 115 GeV, at the very limit of sensitivity; but the machine operations ended nonetheless. So until 2007, Fermilab has the playing field to itself.

The tool we shall use is called the Tevatron Collider. It is a three-mile circular particle accelerator about thirty miles west of Chicago. Inside this ring, protons and antiprotons are accelerated to high energies and brought into collision. The results of these collisions are studied by two giant arrays of instrumentation, the CDF and DØ detectors. The complex has an illustrious past as well as a big future: the bottom and top quarks and the tau neutrino were all discovered here. Since 1996 the accelerator has been turned off for major enhancements to the series of storage rings that feed into the Tevatron and also substantial upgrades to the detectors to boost the data collection rate and their capabilities. Operations resumed March 1, 2001. The first three years will deliver 20 times the sample that was already recorded; by the time the LHC starts running, this will have increased to a factor of 150. This huge increase in data is what will enable the detectors to see much rarer processes that would have escaped detection earlier—like the Higgs.

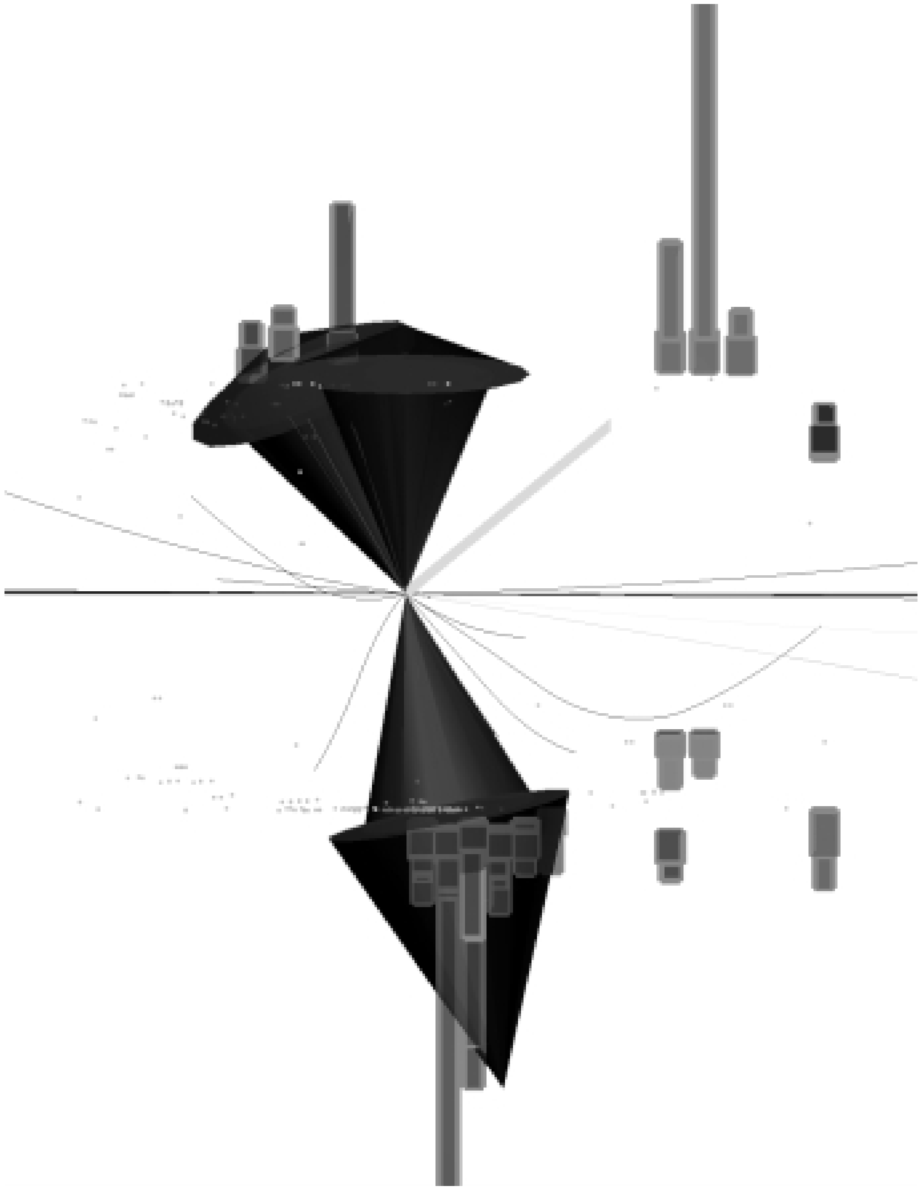
Each of the big detectors, CDF and DØ, contains a large array of sensitive elements surrounding the point in the Tevatron where the protons and antiprotons collide. These try to intercept, measure, and identify all the products of the collisions. A key tool for the observation of a Higgs—a silicon vertex detector—is placed closest to the collision point, and both CDF and DØ have built elaborate new silicon detectors for the next run. Silicon detectors are basically big arrays of the same kind of silicon that's inside integrated circuits. When a charged particle passes through, a little charge gets liberated in the silicon, and that can be detected and used to localize the particle track. The big advantage is that one can make very precise measurements of the track position, because the silicon can have very fine sensing electrode structures deposited on it by the standard integrated circuit techniques. Such precise measurements enable the tracks to be projected back to the proton-antiproton collision point with 10–15 μm precision. This is sufficient to distinguish tracks that originated from the primary collision from those that were generated later, and especially those coming from the decays of *B*-mesons (unstable particles that decay after traveling a millimeter or so). *B*-mesons contain *b*-quarks and *b*-quarks are the most probable decay products of a Higgs with a mass up to about 150 GeV. With a good silicon detector, one can identify ("tag") about half of all the high energy *b*-quarks while maintaining a false positive rate of half a percent.

So how do we plan to use these tools to find the Higgs? As I mentioned earlier, if you assume a certain Higgs mass, then the production rate and decay properties are all fixed in the Standard Model. (Since the coupling strength of the Higgs to each particle equals that particle's mass, there is no freedom to adjust anything.) At the Tevatron, a 115-GeV Higgs (to choose a mass at random!) would be produced with a cross section about one fifth that of the top quark, resulting in maybe 1000 Higgs particles per experiment by the end of 2002. Alas, the dominant decay mode of these Higgs particles is to two *b*-quarks, and the signal would end up swamped by the huge background from the direct production of *b*-quarks. Thus the best bet appears to be to focus on a rarer process, one where the Higgs is produced together with a *W* or a *Z*. The production rate is a factor five less in this mode, but one has the distinct advantage that by focusing on the decays of the *W* or *Z* to electrons, muons, and neutrinos, one can select events of interest and get rid of a lot of the background. In fact, one can do this online as the data arrive, in the trigger system of the detector. That is an important consideration because proton-antiproton collisions are delivered at a rate of ten million per second and the detectors cannot write information from more than about fifty of those.

Even after selecting events with a *W* and a *Z* together with the two *b*-quarks from Higgs decay, substantial backgrounds remain and must be accounted for. For example, again at 115 GeV, we expect about 200 Higgs events after all the selection requirements, but these will be accompanied by nearly 1400 events from more "mundane" sources like top quarks and the direct production of *W*'s and *Z*'s together with *b* quarks. One key to finding the Higgs particle is to look at the invariant mass of the two *b*-quarks in the event: for the



Probability distribution for the Higgs mass, taking into account indirect constraints and exclusion by direct searches. The arrow shows the approximate range that can be explored at the Tevatron. (Courtesy J. Erler, hep-ph/0010153)



Simulation of the tracks and energy deposits produced by a Higgs event at the Tevatron. This collision produced a Higgs, which decayed to two b*-quarks (seen in the detector as energy deposits at* 11 *and* 5 *o'clock) and a* W *boson, whose decay products are an electron (track at* 2 *o'clock) and a neutrino (inferred from unbalanced momentum–the arrrow at* 12 *o'clock). Discovery of the Higgs will require the accumulation and study of hundreds of events like this one.*

Higgs signal; this should show a peak at the Higgs mass, while the backgrounds will have no such structure. A lot of effort will be needed to optimize this mass resolution and to test that it behaves as expected, using the decay of the *Z* to two *b*-quarks as a calibration signal. Other key areas for success will be the performance of the *b*-tagging; electron and muon identification; and the indirect measurement of neutrinos through transverse momentum balancing in the detectors. All of these have to work well—and continue to work well as the beam intensity in the machine is increased to deliver enough Higgs-producing collisions. Of course, it will take some time for operations to come up to speed. If the hints from LEP turn out to be incorrect, our studies imply that we will be able to say so by 2003. One or two years later we would be able to see a signal, and we expect a five standard deviation discovery at this mass by 2007. If we do see something, we will want to test whether it is really a Higgs particle by comparing its production rate with that expected, and by searching for its decays to particles other than *b*-quarks (for example, *W*'s and tau pairs). Since all of these rates are precisely fixed for a Higgs, any deviation from their expected values would tell us that we had caught a different kind of fish.

THE STANDARD MODEL makes predictions that work at the level of one part in a thousand, and it would be completed by the observation of a Higgs particle. But rather than being the end of the road, many of us expect it to be the first window to a new domain of physics. This is because there are strong suggestions that the Higgs is not all we are missing. For one, the Higgs particle is unlike anything else in the Standard Model (there are no other elementary spin-zero particles). Another problem is that the mass of a Higgs itself would suffer very large perturbations from quantum effects and is mathematically very badly behaved (it ought naturally to be infinite, or at least close to that). The observation of a Higgs particle would explain how the particles got their masses, but it wouldn't explain why those masses have the values they do, or why there are three generations with a repeating pattern.

It is tempting then to imagine that the Standard Model is not complete and all-encompassing, but is merely an approximation (albeit a very good one at the energies we have explored). This happens naturally if it is part of a larger theory. Searching for hints of this larger theory will be a very important part of the Tevatron program. Theoretically by far the most attractive option for this larger theory is called supersymmetry (see "Is Supersymmetry the Next Layer of Structure?" by Michael Dine in the Winter 1999 *Beam Line*, Vol. 29, No. 3).

Just as every particle has a corresponding antiparticle, if the Universe is supersymmetric every particle also has a "superpartner" with the same properties except for a different value of spin (the particle's internal angular momentum). Of course we know that the electron doesn't have a spin-zero relative with the same mass—and neither do any of the known particles, so supersymmetry (if it exists) is a broken symmetry in the sense that the superpartners are much more massive than the normal particles. However, as long as these new particles aren't way off scale in terms of mass—maybe in the range of a few hundred GeV—supersymmetry can make the Higgs much better behaved and solve some of the problems with the Standard Model. While closely approximating the Standard Model at low energies, a supersymmetric extension allows the electromagnetic, weak and strong forces to be unified at high energies and provides a path towards the unification of gravity as well. Viable quantum theories of gravity all seem to require supersymmetry. All these nice features come at the cost of invoking a whole spectrum of new particles: multiple Higgs bosons (one of which looks very much like the Standard Model Higgs), strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos, and neutralinos. (The lightest of these new particles may well be stable, and if they were produced in the Big Bang the Universe would still be filled with them just like it is filled with the microwave background—which may be very relevant to dark matter.) So far, however, all searches for each and every one of these supersymmetric particles have proved negative. This failure to see anything allows us to set lower limits on their masses. And while we can't be as precise as we can about the Higgs, physicists are starting to get the distinct feeling that at least some of these particles ought to be within reach of the Tevatron if supersymmetry is relevant for the Higgs.

Supersymmetry searches will therefore be an important part of the Tevatron program. They will be pursued on several fronts. First, the experiments will search for the strongly interacting squarks and gluinos, which are relatively copiously produced but decay hadronically and therefore suffer from large backgrounds. This is complemented by searches for the weakly interacting charginos and neutralinos (superpartners of the *W* and *Z*) which have leptonic decays, some of which have very low Standard Model backgrounds (one very nice final state involves three electrons or muons). In addition, there are extra Higgs production mechanisms in super-

SLEUTH

A LOT OF WHAT I have described here has used phrases like "theoretically the most popular model." However, experimentalists—and I am one—are wary of implicitly assuming that theorists describe the Universe and experiments prove them right. We like to believe that the role of experiment is crucial, and we are just as likely to turn up something completely unexpected as we are to prove expectations correct. To make sure that we are not missing the completely unexpected, physicists in the DØ experiment have devised a new tool called "Sleuth" which is an attempt at a model-independent search for new physics. Sleuth doesn't need to know anything about what you are searching for, it just needs the data events and a comprehensive set of the Standard Model processes that should account for them. Sleuth will then pick out the event or events that are least likely to arise from the Standard Model, and (this is the tricky part) quantify exactly what fraction of the time such results would be expected to arise by chance. Such an approach will never be as sensitive as a targeted search, because there are always special features to exploit if you know what you are looking for; but it has the great advantage that it is open to anything. DØ has carried out a systematic Sleuth study of 32 selected data samples from their 1992–1996 data, containing various combinations of electrons, muons, *W*'s, *Z*'s, photons, jets of hadrons, and so on. While a couple of these data sets have an excess of events over the expectation, Sleuth puts the overall agreement with the Standard Model at the 89 percent probability level. So we haven't discovered anything yet—but recall that we are going to increase this data sample size by a factor of 150. Tools like Sleuth will be an important part of our armory.

symmetric extensions of the Standard Model that will give us additional ways to look for these particles. It is quite conceivable that the Tevatron experiments could discover supersymmetry before they find the Higgs.

At the beginning of this article, I mentioned that the connection between the particle physics of mass and gravity hasn't been made. Theoreticians had usually assumed that this connection would take place at extraordinarily high energies, of order 10^{19} GeV, where the strength of gravity becomes comparable to that of the other forces. Recent revolutionary ideas have changed all that. The new concept is that while the quarks and leptons (us, in other words) remain trapped within the familiar three dimensions of space plus one of time, gravity may be free to propagate in a larger spacetime. This is pretty weird: hold up your finger, and imagine that every point on your finger extends some finite distance in an invisible dimension through which only gravity can travel. Weirder yet is the idea that such extra dimensions might be of macroscopic extent—as large as a millimeter. One consequence is that gravity may become strong not at 10^{19} GeV but at the 1 TeV scale that can be explored at Fermilab. The effects could be indirect and subtle, like a small deviation in the production rate of high energy electron pairs. They could also be direct and spectacular: high energy particles recoiling against what appears to be nothing at all, because their momentum is balanced by a graviton that has "escaped" into another dimension.

What I've described here is the work of many, many people. Each of the experiments is built and operated by collaborations of close to 500 physicists, of whom about 100 are graduate students pursuing degrees in high-energy physics. All of these physicists are working extremely hard right now to install and commission the detectors and the associated software. The Tevatron collider program in the next five years offers a real opportunity to advance significantly our understanding of the fundamental properties of matter. It is an exciting, challenging program that goes straight to the heart of the highest priority of high-energy physics worldwide.

Further Information

For readers wishing to pursue this topic in greater detail, the following URLs will be helpful:

Fermilab
http://www.fnal.gov

CDF Experiment
http://www-cdf.fnal.gov

DØ Experiment:
http://www.d0.fnal.gov