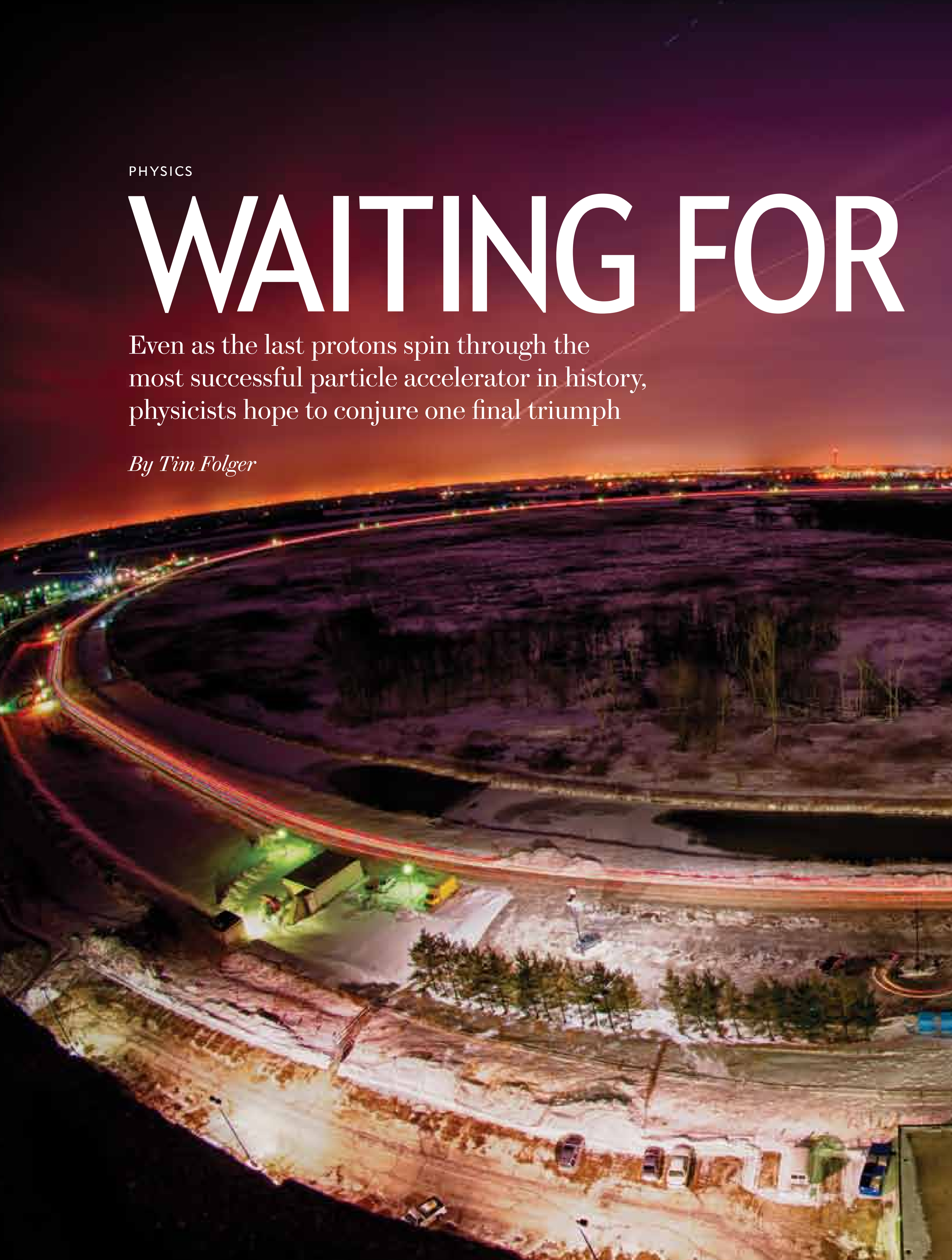
PHYSICS

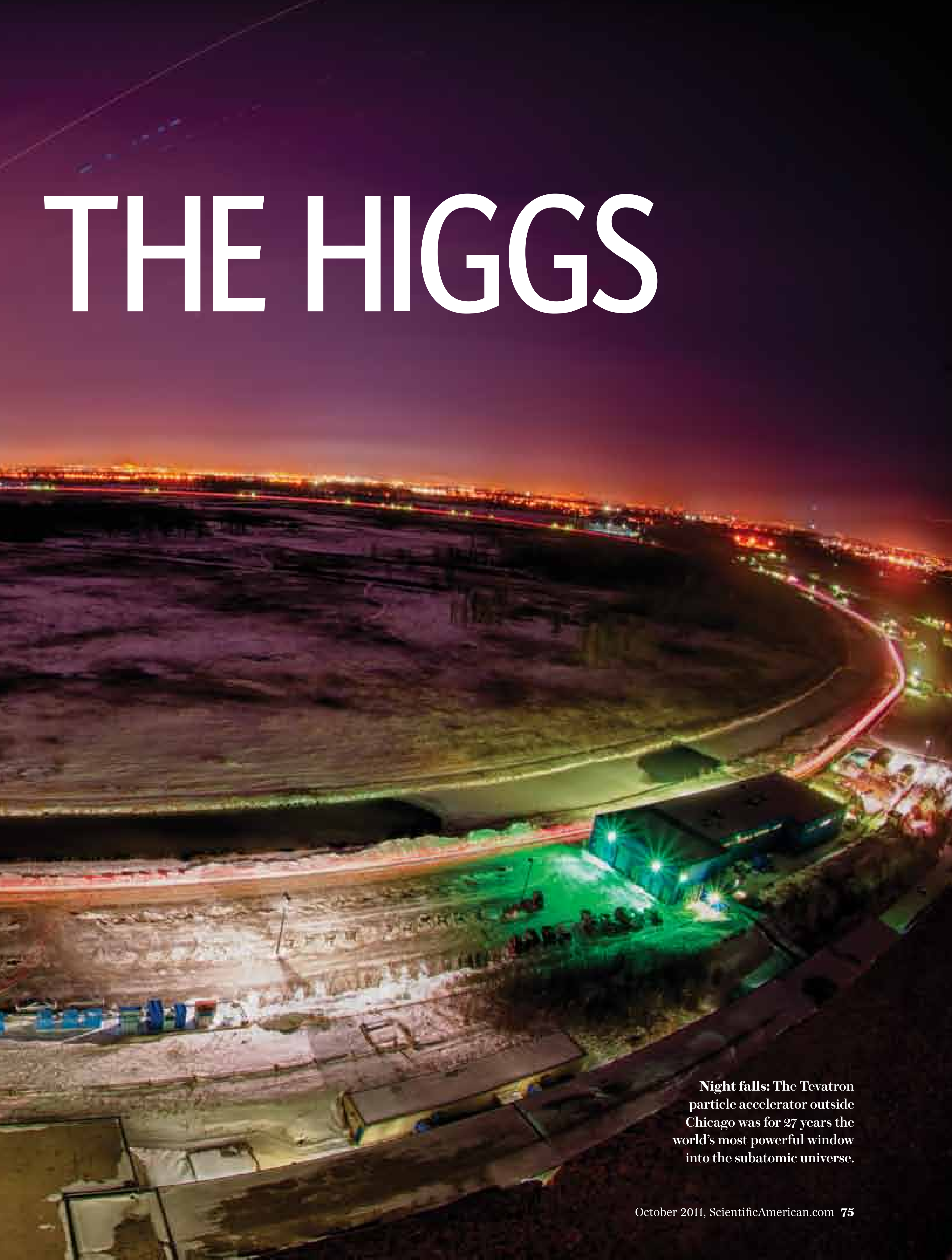
WAITING FOR

Even as the last protons spin through the most successful particle accelerator in history, physicists hope to conjure one final triumph

By Tim Folger



THE HIGGS



Night falls: The Tevatron particle accelerator outside Chicago was for 27 years the world's most powerful window into the subatomic universe.

Tim Folger is an award-winning science writer and the series editor of *The Best American Science and Nature Writing,* an annual anthology published by Houghton Mifflin.

UNDERNEATH A RELICT PATCH OF ILLINOIS PRAIRIE, COMPLETE WITH A SMALL HERD OF GRAZING buffalo, protons and antiprotons whiz along in opposite paths around a four-mile-long tunnel. And every second, hundreds of thousands of them slam together in a burst of obscure particles. It's another day at the Tevatron, a particle accelerator embedded in the verdant grounds of the 6,800-acre Fermi National Accelerator Laboratory complex in Batavia, about 50 miles due west of Chicago. There have been many days like this one, some routine, some spectacular; of the 17 fundamental particles that physicists believe constitute all the ordinary matter and energy in the universe, three were discovered here. But there won't be many more such days. By October 1 the power supplies for more than 1,000 liquid-helium-cooled superconducting magnets will have been turned off forever, the last feeble stream of particles absorbed by a metal target, ending the 28-year run of what was until recently the most powerful particle accelerator in the world.

For several hundred physicists here who have spent nearly two decades searching for a hypothetical particle called the Higgs boson, the closure means ceding the hunt—and possible Nobel glory—to their archrival, the Large Hadron Collider, a newer, more powerful accelerator at CERN on the Swiss-French border. With its 17-mile circumference and higher energies, the LHC has displaced the Tevatron as the world's premier particle physics research instrument, a position it will retain well into the next decade.

The U.S. Department of Energy's decision to shut down the Tevatron at the close of this fiscal year did not surprise anyone at Fermilab. Some physicists had recommended that the DOE fund the aging accelerator for another three years, giving it a final crack at finding the elusive Higgs, a particle that theorists believe is responsible for endowing all other particles with mass. But even the most ardent Tevatron veterans admit that the old machine has finally been made redundant. "I don't have sadness," says Dmitri Denisov. "It's like your old car. The whole history of science is one of new tools. This one lasted for more than 25 years. It's time to move on."

That can't be an easy admission for Denisov, the co-spokesperson for the team that runs D-Zero, one of two hulking detectors that straddle the Tevatron. Two years ago, during a press conference at the annual meeting of the American Association for the Advancement of Science, Denisov said, "We now have a very, very good chance that we will see hints of the Higgs before the LHC will." At the time, an electrical failure had closed the LHC for several months, and Denisov's confidence was shared by many at Fermilab. But it was not to be. When the LHC came back online in November 2009, it quickly ramped up to energies three times higher than the Tevatron could match.

For the past three decades, D-Zero's main competition has been the Tevatron's other enormous detector, the Collider Detector at Fermilab, or CDF, which sits atop the accelerator a grassy mile away from D-Zero. Hundreds of physicists from dozens of countries work at each.

This past spring physicists at the CDF announced that they had found hints in their data of what appeared to be a new particle. Might the Tevatron, in its waning days, have found the first telltale signs of the Higgs? Denisov and his colleagues at D-Zero immediately began to double-check the CDF results. As SCIENTIFIC AMERICAN went to press, the issue remained unsettled. Yet one thing is clear: the intra-accelerator competition is not yet over.

IN BRIEF

The Tevatron, formerly the world's most powerful particle collider, will cease operations by October 1. It has been supplanted by the Large Hadron Collider.

Despite the shutdown, physicists at the facility are poring over data that might reveal evidence of the long-sought Higgs boson.

Scientists at Fermilab hope to build a new accelerator called Project X by 2020 and, after that, a successor to the LHC.

COURTESY OF FERMILAB (*preceding pages*)

"I want to beat Dmitri, and vice versa," says Rob Roser, leader of the CDF team. "We're cordial; we talk; we're friends. But we always wanted to beat each other. Now the endgame is different. The LHC is the bad guy. It used to be Dmitri. I never wanted the LHC to beat either one of us. It's like, you can't beat up my little brother—only I can."

With old rivalries ending (almost) and new projects just starting, Fermilab is passing through an uncertain period. The same could be said for the entire discipline of particle physics. Physicists have been waiting a very long time for a machine that might give them access to some new realm of physical reality. Given that the LHC is expected to double its collision energies within the next two years, there is no shortage of ideas about what it might discover: extra dimensions, supersymmetry (the idea that every known particle has a so-called supersymmetric twin), the Higgs, of course. Best of all would be something completely unexpected. There is another possibility, however, usually dismissed but impossible to discount. And it simultaneously worries and intrigues physicists: What if the LHC, as well as the particle physics experiments planned at a Tevatron-less Fermilab for the next decade, finds nothing unexpected at all?

DESTINATION UNKNOWN

THERE WAS A TIME, not long ago, when physicists had many of the same hopes for the Tevatron that they now have for the LHC. Fifteen years before the LHC was turned on, physicists at Fermilab thought the Tevatron might bag the Higgs, find evidence for supersymmetry, identify the nature of dark matter, and more.

Besides netting a Nobel Prize, the discovery of the Higgs would provide the capstone to an illustrious era in physics. The Higgs boson is the last missing piece of the Standard Model, a complex theoretical edifice that describes the universe in terms of the interactions of the 17 fundamental particles. It unifies three of the four forces of nature: the strong force, which binds atomic nuclei; the weak force, which is responsible for particle decay; and the more familiar electromagnetic force. (Gravity is the only force not described by the Standard Model.) Theorists put the finishing touches on the Standard Model nearly 40 years ago, and since then every one of its predictions has been confirmed by experiment.

In 1995 the CDF and D-Zero teams made one of the most impressive confirmations with the discovery of the top quark—a massive elementary particle whose existence was first predicted in 1973. In that race, the Tevatron beat a European collider called the Super Proton Synchrotron, which is now used to feed particles into the LHC. It was the Tevatron's greatest triumph and established that the Standard Model was an incredibly accurate description of the universe, at least at the energies that physicists could probe with their best accelerators.

In 2001, after a five-year upgrade, the world's best accelerator became even better. Physicists hoped that the new, improved Tevatron would not only discover the Higgs—the last undiscovered piece of the Standard Model—but also uncover new phenomena lying beyond the Standard Model. For all the Standard Model's predictive power, physicists know that it cannot be a complete description of nature. Besides its failure to incorporate gravity, it has two other glaring shortcomings. The Standard Model provides no explanation of dark matter, which influ-

COURTESY OF FERMILAB

MILESTONES

Three Decades of Discovery

Most everything you need to know about a particle collider can be summed up with just two numbers. The first is its energy—higher energies let scientists conjure up more massive particles (measured in gigaelectron volts, or GeV). The second is its luminosity, or the number of collisions per second. Engineers spent the first decade of the Tevatron pushing up its energy; they've spent the past two opening a trickle of collisions into a firehose. Here are a few of the more notable events in the life of the collider.

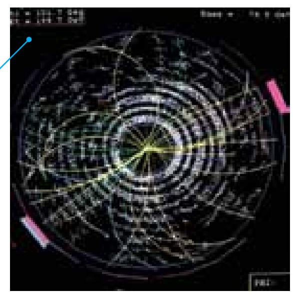
JULY 5, 1979
The Department of Energy authorizes Fermilab to build a superconducting accelerator, later named the Tevatron.

JULY 3, 1983
The Tevatron accelerates protons to a world-record energy of 512 GeV.

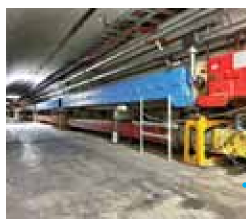
OCTOBER 1, 1983
Experiments begin. At first, a single beam of protons strikes a fixed target.

OCTOBER 13, 1985
The newly installed antiproton beam begins to collide with the protons. The CDF witnesses the first proton-antiproton collisions at 1,600 GeV.

MARCH 3, 1995
Scientists from the CDF and D-Zero experiments announce the discovery of the top quark.



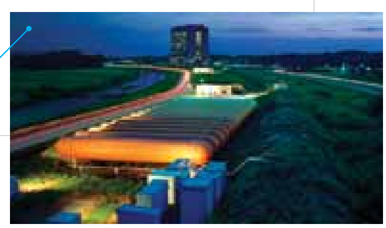
AUGUST 31, 1992
The first long run of collision experiments begins at an energy of 1,800 GeV.



JULY 20, 2000
The DONuT experiment reports the first evidence for the direct observation of the tau neutrino.

MARCH 1, 2001
Upgrades push the energy up to 2,000 GeV, and the second collider run begins. Over the next decade its luminosity will more than quadruple.

SEPTEMBER 30, 2011
The Tevatron produces its final proton-antiproton collisions; data analysis will continue for several years.



AUGUST 4, 2008
Tevatron scientists announce that the Higgs boson does not have a high mass of 170 GeV. More searching is required.

ences the motions of galaxies but otherwise does not seem to interact with ordinary matter. It also fails to account for dark energy, an utterly baffling phenomenon that appears to be accelerating the expansion of the universe.

But despite the upgrade, the Tevatron failed to move beyond the theory it had so spectacularly validated. "Ten years ago we anticipated cracking this nut, but we haven't yet," says Bob Tschirhart, a theoretical physicist at Fermilab. "There's a layer of existence out there that we haven't discovered. The Standard Model has been so good at predicting so much, but it has such obvious inadequacies. It's like an idiot savant."

In some sense, the legacy of the Tevatron is that the Standard Model works really, really well. It's no small achievement, but it was never intended to be the final goal. "We were supposed to find the Higgs, for sure," says Stephen Mrenna, a computational physicist who came to Fermilab in the mid-1990s. "And if supersymmetry was there, we were supposed to find it, too."

Physicists now hope that the LHC will succeed where the Tevatron failed by leading them into new territory and providing clues that might eventually enable them to replace the Standard Model. Mrenna, like most of his colleagues, believes that the LHC will find the Higgs sooner rather than later. "I think it will happen this year or next. That's where I would place my bet," he says. "If we don't find it, my belief that we won't find anything will go up greatly."

This is the problem with exploration: perhaps nothing is out there. Some physicists speculate that an "energy desert" exists between the realms they are able to probe now and the realm where truly new physics might emerge. If that's the case, new discoveries might be decades away. The LHC might be the most powerful accelerator ever built, but it is not so powerful that physicists can be completely sure it will punch through to another level of reality.

The real tool for that job was the Superconducting Super Collider (SSC), a machine that, at 54 miles in circumference, would have dwarfed the LHC. It would have been capable of generating particle beams with nearly three times the LHC's maximum energy. But cost overruns caused Congress to cancel the project in 1993, even though construction had already started near the small town of Waxahachie, Tex. "The SSC was designed from the beginning so that it would probe an energy scale where our expectations were that something new absolutely, positively had to happen," Mrenna says. "It really was the right collider to have built. The LHC is a cheap cousin. But it's good enough for now."

Unless, of course, it is not. If the LHC fails to find the Higgs or to make some other significant discovery, Mrenna says, it would become difficult for physicists to justify the costs of a more advanced accelerator. "You can ask what finding the Higgs boson has to do with the U.S. economy or the war on terror, or whatever," he observes, "and right now we get by saying the knowledge benefits everybody. People want to know how the universe works. And we're training lots of people, and it's always a good idea to take the cleverest people around and give them a really hard problem because usually there's a derivative that comes from it. But at some point the physics becomes less and less relevant."

In other words, if the energy desert is real, we may not be able to summon the will to cross it. "I'm actually a hanger-on from the SSC," Mrenna says. "I was a postdoc in its last year. And I have been waiting for a replacement for it ever since then, surviving in a rather grim job market. We need a success. We need to find something new."

COMPETITION

The Race against the LHC

By Geoff Brumfiel

The Tevatron's operations may be ending, but the hunt for the Higgs boson, the most elusive particle in physics, is charging forward. In a matter of months, data from the Tevatron and the Large Hadron Collider at CERN near Geneva should answer what one physicist describes as the "Shakespeare question": Is it to be? Or not to be?

For nearly half a century scientists have predicted the existence of the Higgs. It is commonly said that the Higgs is the particle responsible for the mass of all the others—which is true—but from a physicist's perspective, the Higgs is important because it serves as a unifier of forces. Physicists love to simplify, and the Higgs provides an elegant way to combine electricity and magnetism with the "weak" nuclear force to create a single "electroweak" entity.

The Higgs can only do this if it exists in the mass-energy range between 100 and 1,000 billion electron volts (GeV). The LHC and the Tevatron are closing in on the most fertile ground. In July at a conference in Grenoble, France, Tevatron scientists concluded that the Higgs cannot be between 156 and 177 GeV, while the LHC knocked out a few broad swaths between 150 and 450 GeV.

Most physicists believe that if the Higgs exists, most likely it is hiding at around 115 to 150 GeV. It is a particularly tricky energy range, however, because such a light Higgs particle will often decay into common particles that are difficult to pick out from other debris inside the giant collider. A few Higgs decays may have already been seen, but telling the difference will require many more times the data produced so far.

Even after its shutdown, the Tevatron will contribute yet to be analyzed data to the hunt. But it will be up to the more powerful LHC to nail the discovery. The larger European machine's current run continues through October, and in that time it should be able to firm up any faint signals. Still, physicists will not be able to announce whether the Higgs is truly "to be" until the end of 2012, when the machine will have collected around 50 petabytes of data—the equivalent of the complete works of Shakespeare 10 billion times over.

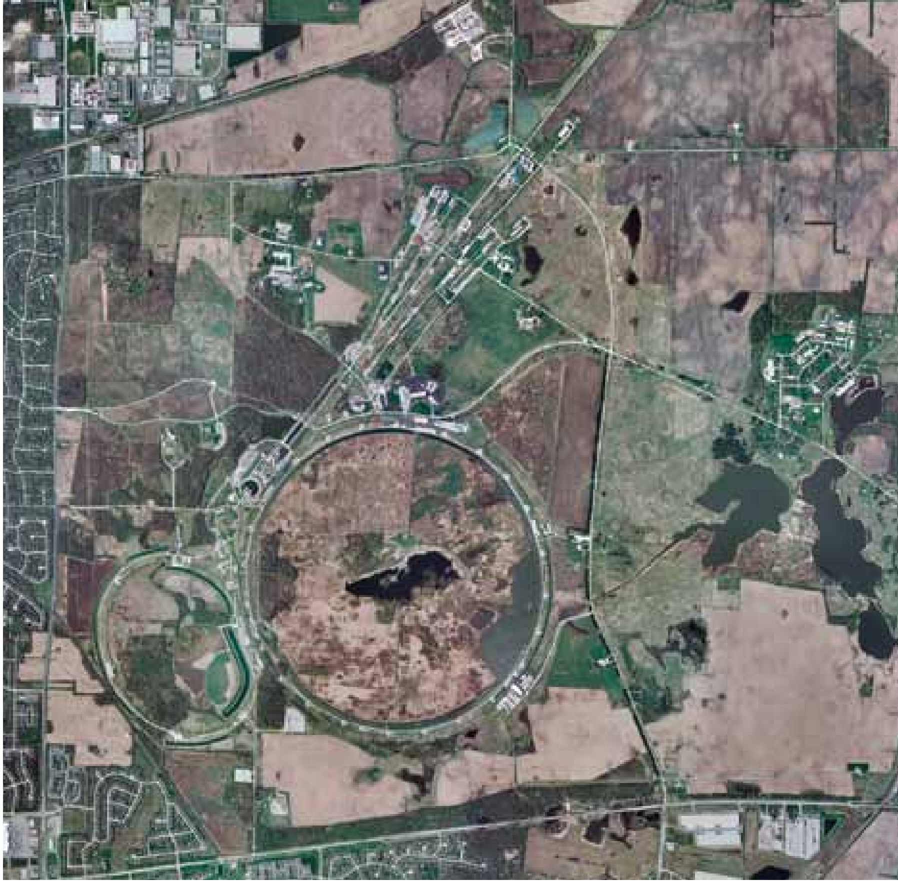
Geoff Brumfiel is a reporter for Nature.

NEXT LIFE

THE WORLD'S FIRST particle accelerator was made in 1929 by Ernest Lawrence, a physicist at the University of California, Berkeley. He called it a proton merry-go-round. It measured five inches across, was made of bronze, sealing wax and glass, and likely cost about $25. The LHC, which fired up about 80 years later, cost $10 billion. Its construction required an international effort, and it covers an area the size of a small town. Even if the LHC is wildly successful, there is little chance for a similar leap in scale in the foreseeable future.

"We know how to go 10 times higher in energy, but it would cost 10 times more," says Pier Oddone, director of Fermilab. "And we're already at the limit of what countries are willing to spend."

For the next decade and beyond the premier physics facility in the U.S. will live in the shadow of the LHC. Oddone says Fermilab will pursue a variety of projects that might have been delayed or canceled had the Tevatron remained in operation, but it is clear that the center of mass in the world of particle physics has shifted. "In an ideal world, we would have kept the Tevatron running without shutting down other stuff," he says. "But the money wasn't there." Experiments are now under way at Fermilab that will study the physics of neutrinos—probably the least understood of all fundamental particles—by shooting them from a source at Fermilab through 450 miles of the earth's crust toward a detector in a mine shaft in Minnesota. Fermilab scientists will also take part in the Dark Energy Survey, an astronomical investigation into the nature of dark energy.



Ready, aim: **The Tevatron (*central ring*) is going dark, but physics continues at Fermilab. Scientists are generating neutrinos using the smaller injector ring (*lower left*) and beaming them through the earth to an underground detector in Soudan, Minn., 450 miles away.**

COURTESY OF FERMILAB

But the overriding institutional goal is to once again host the world's most powerful particle accelerator. By 2020 Oddone hopes the lab will have completed construction of an accelerator called Project X. The near-term purpose of the mile-long machine will be to generate neutrinos and other particles for experiments at Fermilab. In the long term, the relatively small accelerator will serve as a test bed for technologies that might one day make it possible to build an affordable successor to the LHC.

"Project X is a bridge to getting back to the high-energy frontier of physics," says Steve Holmes, the project manager. "It's an opportunity to grab the leadership position and hold it. When people at lunch ask me what's the future for us here, I say that the U.S. led the world in high-energy physics for 70 years. It's the most fundamental field of physics, and as a great country we have to aspire to do that. What I can't tell them is when we'll get there."

We may not have heard the last from the Tevatron itself. Denisov, Roser and their colleagues at the old accelerator's two detectors have collected enough data to keep them busy for at least two years after the shutdown. The huge store of data could help flesh out initial discoveries made by the LHC. There is even an outside chance that some new result lies buried on a hard drive somewhere at Fermilab, just waiting to be analyzed. For a little while this past spring, it looked as if the Tevatron might have given us the first hint of physics beyond the Standard Model.

In April, Roser's CDF team announced that it had found very tentative evidence for a new particle or force of nature in data collected by the CDF. In a small but statistically significant number of cases, the physicists found a bump in the data, an excess of particles above what the Standard Model predicted. The particles appeared to be the decay products of some more massive particle, perhaps an unexpected form of the Higgs boson.

By the end of May the CDF team had analyzed the data again. "The bump is still there," Roser said at the time. Less than two weeks later, though, Roser's longtime colleague and rival Denisov said that the D-Zero team had completed an independent analysis of the CDF data. "We saw nothing," he said at a press conference.

It is not yet clear whether the bump will survive further scrutiny. The two groups are now comparing their results to see where the CDF analysis may have erred—if indeed it did err. For now, it looks like a new era in physics is on hold, as it has been for more than 30 years. It will be a shame if the bump vanishes. Discovering the Higgs would have made for quite an exit for the Tevatron. Within the next year or so, we might all find out if the LHC can do any better. SA

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE
Three decades of discovery: Explore a visual history of the Tevatron at **ScientificAmerican.com/oct2011/tevatron**