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CRASH COURSE

Can a seventeen-mile-long collider unlock the universe?

by Elizabeth Kolbert

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The European Organization for Nuclear Research, known as CERN, has its offices on the outskirts of Geneva, in an area once devoted to dairy farms and now given over to sprawl. The offices occupy several dozen buildings, some of them in Switzerland and the remainder, a few hundred yards away, in France. The buildings are reachable by roads with names like Route Bohr, Route Schrödinger, and Route Curie. By the entrance to the complex, there is a museum—nearly empty the day I visited—that attempts to make particle physics comprehensible to the general public. Behind that there is a park where bits of old cyclotrons are displayed, like playground equipment from Mars.

If you think of the sciences as a tower, with one field resting on another until you reach, say, botany or physiology, then particle physics represents the bottommost floor. The first key experiment was conducted in 1909, under the direction of Ernest Rutherford. When Rutherford shot alpha particles at a wafer-thin sheet of gold foil, a small proportion of the particles bounced right back, a phenomenon that he described as "almost as incredible as if you fired a fifteen-inch shell at a piece of tissue paper and it came back to hit you." Rutherford's work led to the realization that most of an atom's mass was concentrated in a tiny area, the nucleus. "All science is either physics or stamp-collecting," he is supposed to have said.

Since Rutherford's discovery, particle physics has provided one extraordinary—if increasingly implausible-sounding—revelation after another: first protons and neutrons, then antimatter, gluons, neutrinos, and quarks. In 1967, the existence of particles to mediate the weak force, which is responsible for radioactive decay, was theorized; in 1983, at CERN, these particles—the W and the Z—were observed and their properties measured. In 1977, the existence of what became known as the "top" quark was predicted; in 1995, at Fermilab, in Illinois, it, too, was found.

And yet, for all its triumphs, the field has been haunted by failure. The more physicists have learned about the way matter behaves at its most fundamental level, the more acutely they have become aware that something—a big something—is missing from their accounts. Among the many possibilities proposed for what's often called "new physics" is that the universe actually consists of tiny strands (or strings) of energy; that it contains several dimensions beyond those that we perceive; that it is full of mysterious particles—"sparticles"—that have yet to be detected; that it is not a universe at all but a multiverse; and that it began not with a bang but with a splat.

Sometime in the next few months, physicists at CERN will finish preparations for the most ambitious particle-physics experiment ever, which will be conducted in an apparatus modestly referred to as the Large Hadron Collider, or L.H.C. The L.H.C. fills a circular tunnel seventeen miles in circumference. To get from one side of it to the other, it is necessary to drive through several towns, and then descend three hundred feet in an elevator. Alternatively, it is possible to ride through the tunnel in one of the dozens of bicycles CERN provides for its staff, but in that case a supply of emergency oxygen is required.

The L.H.C. is considered the best—some would say the only—hope for testing the theories of "new physics" against material reality. Once the collider begins operating at full power—in early 2008, if all goes well—nearly half the particle physicists in the world will be involved in analyzing its four-million-megabyte-per-hour stream of data. Few events in the history of science have had a bigger buildup. It's been suggested that the L.H.C. will unlock the secrets of the universe or, barring that, prove this ambition to be hopeless.

The L.H.C. is a kind of Babel built underground. Dozens of countries have manufactured its components, and dozens more have lent manpower and expertise. (Some contracts went to Russian physicists who previously worked for the Soviet military; in this way, the collider has provided a livelihood for scientists whose employment options might otherwise include selling nuclear secrets.) When I ate in CERN's lunchroom, I heard people speaking English, French, German, and Italian, as well as several languages that I couldn't identify. The place was so crowded that it took me five minutes to pay for a cup of coffee, proving the elemental truth that man can build a superconducting collider but not a functional cafeteria.

CERN's chief scientific officer, Jos Engelen, is from the Netherlands. He serves under the director general, who is from France, and alongside the chief financial officer, who is from Germany. I went to speak to Engelen in his office; behind his desk a chart indicated when the various parts of the collider are supposed to be completed. It was a crazy quilt of multicolored blocks, with lines radiating in all directions. Engelen greeted me with a half-ironic cheerfulness that struck me as very Dutch. Among his responsibilities is dealing with the frequent calls and letters CERN receives about the possibility that the Large Hadron Collider will destroy the world. When I asked about this, Engelen picked up a Bic pen and placed it in front of me.

"In quantum mechanics, there is a probability that this pen will fall through the table," he said. "All of a sudden, it will be on the floor. Because it can behave as a wave, it can go through; we call that the 'tunnel effect.' If you calculate the probability that this happens, it is not identical to zero. It is a very small probability. But it never happens. I've never seen it happen. You have never seen it happen. But to the general public you make a casual remark, 'It is not identical to zero, it is very small,' and . . . " He shrugged.

Worries about the end of the planet have shadowed nearly every high-energy experiment. Such concerns were given a boost by *Scientific American*—presumably inadvertently—in 1999. That summer, the magazine ran a letter to the editor about Brookhaven's Relativistic Heavy Ion Collider, then nearing completion. The letter suggested that the Brookhaven collider might produce a "mini black hole" that would be drawn toward the center of the earth, thus "devouring the entire planet within minutes." Frank Wilczek, a physicist who would later win a Nobel Prize, wrote a response for the magazine. Wilczek dismissed the idea of mini black holes devouring the earth, but went on to raise a new possibility: the collider could produce strangelets, a form of matter that some think might exist at the center of neutron stars. In that case, he observed, "one might be concerned about an 'ice-9'-type transition," wherein all surrounding matter could be converted into strangelets and the world as we know it would vanish. Wilczek labelled his own suggestion "not plausible," but the damage had been done. "BIG BANG MACHINE COULD DESTROY EARTH" ran the headline in the London *Times*. Brookhaven was forced to appoint a committee to look into this and other disaster scenarios. (The committee concluded that "we are safe from a strangelet initiated catastrophe.")

"I know Frank Wilczek," Engelen told me. "He is an order of magnitude smarter than I am. But he was perhaps a bit naïve." Engelen said that CERN officials are now instructed, with respect to the L.H.C.'s world-destroying potential, "not to say that the probability is very small but that the probability is *zero*."

I asked Engelen how he would explain the project of particle physics to a non-physicist, or if he thought such an explanation was even advisable. "We simply want to know what the world is made of, and how," he said. "What is in here"—he rapped on his desk with his knuckles—"and how these particles in here constitute a table."

"Let us start with Ernest Rutherford in the beginning of the last century," he went on. "Rutherford understood what an atom looks like. It is a fat, heavy nucleus, with very light electrons orbiting around. The next step is we discovered objects inside the nucleus, one called the proton, the other the neutron. That is the pattern. As a next step, people started to wonder about these protons and neutrons, whether there is structure in there. And they started probing that. And they found that there is structure in there. There are quarks in there. And what we want is to reduce the world to objects that have no structure, that are points, that are as simple as we can imagine. And then build it up from there again."

So far, physicists have succeeded in observing sixteen pointlike, or fundamental, particles, a number that increases if you count antimatter particles, or if you differentiate among, say, the eight types of gluons. Particles in the largest group, called fermions, in honor of Enrico Fermi, are the stuff of matter. Fermions include electrons and quarks, which come in the whimsical-sounding varieties up, down, charm, strange, top, and bottom. (A hadron is a collection of quarks, or quarks and antiquarks. A proton is a hadron composed of two up quarks and one down; a neutron consists of two downs and one up.) Fermions also include neutrinos, which, somewhat unnervingly, stream through our bodies at the rate of trillions per second. “Neutrinos, they are very small,” John Updike’s poem “Cosmic Gall” observes. “And do not interact at all.”

Hypothetically at least, there is also a seventeenth particle, known as the Higgs. The Higgs particle was first postulated more than forty years ago by the Scottish physicist Peter Higgs, and has been sought—fruitlessly—at every major collider built since then. Its discovery would have many fantastic implications, one of which is that the void of space is not really void but is permeated by an invisible field that acts a bit like cosmic molasses. This Higgs field, if it exists, exerts a drag on matter passing through it, lending mass to particles that otherwise wouldn’t have any. Without the Higgs, physicists have no way to explain why fundamental particles weigh anything at all, since, according to theory, they should be massless. The fact that the Higgs is central to modern physics even though it has never been found has prompted one Nobel laureate to label it the rug under which the discipline sweeps its ignorance and a second to dismiss it as the “toilet” into which physics flushes its inconsistencies. A third Nobel winner has labelled it the “God particle.”

“We are going to make that particle,” Engelen told me. “Or we are going to show that it doesn’t exist.”

The day that I met with Engelen, I also spoke with the deputy head of CERN’s physics department, Michael Doser. Doser is tall and lanky, with fuzzy blondish hair and a narrow stripe of beard that runs down the middle of his chin. His primary interest is antimatter.

“If you think about what matter is, you end up with a very Zen-like answer,” he told me. “If you look at what a quark is, or an electron, the primary constituents of matter, they’re pointlike particles. They have no spatial extent. They have a number of properties, like mass and charge, and that’s it. In a way, they’re mathematical figments, and they’re separated by vacuum—mathematical figments in nothing. And antimatter is the opposite—mathematical figments with the opposite charge.” When matter and antimatter meet, they annihilate each other in a burst of energy. It is believed that in the Big Bang equal quantities of matter and antimatter were produced. But this theory makes it difficult to explain certain basic facts, like you and me and countless galaxies. How to account for the abundance of matter in the universe, and the shortage of antimatter, Doser told me, “is one of the most embarrassing questions in particle physics.”

Doser began his career at CERN in 1991, at which point most of the physicists at the organization were working on a project known as the Large Electron-Positron Collider, or LEP. Basically, LEP was a high-precision matter/antimatter demolition-derby track. Billions of electrons looping around in one direction were, at discrete intervals, made to cross paths with billions of antielectrons—or positrons—moving the opposite way. Where the beams crossed, huge detectors were set up to record the smashups.

The L.H.C., Doser explained, relies on much the same design, and, in fact, makes use of the tunnel originally dug for LEP. Instead of electrons and positrons, however, the L.H.C. will send two beams of protons circling in opposite directions. Protons are a good deal more massive than electrons—roughly eighteen hundred times more—which means they can carry more energy. For this reason, they are also much harder to manage.

“Basically, what you must have to accelerate any charged particles is a very strong electric field,” Doser said. “And the longer you apply it the more energy you can give them. In principle, what you’d want is an infinitely long linear structure, in which particles just keep getting pushed faster and faster. Now, because you can’t build an infinitely long accelerator, you build a circular accelerator.” Every time a proton makes a circuit around the L.H.C. tunnel, it will receive electromagnetic nudges to make it go faster until, eventually, it is travelling at 99.9999991 per cent of the speed of light. “It gets to a hair below the speed of light very rapidly, and the rest of the time is just trying to sliver down this hair.” At this pace, a proton completes eleven thousand two hundred and forty-five circuits in a single second.

“The more energetic the particles are, the more force you need to keep them on orbit,” Doser went on. “They want to go straight. And so you need very strong magnetic fields.” In the L.H.C., such strong fields are required that they cannot be produced by conventional, or so-called “warm,” magnets. Instead, the L.H.C. beam pipe has been encased in superconducting magnets, cooled with superfluid helium. These magnets are supposed to operate at minus 271.25 degrees Celsius—minus 456.25 degrees Fahrenheit—a temperature colder than that of deep space. Doser noted that there are many hazards involved in working with such powerful magnets; for example, if a bolt or a screw is left lying around when they are turned on, it can fly through the apparatus like a bullet. He recalled that as a graduate student he had once lost a wrench in a machine this way: "It cost me a year." Meanwhile, if any of the magnets fail, the beams, each of which is supposed to contain something like three hundred trillion protons, could veer off course and, in short order, burn a hole through the collider. "That's why people are so nervous about starting up," Doser said. (In fact, a few weeks after my visit to CERN, during a test of a set of magnets known as an "inner triplet," a support failed, bursting a pipe and spewing helium into the tunnel. The failure of the support, which was produced in the United States, was attributed to a simple engineering error.)

When protons crash into each other at 99.9999991 per cent the speed of light, the resultant mess is usually just that—the subatomic equivalent of shattered glass and twisted metal. But stranger things can happen. Just as it is possible to convert mass into energy—as in a nuclear explosion—the reverse is also true: energy can be transformed into mass according to the Einsteinian equation *E*=*mc*2 (*c* being the speed of light). In this way, new particles can be produced that are more massive than those that entered the collision in the first place. The process might be compared to smashing two high-speed Priuses into each other and finding that they have rematerialized as a tank.

By now, the Higgs has been sought for so long that physicists have a pretty clear idea of how much it must weigh. The lower bound is around 120 times more than a proton—or roughly 2×10^{-22} grams. The upper bound is about 210 times as much as a proton. The most powerful collider currently in operation is Fermilab's Tevatron, outside Chicago. The Tevatron, which smashes protons into antiprotons, can accelerate particles to an energy of just under a trillion electron volts, or one TeV. (An electron volt is the amount of energy acquired by a single electron falling through a potential difference of one volt.) So far, the Tevatron has failed to reveal the Higgs, though physicists there are actively looking for it. The L.H.C. will accelerate particles to seven TeV, which means that it will be seven times as powerful as the Tevatron. This should be more than enough energy to produce the Higgs, if there is a Higgs to produce. It may also be enough to uncover much more than the Higgs. Depending on how the universe is constructed, extra dimensions, mini black holes, and the source of so-called "dark matter" may all be revealed at CERN. Any black holes created, Doser was quick to assure me, would be entirely benign.

On my second day at CERN, I drove out to the detector farthest from Geneva—the Compact Muon Solenoid—which is to operate in, or really underneath, the town of Cessy, France. Robert Cousins, a physicist visiting CERN from the University of California at Los Angeles, had agreed to show me around. When we met in the C.M.S. parking lot, Cousins was wearing a bright-yellow hard hat. He handed me one to put on.

The L.H.C. will have four main detectors, spaced at intervals around the tunnel like beads on a bracelet. Each is being constructed by a different team according to a different design, the theory being that any interesting phenomena missed by one should be captured by the others. The teams share information, but there is a certain amount of cheerful rivalry among them. C.M.S., in particular, has been plagued by difficulties—during excavations, the soil in Cessy proved so soupy that the ground had to be frozen with liquid nitrogen—and before I went to look at it a physicist who is not affiliated with the project told me that C.M.S. was sometimes referred to as "See a Mess."

Cousins led me into a vast, hangarlike building where the detector was being assembled. There was a loud clanging coming from all directions. Iron rings several stories high were sitting on hydraulic lifts. At the far end of the hangar, a huge shaft dropped down several hundred feet. Cousins said that the shaft would be used to lower the detector, piece by piece, to the level of the L.H.C. tunnel. We boarded an elevator, and got out near the bottom. A section of the detector that had already been lowered into place loomed up in front of us. It looked like the underside of a rocket ship.

It is one of the paradoxes of particle physics that fundamental particles, though pointlike and indivisible, are also generally unstable. In fact, the heavier particles are so short-lived that even to speak of their having an existence seems faintly ludicrous; a top quark, for example, is estimated to last no more than 1×10^{-24} seconds. (For comparison's sake, 1×10^{-24} centuries comes to three millionths of a billionth of a second.) When unstable particles break down, new, lighter particles are produced. Some of these are likely to be unstable as well, and to break down further. The outcome of this process is a distinctive scattering of "decay products," which physicists refer to as a particle's "signature."

In order to "read" such a signature, a detector has to capture all the decay products that come flying out after a collision and measure their properties. This requires layer after layer of detecting elements; at C.M.S., these are arranged in the shape of an enormous jelly roll. The innermost layer, known as the tracker, consists of some seventy-five million silicon sensors. The next layer, which measures the energies of photons and electrons, contains eighty thousand crystals of lead tungstate. Surrounding this are brass-and-plastic scintillators for tracking hadrons and a tubeshaped magnet—a superconducting solenoid—twenty feet in diameter. Finally, there are several iron rings of increasing circumference. These hold sensors to detect muons, which are essentially heavy electrons. (Neutrinos can't be measured directly, and are therefore factored in as an absence.) All told, the Compact Muon Solenoid will weigh twenty-eight million pounds. It will hold enough iron to reconstruct the Eiffel Tower. Apparently, "compact" is a relative term.

Cousins explained that the information gathered by each layer of C.M.S. would be analyzed virtually instantaneously, and a decision made by the detector's computers whether to ignore the collision or to save the results for further study by recording them on tape. "There are famous high-energy-physics experiments that missed discoveries because they weren't writing them to tape," he told me. We were walking back through the hangar, past the giant iron rings, which were painted fire-truck red. "This is why we try not to be too specific about which theoretical speculations we care about. We add up all the energy, and if it's a huge number we write that event to tape. If on one side of the detector it's a not-so-huge number, but there is nothing on the other side, so it's a huge imbalance, we get excited about that, and we write that to tape, too."

Only a small fraction of the protons zipping through C.M.S. at any given moment will actually crash into one another. Still, this fraction represents an enormous number. When the L.H.C. is operating at full "luminosity," it is expected that the beams will cross forty million times a second and that each crossing will produce twenty collisions. C.M.S. will write fewer than .001 per cent of the crossings to tape; even so, it will be recording six thousand per minute, or three hundred and sixty thousand per hour, or some six million per week. The three other main detectors at CERN will generate similar amounts of data. There are many ways to represent a data stream of this magnitude; one that stuck with me was in terms of CDs. If all the L.H.C. data were burned onto disks, the stack would rise at the rate of a mile a month.

Lodged somewhere in this tower of information should be the signature of the Higgs, or, really, signatures, since the particle is expected to decay in a variety of ways. These signatures will look an awful lot like the signatures of other unstable particles. One physicist I spoke to compared the computational challenge of distinguishing a Higgs to finding a needle not in one haystack but in ten. I thought it sounded more like finding a needle in a needle factory.

Particle physicists come in two distinct varieties, which, rather like matter and antimatter, are very much intertwined and, at the same time, agonistic. Experimentalists build machines. Theorists sit around and think. "I am happy to eat Chinese dinners with theorists," the Nobel Prize-winning experimentalist Samuel C. C. Ting once reportedly said. "But to spend your life doing what they tell you is a waste of time."

"If I occasionally neglect to cite a theorist, it's not because I've forgotten," Leon Lederman, another Nobel-winning experimentalist, writes in his chronicle of the search for the Higgs. "It's probably because I hate him."

A few weeks after I returned from talking to the experimentalists at CERN, I went to speak to Nima Arkani-Hamed, a theorist at Harvard. Arkani-Hamed, who is thirty-five, has an oval face, deep-set eyes, and dark, shoulder-length hair. The day I visited, he was dressed entirely in black. He immediately offered me an espresso, which he made at a little machine that spit out one cupful at a time. "I've been trying to understand something about the fact that the universe is accelerating," he explained, erasing a double-wide blackboard covered with equations.

"Often, this kind of physics is referred to as particle physics, which I don't like," Arkani-Hamed told me. "People get the mistaken impression that what we care about is the particles. The science is characterized like: What are things made of? What are the ultimate building blocks of matter? I hate that. That sounds a lot like chemistry, and it's not like that at all. There are many, many more exciting things in nature than some random elementary particles.

"The reason we go to short distances isn't to probe the building blocks of matter," he went on. "It's because for four hundred years fundamental physics has been on this trajectory of unifying seemingly disparate things. We've found that, as we understand more, apparently incredibly disparate phenomena turn out to be different aspects of a more surprising, more beautiful answer than we could have anticipated—and often even hoped for. This started with Newton, who realized that the force dragging the apple down was the same force holding the moon around the earth. It continued with the realization that electricity and magnetism are different aspects of the same thing. Relativity told us that space and time are different aspects of the same thing. There's more and more unity in our understanding of nature. And we've seen, especially over the last hundred years, that the essential unity and the essential simplicity best reveal themselves at short-distance scales. So it's not that we care about the particles. We care about the laws."

Taped to the wall of Arkani-Hamed's office is a graph labelled "LHC Luminosity Profile." It shows when various phenomena—including the Higgs—should, if they exist, be revealed. Arkani-Hamed is a frequent visitor to CERN, and every time he goes, he told me, "it's like a religious experience." To prepare for the start-up of the collider, he has helped organize a series of dress rehearsals, called the L.H.C. Olympics. In these exercises, one team, playing God, chooses, out of the many models of the universe proposed by theorists, one to be true. The team then generates the sort of data that, according to this model, should be produced at the L.H.C. The other teams have to analyze the data to try to arrive back at the theoretical model the numbers are supposed to reflect. There are no winners or losers, Arkani-Hamed explained. "But afterward some people are high-fiving each other and other people are being consoled." He added, "It's an amazing blast."

One source of tension between experimentalists and theorists is the awkward matter of credit. Who should get the glory when a discovery is made: the theorist who proposed the idea, or the experimentalist who found the evidence for it? In this context, even access to L.H.C. data is a vexed subject; in the United States, the groups that have worked on building the detectors will receive the raw data, but they're not likely to share it. Arkani-Hamed joked that in order to get at the information theorists might have to find a "Deep Throat" who will pass them the data in secret.

"There is a sense among many experimentalists that theorists are a bunch of irresponsible little spoiled brats who get to sit around all day, having all these fun ideas, drinking espresso and goofing off, with next to no accountability," he said. "Meanwhile, they're out there, nose to the grindstone, for ten years; they've built this damn detector, and damn it if they're not going to be the ones to figure it out! And so this stuff that we're doing, there's some Johnny-come-lately feeling like 'Oh, now that it's all done the theorists finally want to think about how they're going to solve this'; it's like there are theorists swooping in to try to take it from them. I'm exaggerating slightly, but not much.

"It's a general fact about physics that the people you tend to remember are the theorists," he went on. "At least in the mythology, experiment plays a less central role. And there's a natural reason for that, because the ultimate goal isn't to observe things about nature; the ultimate goal is to understand and explain things about nature. So, for that reason, it's a chicken-and-egg problem. But definitely you want to be the chicken."

Arkani-Hamed is often called a string theorist, although he is more closely associated with ideas like large extra dimensions—large being on the scale of a tenth of a millimetre—and a hybrid theory known as "split supersymmetry." String theory posits that the universe is composed of tiny strands of energy, which vibrate at different frequencies, creating what appear to be different particles. In its most popular form, string theory demands the existence of seven dimensions beyond the usual four—three in space and one in time—that we're familiar with. Supersymmetry, meanwhile, which is often referred to by the acronym SUSY (pronounced soo-see), holds that every particle has a "superpartner" with a different spin, spin here being understood not as it is in everyday life but as a fixed property of a particle that determines some of its basic characteristics. Under the naming system that's been devised for these hypothetical superpartners, the counterpart of a quark would be a squark, and that of a photon a photino. (The superpartner of the as yet undiscovered Higgs would be a Higgsino.) It has been proposed that these "superparticles" could account for the dark matter that physicists estimate makes up nearly a quarter of the universe.

String theory and supersymmetry are enormously compelling to theorists, so much so that their proponents dominate the theory groups at most élite universities. (As of 2000, at least ten thousand scientific papers on supersymmetry, and several thousand more on string theory, had been written.) Both aim at further unification, and both—to varying degrees—resolve problems that have frustrated physicists for decades. Arkani-Hamed spent nearly two hours trying to take me through the details of just one of these—the so-called "hierarchy problem." In the process, he consumed four or five or six cups of espresso—even this I lost track of. Broadly speaking, the hierarchy problem has to do with mathematical contortions, known to physicists as "fine-tuning," that must be performed in order to account for the fact that gravity is so weak compared to the other forces.

"This is not just a little weird," Arkani-Hamed told me. "It's incredibly weird. The big question that we don't have an answer to, or that we have an answer to but it seems absurd, is: Why do we have a macroscopic universe at all?"

The trouble with string theory and supersymmetry is that, at this point, they remain entirely theoretical. The last confirmed breakthrough in particle physics was a set of equations known as the Standard Model. Developed in the early nineteen-seventies, the equations describe the behavior of all known forms of matter and all known forces, with the notable exception of gravity. Despite the model's limitations as a fundamental theory of nature—the hierarchy problem is just one of its many shortcomings—the predictions it has generated have been borne out, with astonishing precision, at one collider after another. (The Higgs would represent the last element of the model to be confirmed.)

String theory, by contrast, has yet to provide a single prediction that could be definitively tested. As for supersymmetry, which is generally considered a precondition for string theory, all efforts to confirm its predictions have so far failed: at the energy levels achieved by colliders to date, not a trace of a squark or a photino has turned up. As Lee Smolin, a physicist at Canada's Perimeter Institute, observed in a recent critique of contemporary theory, eventually "you begin to feel like Sbozo the clown. Or Bozo the clownino. Or swhatever."

To theorists, the tantalizing promise of the L.H.C. is that it will, finally, supply the evidence of "new physics" that they've been waiting for. Certain patterns of missing energy, for example, would suggest the existence of extra dimensions, as would the creation of mini black holes. Different results—also in the form of missing energy—would indicate the existence of squarks or other superparticles. There are good theoretical reasons to expect these phenomena to begin to appear at the energy level of the L.H.C., or so at least Arkani-Hamed tried to explain to me over several more espressos. He told me that he was completely confident the Higgs would be found at the collider: "I would bet many, many months' salary." He also said that if the Higgs was the only result, the L.H.C. would be a disappointment. "We theorists, we're a hard lot to please. We've taken things for granted for so long we say, 'Oh, yeah, for sure you'll discover the Higgs.' But the things we're really interested in are all these major puzzles."

Eventually, some of Arkani-Hamed's graduate students wandered into his office. They had brought with them a Diet Coke, which Arkani-Hamed began to drink out of his espresso cup, and a hundred-page paper that they—and he—were planning to release that day. The opening sentence of the paper declared, "With the upcoming turn-on of the Large Hadron Collider (LHC), high energy physics is on the verge of entering its most exciting period in a generation." (A later sentence noted, "As the reader might find intuitive, we can tremendously improve our scheme over the constant approximation by including the leading order near-threshold behavior of matrix elements.")

In 1969, the Congressional Joint Committee on Atomic Energy held a hearing at which the physicist Robert Wilson was called to testify. Wilson, who had served as the chief of experimental nuclear physics for the Manhattan Project, was at that point the head of CERN's main rival, Fermilab, and in charge of $250 million that Congress had recently allocated for the lab to build a new collider. Senator John Pastore, of Rhode Island, wanted to know the rationale behind a government expenditure of that size. Did the collider have anything to do with promoting "the security of the country"?

> WILSON: No sir, I don't believe so.
> PASTORE: Nothing at all?
> WILSON: Nothing at all.
> PASTORE: It has no value in that respect?
> WILSON: It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. . . . It has to do with are we good painters, good sculptors, great poets? I mean all the things we really venerate in our country and are patriotic about. . . . It has nothing to do directly with defending our country except to make it worth defending.

Asked to explain how their work, supported by public funds, contributes to the public good, particle physicists often cite Wilson, or offer some variation on his non-answer answer: the search for knowledge cannot be justified on other grounds; its value, like the particles under study, is irreducible.

The cost of the L.H.C. is expected to run to more than $8 billion, and this doesn't include the price of the tunnel, which was originally dug for LEP. Most of the funding is being provided by European taxpayers; Germany has contributed the most—around twenty per cent of the total—and Britain and France have each contributed slightly less than that. (The United States is contributing a little more than $500 million.) Meanwhile, physicists are already lobbying for the next generation of machines. The plan for the International Linear Collider, which, as its name suggests, would be built in a straight line rather than a ring, calls for smashing electrons and positrons together at the midpoint of a tunnel twenty miles long. According to the Web site that has been set up for the I.L.C., the hypothetical collider's design would allow for "an upgrade" to a thirty-mile-long machine "during the second stage of the project." The even more ambitious Very Large Hadron Collider would occupy a tunnel a hundred and forty miles in circumference.

In principle, colliders could just keep on getting bigger—the Incredibly Large Hadron Collider!—and commensurately more expensive. As a practical matter, of course, there's a limit, and it's quite possible that limit has already been reached. At CERN, nearly every physicist I spoke to recalled the sad—very sad—story of the Superconducting Super Collider. Announced with much fanfare by President Ronald Reagan in 1987, the

Superconducting Super Collider was supposed to occupy a tunnel fifty-four miles in circumference under Waxahachie, Texas. It was designed to generate beam energies of 20 TeV, roughly three times as high as those that will be achieved at CERN. Fourteen miles of the tunnel had been excavated—and $2 billion spent—when, in 1993, Congress pulled the plug. "If we find more basic building blocks of the universe, it's not going to change the way people live" is how Representative Martin R. Hoke, of Ohio, shrugged off his vote. As the historian of science Peter Galison pointed out to me, it is probably no coincidence that funding for the supercollider was cancelled almost immediately after the fall of the Soviet Union. The "dignity of men" defense of particle physics worked best at the height of the Cold War, when no one, except maybe the scientists involved, entirely believed it.

Unless funding for another collider materializes, a lot of experimentalists will soon find themselves out of work. "Half of those guys already have résumés in at hedge funds," one theorist joked to me. Arguably, the theorists' situation is not all that much more secure; at a certain point, speculations about the nature of the universe that can't be put to the test cease to be physics. The promise of the Large Hadron Collider is thus also its great burden. A truly astonishing discovery there—proof, say, of extra dimensions, or of something even weirder than that, which theorists have yet to conceive of—would provide a powerful impetus to keep particle physics going for another generation. Barring a breakthrough, it's hard to imagine how the project can continue. Such an outcome would not mean that the fundamental order of the universe is unknowable. But it might well mean that we will never know it. ♦

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