God's Laboratory

By Dan Falk

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This spring, an international team of physicists, including several from U of T, will launch the most ambitious science experiment ever devised. Their goal: to unlock the secrets of the universe.

The European Centre For Nuclear Research – known by its French acronym, CERN – occupies a sprawling complex on the outskirts of Geneva, Switzerland. The cluster of nondescript white buildings doesn't look much like a science laboratory, let alone one of the foremost labs in the world. But here, in just a few months, physicists and engineers from around the world will fire up a machine to answer some of the most fundamental questions about the structure of the universe. To a first-time visitor, only the street signs – Route Newton, Route Einstein – offer a hint of what is going on here.

The real excitement is below ground.

Accompanied by an official from CERN's press office, I make my way to the northeastern corner of the complex – to Building 2155 – where Mike Lamont, a senior CERN engineer, greets me. Lamont hands me a hard hat and ushers me through a series of security doors and into what looks like a large freight elevator. We descend 80 metres below ground to the Large Hadron Collider (LHC). When it's switched on this spring, the $8-billion facility will be the world's largest and most powerful particle accelerator – and the biggest, most complex science experiment ever devised.

The accelerator is being built in a tunnel that's shaped like an enormous doughnut, 8.5 kilometres in diameter. Longer than the London Underground's Circle Line, the tunnel straddles the border between Switzerland and France, lying underneath towns and farms in both countries. As I look down the length of the tunnel's concrete walls, I can just see where it begins to curve. Lamont tells me that were I to broach the security doors and enter the tunnel when the accelerator was running, the radiation would make my visit brief. “You’d be dead within a few minutes,” he says dryly.

Work crews are still constructing the LHC, although the section we’re visiting is almost complete. As Lamont and I stand by the tunnel wall, the only sounds we can hear are the rumbling of vacuum pumps and the distant footsteps of engineers and scientists. In front of us is a blue and silver metal pipe about a metre wide, which runs the length of the tunnel. Lamont explains that inside the pipe, streams of protons will be accelerated to within a fraction of the speed of light. (The protons will move so close to the speed of light, in fact, that if they chased a beam of light on the four-year journey to Alpha Centauri, the nearest star to our sun, they’d lose the race by a single second.) The world’s largest array of superconducting electromagnets will steer the accelerated protons around the pipe. To keep the current flowing in these magnets resistance-free, huge tanks of liquid helium will cool them to a temperature of 1.9 degrees above absolute zero – about one degree colder than outer space. The protons will zip around the pipe at a rate of more than 11,000 laps per second, passing breezily back and forth between France and Switzerland on every lap.

At the same time, the scientists will send a second stream of protons whizzing through the pipe in the opposite direction. The debris from the resulting proton collisions will be like gold to the physicists – who include a large U of T contingent. The LHC will allow scientists to glimpse exotic particles and, by simulating the conditions in the early universe, help them understand how the fundamental building blocks of matter interact. Experiments at the LHC could help explain why there’s so much matter and so little antimatter in the universe. They could give physicists a peek at possible extra dimensions beyond the three dimensions of space – and one for time – that we’re familiar with. And, perhaps above all, they may help explain the origin of mass – why the universe is full of stars and galaxies in the first place.

Erich Poppitz, a U of T theoretical physicist who was spending a month at CERN when I visited last summer, described the LHC as “the most important experiment to come online in particle physics in the last 20 or 30 years. It is certainly the most important experiment in my lifetime in physics."

Particle physics has come a long way since scientists first began to probe the structure of the atom at the start of the 20th century. While the ancient Greeks imagined that the atom's nucleus was an indivisible entity, scientists now know that the nucleus is made of two sorts of heavy particles – protons, with a positive electrical charge, and neutrons, with no charge. Swirling around these heavy particles are much lighter electrons, with a negative charge. By the 1970s, the number of fundamental particles (those thought not to be made up of anything smaller) swelled dramatically. Scientists discovered that protons and neutrons were made up of two kinds of quarks, dubbed "up" and "down." Four other quarks, given such fanciful names as "charm," "strange," "top" and "bottom," rarely show themselves in nature but have been created in particle accelerators. The electron has heavier cousins (also carrying a negative electrical charge) known as the muon and the tau. Physicists have also learned that the electron, muon and tau are each associated with a tiny, chargeless particle called a neutrino. And a handful of messenger particles, known as bosons, mediate interactions between all of the other particles. (If we think of quarks and electrons – the building blocks of solid matter – as political leaders, then bosons are the diplomats who shuttle information back and forth between them.) The mathematical description for these particles and their interactions is the Standard Model of particle physics.

In many ways, the Standard Model – developed more than 30 years ago – has held up remarkably well to experimental scrutiny. Several particles predicted by the model have subsequently been observed. (Scientists postulated the existence of the W and Z bosons in the late 1960s and discovered them at CERN in the 1980s.) The theory still suffers a significant flaw, though. A particle called the Higgs boson, first theorized in 1964 by Scottish physicist Peter Higgs, has yet to be observed. Finding the Higgs is a priority of LHC scientists. "It is really the one missing piece of the Standard Model," says Richard Teuscher, a U of T experimental physicist who has been working on the LHC for nearly a decade. "It's as if you've taken a whole chunk out of the puzzle; it doesn't hold together."

In the world of particle physics, the Higgs shoulders a lot of responsibility. Some physicists jokingly refer to it as “the God particle.”

The Higgs boson is a vital part of the Standard Model because it explains why other particles exhibit the mass that they do. It explains, for example, why the top quark is so heavy (it’s almost as massive as an atom of gold), and why the electron is so light. The Higgs is thought to create a field (like an electromagnetic field) that permeates all of space. This field makes other particles seem heavy as they struggle to move through it. John Ellis, a theorist based at CERN, provides the analogy of a snow-covered field: “Imagine various people trying to cross the field,” he says. “If you’re wearing cross-country skis, you can go pretty fast.” The skiers correspond to a massless particle, like the photon, which travels at the speed of light. Now, consider somebody on snowshoes. “They go somewhat slower; they sink a little bit into the snow – they don’t travel at the speed of light, and for us that means that they have a non-zero mass.” Finally, consider someone trying to cross the field in hiking boots. “They’re going to sink way down into the snow; they’re going to go very, very slow indeed – and that will be a particle which has a very large mass.”

Most theorists are confident that the Higgs boson exists, believing that the only reason why no one has observed it yet is because of its large mass. Until now, no particle accelerator has been powerful enough to bring the Higgs into view. “For me, as an experimental physicist, until I’ve seen it, touched it, played with it, manipulated it in the lab, I don’t think we really have an understanding of it,” says William Trischuk, a U of T physics professor. “We have a mathematical model. Until we actually make one, it’s not really physics.” If the Higgs is real, the LHC ought to be able to find it – or else show that it doesn’t exist.

The LHC’s most sophisticated components are four particle detectors that are being assembled at different points along the circumference of the main tunnel. ATLAS (which stands for A Toroidal LHC ApparatuS) is one of the largest of these detectors. Scientists hope it will identify the exotic particles that appear when the two beams of protons smash into one another.

Like all of the LHC detectors, ATLAS lies deep below ground, in a concrete cavern that's roughly the size of the main lobby of Toronto's Union Station. Professor Teuscher guides me along the scaffolding that surrounds what looks like a jet engine – if you can imagine a jet engine the size of a small office building. When it's finished, ATLAS will weigh 7,000 tonnes and be made from the same amount of steel that was used to construct the Eiffel Tower, says Teuscher.

Like many of the U of T faculty involved in assembling ATLAS, Teuscher is spending most of his time at CERN these days – especially now that the final stages of the detector are taking shape. Besides professors Teuscher and Trischuk, five other U of T physicists are directly involved with ATLAS: Robert Orr, who heads Canada's ATLAS team; Pekka Sinervo, who will be stepping down as dean of the Faculty of Arts and Science next summer to work on the detector; and professors David Bailey, Peter Krieger and Pierre Savard. More than a dozen research associates and students (graduate and undergraduate) are also involved.

Teuscher points out some of ATLAS's shiny metal components, explaining that magnets will steer the particles, calorimeters will measure their energy content, and a variety of tracking devices and detectors will record where the particles end up. A staggering array of electronic equipment will keep ATLAS's parts working in concert. Many of the components that make up the calorimeters were built at U of T and shipped to CERN, where they will help Teuscher and his colleagues identify the particles being created deep within the detector.

The protons that will whiz through the accelerator will contain enormous amounts of energy. When they collide, some of that energy will be converted into matter, or particles with mass. (Einstein showed us how mass and energy are related with his iconic equation, E = mc2.) Usually these particles will be the familiar kind: quarks, electrons and muons. But very occasionally, the collisions may produce new particles, such as the long-sought-after Higgs. Other exotic particles that newer theories have proposed could also turn up – perhaps for the first time since the big bang, some 13.7 billion years ago.

While the LHC is better equipped than any other accelerator to create these exotic heavy particles, detecting them will still be enormously difficult. Heavy particles decay in an infinitesimally small fraction of a second, leaving only a puff of more familiar, stable particles. It's this burst of secondary particles that ATLAS will detect. And with a clear picture of what these particles are doing – how fast they're moving and in what direction – physicists hope to work backward to deduce what kinds of particles popped into existence inside the detector before they vanished. Apparently, catching particles is not quite like collecting butterflies with a net; instead, it's more like identifying the Cheshire cat based on a snapshot of its fading smile.

To find the elusive Higgs, physicists will wade through oceans of data. The LHC will produce a staggering 600 million proton collisions every second. The raw data from the collisions will flow out of the detectors at a rate of 28 gigabytes a minute – enough to fill three million DVDs a year. Teuscher says that most of the collisions will be "uninteresting" – the protons will "just scatter off at an angle" rather than collide with the full force of the accelerator. "But a few times, there'll be very interesting collisions," he says – perhaps as many as 200 per second. That's still an enormous amount of data, and it's no surprise that physicists at the LHC will spend a lot of time at their computers – writing the programs to sift through the numbers, highlighting some collisions and ignoring others, and carefully examining the results.

The ATLAS team won't be the only group looking for the Higgs. A second detector, the Compact Muon Solenoid (CMS), sits just a few kilometres down the tunnel. (The word "compact" is misleading; when CMS is finished, it will weigh more than 12,000 tonnes.) CMS, like ATLAS, is being assembled in its own enormous underground chamber. It's more of a "friendly competition" than a race, says Claire Timlin, a PhD student at Imperial College in London who is now based at CERN to work on the final stages of the CMS detector. If both teams are able to glimpse the fabled particle – two detections from two very different machines – it will confirm the idea that the Higgs really exists. Plus, she adds, it "gives both teams a push to achieve as much as they possibly can."

In the 30 years since proposing the Standard Model, theoretical physicists have forged ahead with ever-more complex theories to explain how the universe works. One such theory – string theory – envisions a universe composed of tiny vibrating strings, along with unseen extra dimensions and perhaps universes beyond our own. Physicists are also looking for signs of supersymmetry – a model that suggests that the particles we have observed each have heavier, not-yet-seen partners. Supersymmetry could help explain why the masses of the known particles differ so greatly, and assist in the construction of the long-sought unified theory of physics. Yet without evidence that either supersymmetrical partner particles or string theory's hidden dimension exist, such musings remain only that. Data from the LHC may finally show which of these new ideas is worth exploring further and which is a dead end.

Finding evidence at the LHC to support extra dimension or supersymmetry theory would herald a revolution in our view of the universe, says Teuscher. "For the first time, we'd have proof that these are not just dreams of ours – that they're really something solid." It's no wonder that the completion of the LHC is one of the most anticipated events in the international physics community. When the LHC comes online next summer, it will mark the high point in the careers of hundreds of scientists. These theorists and experimentalists have been waiting for decades to see what lies beyond the familiar quarks and photons and electrons of the Standard Model. "It will be all unknown," says Teuscher. "It will be like going to a continent for the first time and exploring a new, uncharted territory."