quick study

Eyes on the LHC

Fabiola Gianotti and Chris Quigg

Particle physicists don't know for sure what explorations at the Large Hadron Collider will bring. But they do know that many mysteries in their field point toward solutions at the LHC's impressive TeV energy scale.

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Over the next few years, the Large Hadron Collider at CERN will advance the experimental frontier of particle physics to energies around 10^{12} eV, or 1 TeV, for collisions among the basic constituents of matter that make up the proton. The energy of the colliding protons themselves will be some 7 TeV. This sevenfold increase over the Fermilab Tevatron's energy opens vast uncharted terrain and promises a profusion of exciting results.

Consider, for example, the electroweak theory—the quantum field theory that unifies electromagnetism with the weak force responsible for nuclear beta decay. The theory has survived dozens of experimental tests at the level of one part in a thousand. But one essential piece has eluded detection: the Higgs boson, the avatar of the so-called electroweak symmetry breaking that gives mass to quarks, leptons such as the electron and muon, and the $W^{\pm}$ and Z gauge bosons—the weak partners of the photon. Particle theorists have considered how collisions among the electroweak gauge bosons and the Higgs boson would behave at very high energies, and they have concluded that either the Higgs boson will be found and its mass determined or the weak interactions among the gauge bosons will become strong. The tipping point occurs for a Higgs-boson mass of about 1 TeV. One way or another, something new is to be found in the electroweak interactions at energies not much larger than 1 TeV.

Other evidence hints at rich TeV-scale physics. The electroweak theory does not explain what prevents quantum shifts from tugging the Higgs-boson mass far above 1 TeV. To solve that "hierarchy problem," theorists have advanced many extensions of electroweak theory—supersymmetry and technicolor, for example—that compel additional new phenomena near 1 TeV.

The collider and detectors

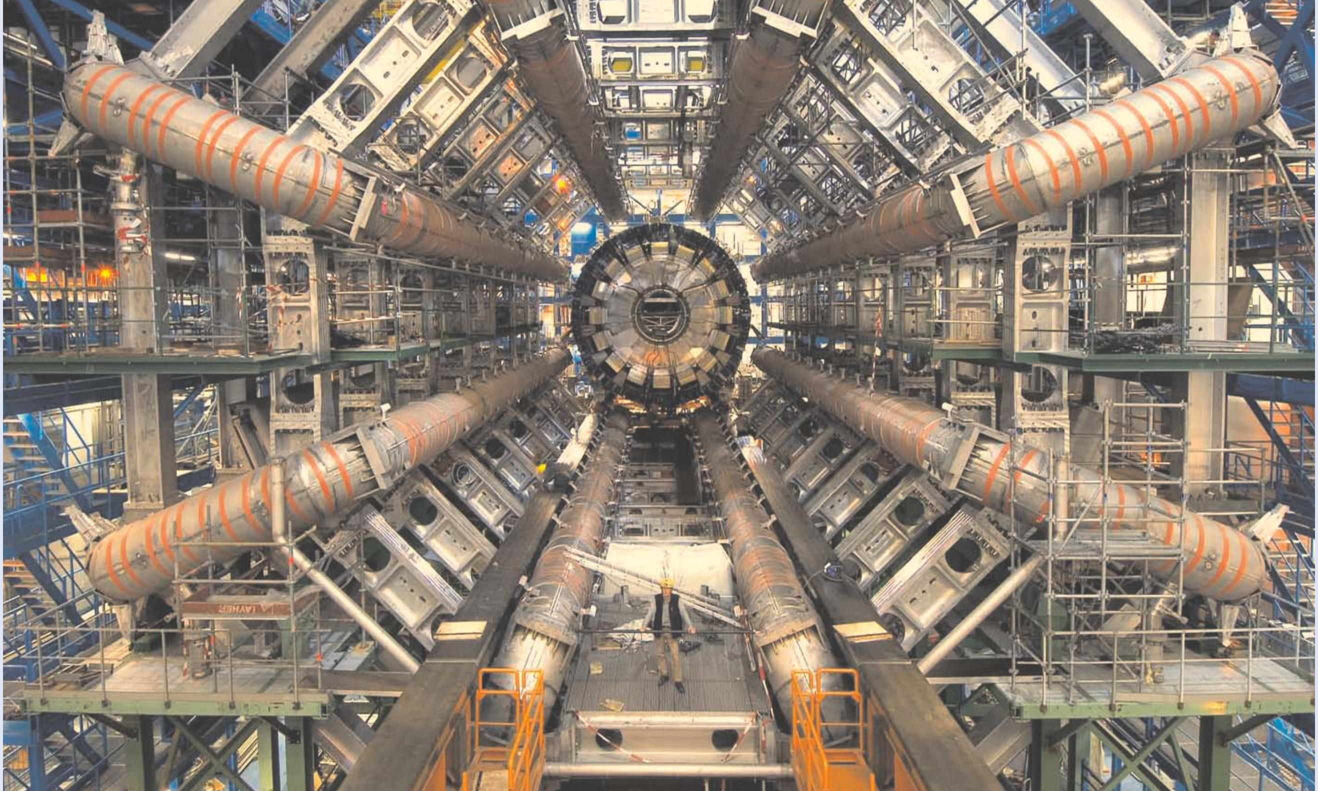
Colliding two intense beams of highly energetic, stable, charged particles has become the particle physicist's tool of choice for exploring the structure and interactions of the minuscule constituents of matter. It is now practical to accelerate protons to many TeV and to study the collisions among the quarks and gluons—gauge bosons in the theory of strong interactions—that share the proton's momentum. Essential elements of modern experiments are the accelerators that create the high-energy beams and bring them into collision, sophisticated detectors that record the collision products and reconstruct the elementary events that occur in proton–proton collisions, and massive, flexible computing resources that analyze the huge volume of data needed to uncover rare phenomena.

The LHC is housed in a 27-km ring that lies about 100 m below semirural terrain on the French–Swiss border. Counterrotating beams of protons accelerated to within 10 km/h of the speed of light collide at four interaction regions spaced around the ring, where collision products are analyzed in the four detectors—ALICE, ATLAS, CMS, and LHC*b*. More than 1200 superconducting dipole magnets, each providing an 8.33-tesla field, confine the 7-TeV proton beams. Superfluid helium at 1.9 K—lower in temperature than the relic photons from the Big Bang—maintains the niobium–titanium cable in the superconducting state.

Each beam of more than 3×10^{14} protons is organized into 2808 bunches spaced by 25 nanoseconds. When the LHC is running at full capability, each of the 40 million bunch crossings per second will yield about 25 proton–proton interactions that will spray the detectors with thousands of particles. An exquisite vacuum makes it possible to keep the beams circulating for approximately one day. A proton in the LHC could make the equivalent of a dozen round trips between Earth and Neptune before encountering a stray air molecule.

To unravel what happens in a high-energy collision, physicists need to detect, identify, and measure as many of the produced particles as possible. To that end, they surround the interaction point with, in essence, giant digital cameras that snap pictures of the events. The "cameras" consist of concentric layers of various detector elements using diverse technologies and directed to complementary purposes. For instance, silicon strips and pixels as small as tens of micrometers precisely localize the trajectories of charged particles, including protons, electrons, and pions. Liquid-argon, crystal, or scintillator-based calorimeters identify electrons and photons and measure the energy they carry. Gas-based detectors immersed in strong magnetic fields, possibly interleaved with iron absorber, identify muons, reconstruct their trajectories, and measure their momenta.

The LHC detectors represent extraordinary leaps beyond such predecessors as the CDF and D0 detectors at the Tevatron. The figure shows the biggest of the LHC detectors, ATLAS, which is roughly cylindrical, 45 m long, and 25 m high. Such large volumes are needed to absorb and study the highly energetic particles produced in TeV-scale phenomena. The LHC detectors feature very fast response times, matched to the 40-MHz crossing rate, and are made of special materials highly resistant to radiation. ATLAS and CMS each gather signals from about 100 million electronic channels to provide the granularity necessary to distinguish the thousands of particles produced at each beam crossing.



The ATLAS underground cavern, photographed in October 2005. The round calorimeter in the center is surrounded by eight toroidal superconducting coils. (Photo courtesy of CERN.)

The teams of scientists are also spectacular in size and diversity. The 1900 ATLAS physicists are drawn from more than 160 institutions and 35 countries.

Each year the LHC experiments will record enough data to fill a 2-km-high stack of DVDs. About 100 000 of today's fastest PC processors will be required to reconstruct and simulate the billion events per year. The huge data stream and the intercontinental reach of the experimental collaborations call for distributed computing. That need is met by the LHC Computing Grid Project, an ensemble of computing centers all over the globe linked by high-speed networks. A Tokyo student might transfer to Lyon data residing at the Brookhaven National Laboratory in New York and analyze them on processors located in France. The sun never sets on activities of the LHC experiments.

What to look for early on

Rediscovering the standard model of particle physics will be the first goal of experiments, so that standard-model landmarks may orient exploration of the new landscape. An ongoing task will be to refine triggers, to select 100–200 events per second for offline study from the torrent of several million—eventually a billion—raw events every second.

Some provocative observations may come quickly: an unexpected event structure or a dilepton resonance that might represent a new force of nature or the hint of extra dimensions.

An essential first step toward decoding electroweak symmetry breaking is to find the Higgs boson and learn its properties. One promising channel for an early discovery is $H \to ZZ \to 4$ charged leptons. Backgrounds are very small, so even a handful of events would suffice for a claim of discovery. Establishing the signal will require efficient electron and muon reconstruction and identification down to a few GeV.

The LHC is poised to solve one of astronomy's greatest puzzles by creating in the laboratory the dark matter that makes up 25% of the universe's energy density. The rotation curves of spiral galaxies, along with supporting evidence from the cosmic microwave background and large-scale structure, point to a neutral relic from the early universe. A few-hundred-GeV particle that couples with weak-interaction strength could supply the missing mass. No known particle fills the role, but many contenders pop up in extensions to the standard model, including supersymmetry (see PHYSICS TODAY, August 2007, page 16).

Should supersymmetry be nature's choice, squarks and gluinos (superpartners of quarks and gluons, respectively) produced by strong interactions at the LHC might decay by chains that end in dark-matter-candidate neutralinos. Neutralinos leave no trace in ATLAS or CMS; their presence is signaled by unbalanced energy flow perpendicular to the beam direction. Great care will be required to prove that apparently missing energy is not an artifact of detector response and that the interesting events cannot be explained by conventional processes resulting in undetectable energetic neutrinos.

By reaping important insights into the nature of electroweak symmetry breaking, experimentation at the LHC will lift the veil that obscures the view of physics at subattometer distances and will enable scientists to sharpen questions about dark matter, the pattern of fermion masses, and the unification of forces. We anticipate that the discoveries made there and the puzzles encountered will transfigure particle physics and stimulate rich new conversations with neighboring disciplines. What better reward for several thousand scientists from all over the world who worked hard for two decades to build an accelerator and develop experiments of unprecedented scope, complexity, and performance?

The online version of this Quick Study provides links to further resources and illustrations.

Additional resources

- ▶ ATLAS experiment webpage, http://atlas.ch.
- ▶ CMS webpage, http://cms.cern.ch.
- ▶ C. Quigg, in *The New Physics for the Twenty-first Century*, G. Fraser, ed., Cambridge U. Press, New York (2006), chap. 4. ■