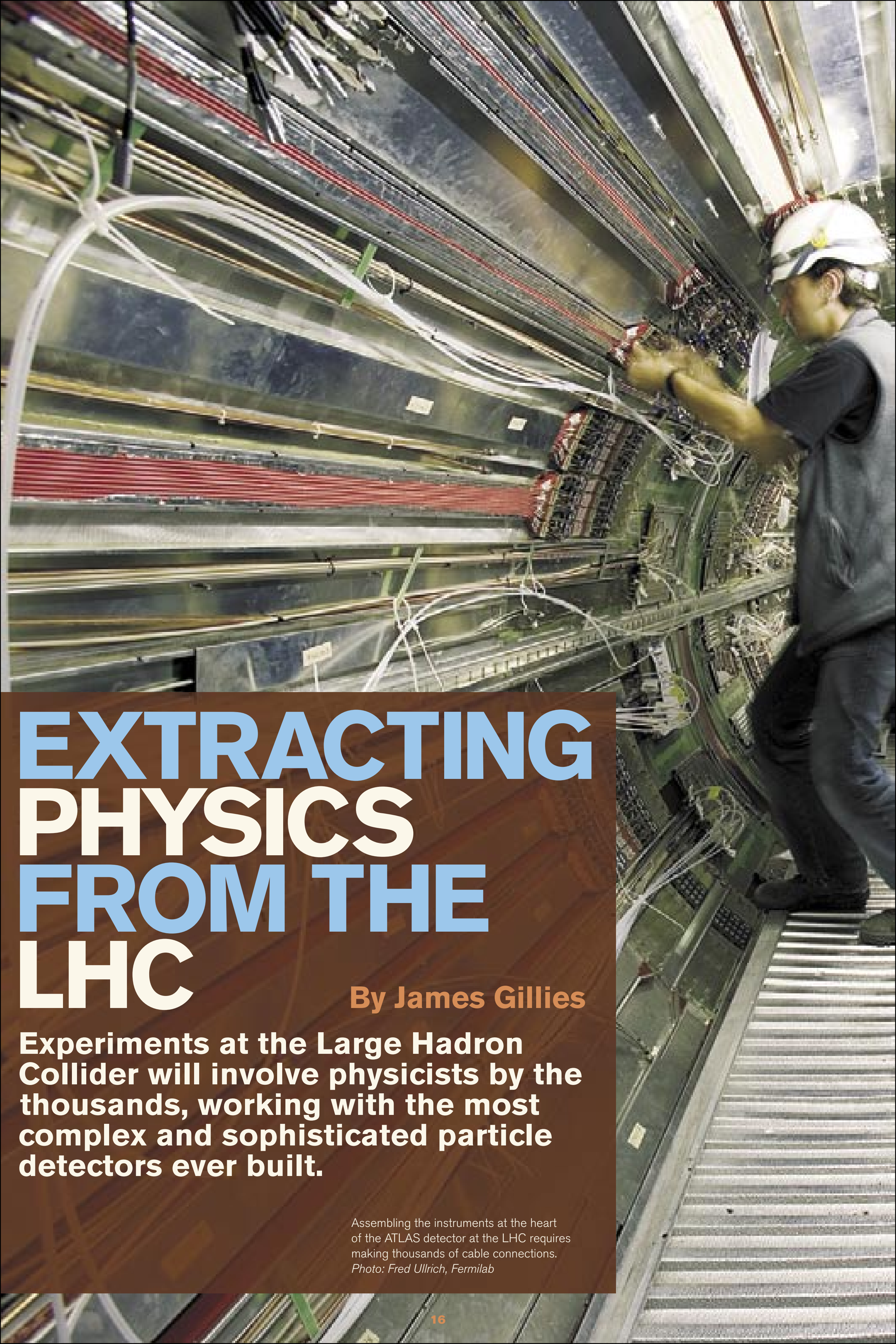


EXTRACTING PHYSICS FROM THE LHC

By James Gillies

Experiments at the Large Hadron Collider will involve physicists by the thousands, working with the most complex and sophisticated particle detectors ever built.

Assembling the instruments at the heart of the ATLAS detector at the LHC requires making thousands of cable connections.
Photo: Fred Ullrich, Fermilab

A proton travels around a 27-kilometer ring at nearly the speed of light. Along with a bunch of other protons, it passes through the hearts of each of a series of detectors more than ten thousand times per second. Then, on one pass, it slams into a proton coming from the other direction.

As the protons collide, some of their inner quarks or gluons transform, via a burst of energy, into a new set of particles, many of them mundane, but some of them exotic. Those exotic particles tell stories that scientists have never heard before. By listening closely, physicists can answer some of their most fundamental questions.

But listening to the stories is not an easy task. It requires some of the most advanced technology ever created by humanity, in some of the most elaborate experiments ever built. The experiments will be based around detectors known by their acronyms: ALICE, ATLAS, CMS, LHCb, TOTEM, and LHCf.

In a year or so, these experiments will start to catch the fleeting remnants of particles produced in collisions in the world's highest-energy particle collider, fulfilling the dreams of many who have worked for decades toward this goal, and launching the careers of others who are just starting on their own personal particle adventures.

Meet the experiments

The LHC has six approved experiments so far. Two large, general-purpose detectors (ATLAS and CMS) will examine the plethora of particles escaping from collisions at the LHC. Two medium ones (ALICE and LHCb) will study the collisions in more specific ways to yield information on more specific phenomena. Two much smaller experiments (TOTEM and LHCf) have recently been approved, and other proposals, such as the MOEDAL experiment to search for exotic particles such as magnetic monopoles, are on the table.

Unprecedented scale

Within the last two decades, particle physics experiments have changed beyond recognition: in size, in complexity, and in their social organization. The challenge of designing detectors for the LHC is unprecedented.

Each detector will observe up to 600 million collisions each second. Particles emerging from one collision will still be traveling through a detector when the next collision occurs. However, some of the phenomena physicists are looking for are so rare that they will take place at the rate of around one per day.

The LHC detector electronics and online computers can filter out the uninteresting from the interesting, reducing the data to be stored for analysis to around 100 collisions per second. Even after this draconian reduction, the total amount of data to be stored will be equivalent to a stack of CDs 20 kilometers tall per year.

The huge number of particles produced also means that detector components need to be extremely robust. Individual detector elements need to be as small as possible so that the particles traversing the detectors are caught and observed independently.

The high energy of the collisions requires that the detectors have to be big to record all particle trajectories and decays. ATLAS, the largest of the LHC experiments, fills a cavern the size of the nave of Notre Dame cathedral in Paris. And CMS, whose "C" stands for "compact," weighs in at 12,500 tons, the equivalent of around 40 large airplanes.

Catching nature in action

Both ATLAS and CMS are general-purpose detectors. They are designed to fully enclose the collision points at the center of each detector, leaving no gaps for emerging particles to escape through. Each performs the same set of measurements on the particles bursting out of a collision: their paths, their energies, and their identities. With some high-tech sleuthing, physicists will use the information they record to reconstruct what happened in the collision.

At the core of each detector, closest to the collision point, are trackers that record particle trajectories with great precision. Both detectors use silicon technology for the innermost tracking devices. Charged particles traversing silicon wafers give rise to electrical signals that betray their passage. In the case of CMS, the total surface area of the silicon wafers stacked inside the tracker is large enough to cover a 25-meter swimming pool. These new behemoths of detectors are only possible now that silicon technology has matured and become cheap enough that this vast quantity of silicon detector is affordable.

Located just outside the trackers are calorimeters, which slow down and absorb particles, measuring their energy. The final detection subsystems are muon trackers, which form the outermost parts of collider detectors. These instruments identify muons: heavy relatives of electrons. Muons are the only particles that can survive the calorimeter systems and be seen before exiting a detector. Both ATLAS and CMS pay great attention to the detection of muons since they are indicators for a wide range of interesting phenomena.

The detection subsystems of both ATLAS and CMS are each built around a powerful magnet system. Magnetic fields cause charged particles to follow curved paths that allow each particle's momentum to be measured.

Beyond their similarities, the CMS and ATLAS collaborations have adopted radically different approaches to the designs of their detectors' magnet systems. CMS has built its detector around a large solenoid magnet, a cylindrical coil of superconducting cable that will generate a magnetic field roughly 100,000 times that of the Earth. The magnetic field is confined by a steel yoke that forms the bulk of the detector's 12,500 tons.

Using a different geometry, ATLAS employs an enormous toroidal (doughnut-shaped) magnet system. It consists of eight race-track-shaped superconducting magnet coils, each 25 meters long, placed symmetrically as if around the face of a watch. When it is operating, the magnetic field is contained within the cylinder defined by the coils. This design requires no yoke and allows ATLAS to be some eight times the size of CMS although weighing only a little over half as much. The complete ATLAS magnet system also includes two smaller toroid systems, one at each end of the detector, and a central solenoid.

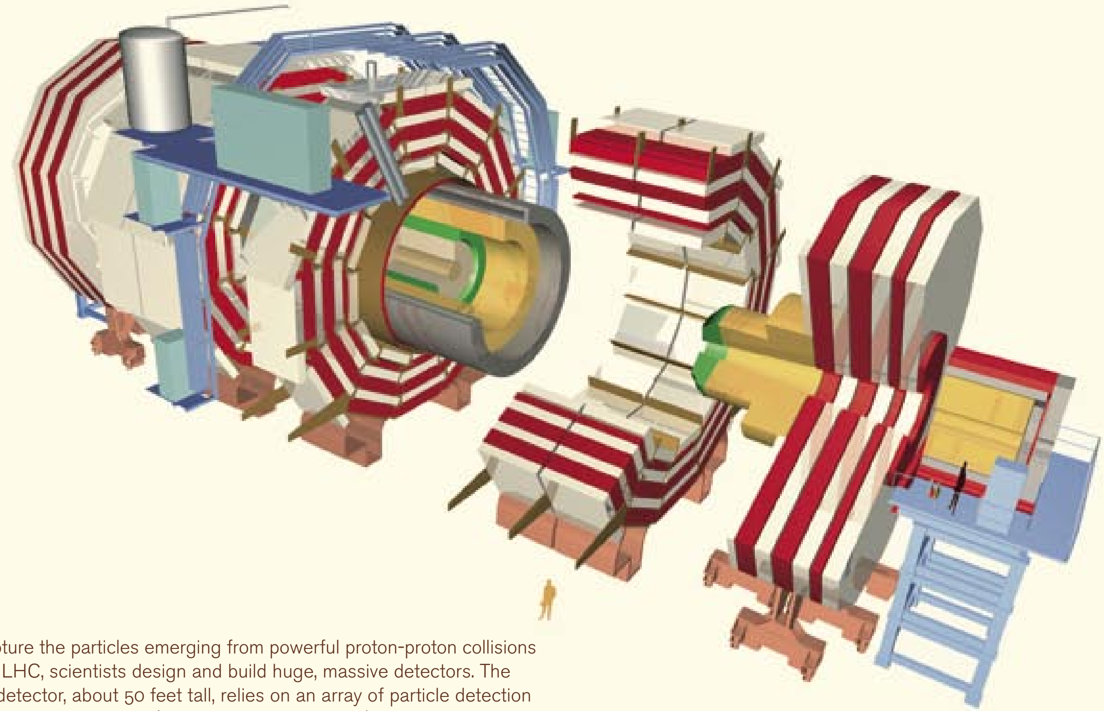
Small experiments, big goals

The ALICE and LHCb collaborations have designed detectors that are smaller than ATLAS and CMS, matching the specific research goals of these collaborations. ALICE will observe the collisions of high-energy lead nuclei when the LHC accelerates lead ions instead of protons. With this experiment, the collaboration will study the evolution of matter in the universe, from the first fraction of a second of our universe's existence to the time when the ordinary matter, from which today's visible universe is made, was formed. Key to this endeavor is the measurement of the thousands of particles that will emerge from lead-lead collisions.

LHCb will study the difference between matter and antimatter, helping us understand why we live in a universe that is apparently made entirely of matter. A difference in the behavior of matter and antimatter has already been observed, but what has been seen so far is not nearly enough to account for the observed matter-antimatter imbalance in the universe. A full explanation looks like being due to new physics, which could be revealed at the LHC by recreating the moment, 13.7 billion years ago, when particles called *b* and anti-*b* quarks were produced in pairs. The LHC will produce particles containing these and other quarks in abundance, but they decay very quickly. To catch them, LHCb has developed sophisticated mobile tracking detectors that literally graze the path of the proton beams circling the LHC ring. The innermost detector can be moved as needed to edge ever closer to the high-energy proton beam.

Some of the 1800-plus members of the ATLAS collaboration gather for a group photo at CERN.

Photo: CERN



To capture the particles emerging from powerful proton-proton collisions at the LHC, scientists design and build huge, massive detectors. The CMS detector, about 50 feet tall, relies on an array of particle detection subsystems. The tracker (the subsystem at its core) records particle tracks with ultrahigh precision. The intermediate subsystem, the calorimeter, determines the energy of the particles escaping the collision. The outermost devices identify muons, heavy electron-like particles that can travel long distances.

Graphic: CMS collaboration

TOTEM will observe protons that collide with other protons but don't transform into other particles. A good understanding of this process is essential to interpreting other results from the LHC, and could open up a window on new phenomena.

LHCf is a different type of experiment, using the LHC's protons as a source that simulates cosmic rays. It will study how colliding protons cause showers of particles, in particular photons. Analysis of these showers will aid in the interpretation and calibration of large-scale cosmic-ray experiments, which can cover thousands of square kilometers of ground.

Leading by consensus

The LHC experiments involve hundreds or thousands of researchers, with ATLAS and CMS counting around 2000 each. Since the experiments are so complex, physicists can no longer work as jacks-of-all-trades. Instead, they are specialists in their own niches of detector design, electronics, or analysis. Each detector subsystem is represented by a collaboration in its own right.

The collaborations are simply too large for everybody to be involved in every decision. Decisions that only affect one or two of a detector's subsystems are discussed and resolved in subsystem meetings. Recommendations are then discussed in the experiment's Executive Board and presented in plenary meetings that play a primary role in forming a large consensus.

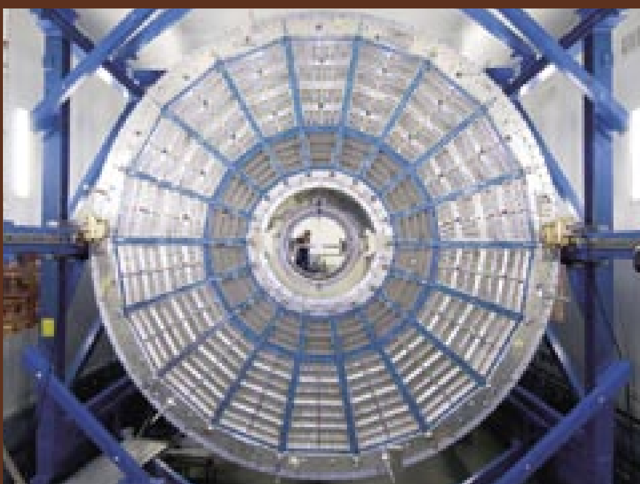
Achieving progress together

Procedurally, there is a clear sequence of steps to make formal decisions, with a hierarchical structure from subsystems to systems. Ultimately, the vote in the Collaboration Board is the final step for major decisions. Nevertheless, the leaders of the collaboration must actively lead the collaboration to decisions that are understandable to all, or at least to a large majority. Decisions are also influenced by practical constraints like costs, schedule, and the available human resources.

The diverse institutional origins of collaborators presents yet another challenge. ATLAS and CMS each involve over 150 institutions from around the world, and each institution's contribution to the experiment is described in a Memorandum of Understanding. Independent resource review boards scrutinize the implementation of these agreements to ensure that everything is proceeding according to plan.

Although particle physics collaborations have long been international, this is a new scale of enterprise. The collaborations have adapted to this growth, and all of the detectors at CERN are progressing well. All will be in a position to take data when the LHC switches on.

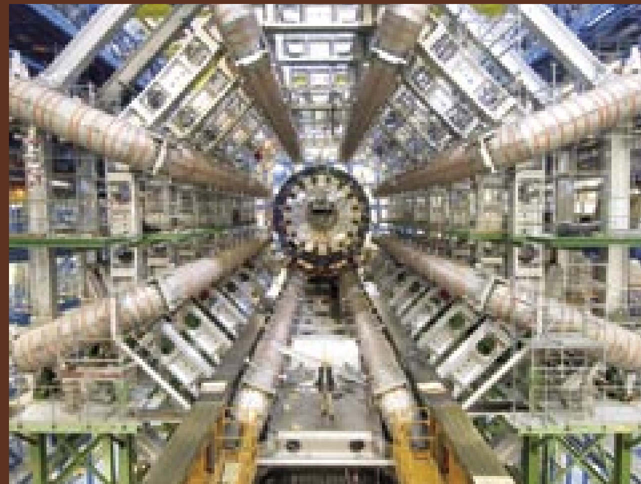
With their enthusiasm for and devotion to some of the great scientific questions of our time, LHC experimenters will be ready to squeeze every last piece of science from the technological marvels they have created.

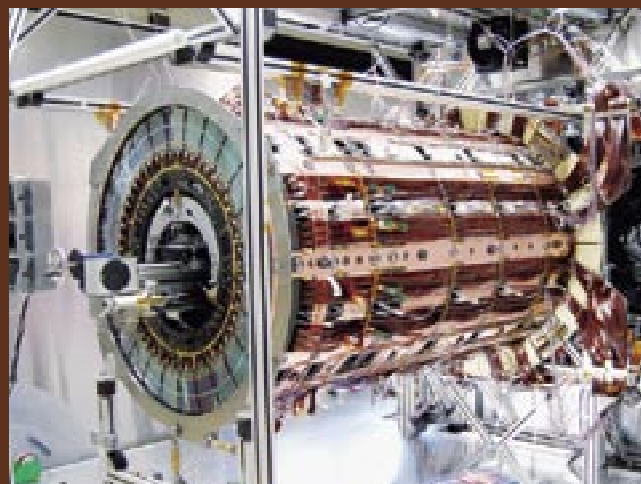


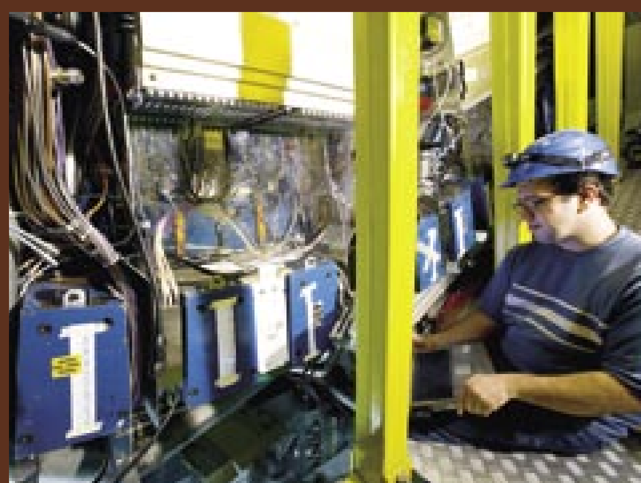
ALICE

The ALICE experiment at the LHC will study lead-ion collisions, which recreate the conditions of the early universe a very short time after the big bang. To build the detector, the ALICE collaboration reuses the huge magnet (top photo) of the L3 experiment, which took data in this cavern using the now-disassembled Large Electron-Positron collider. The center piece of the ALICE detector is its Time Projection Chamber (middle). This detector subsystem, the largest of its kind in the world, will provide the experiment with the capability to map and disentangle the tracks made by thousands of particles emerging from each high-energy lead-lead collision. Other ALICE detector subsystems include a muon spectrometer. In connection with the strong magnetic field created by a special set of coils (bottom), the spectrometer helps to reconstruct the tracks of particles that decay into muons while traversing the detector.

Photos: CERN







ATLAS

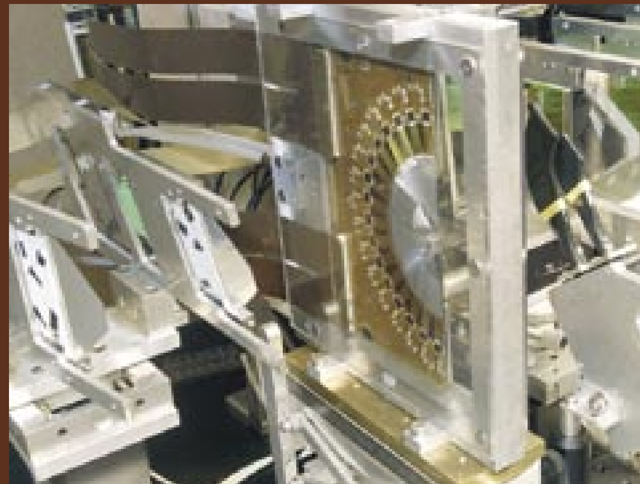
More than 1800 scientists are contributing to the construction of the ATLAS detector, which is larger than a five-story house. The collaboration builds its detector around an enormous toroidal magnet system, which consists of eight race-track-shaped superconducting magnet coils, each 25 meters long (top photo). These magnets help to determine the charge and energy of muons, which can traverse the entire detector. At the heart of the ATLAS detector sits a silicon vertex detector (middle). It determines the tracks of charged particles to a precision better than the width of a hair. Many other detection systems are needed to determine the charge, energy, and trajectories of the particles that emerge from the collisions at the center of the detector. Lots of electronics is necessary to identify and process the signals of these particles. Using a laptop, an ATLAS scientist checks the functionality of a detector component (bottom).

Photos: CERN, NIKHEF, Fermilab

CMS

The construction of the cavern for the CMS detector has been a spectacular feat of engineering. It took six-and-a-half years to build the 53-meter-long, 27-meter-wide, and 24-meter-high underground hall (top photo). The assembly of the 12,500-ton CMS detector proceeds in phases. Once all the parts are assembled in sections, the five slices of the detector (middle photo) will be joined together for final testing before the whole detector is lowered slice-by-slice into the underground hall for installation. The CMS hadronic calorimeter (bottom) is a massive brass structure that fits snuggly inside the CMS magnet. Its central part consists of brass plates held together by 80,000 bolts. Its end caps contain brass recovered from Russian artillery shells. The second step requires lowering the detector modules 90 meters underground for the complete assembly of the CMS detector in its final location.

Photos: CERN, Fermilab



LHCb

The LHCb detector will study matter-antimatter asymmetry by examining the behavior of particles containing bottom quarks and antiquarks. Rather than surrounding the entire collision point with particle detection systems, the high-precision instruments of LHCb are lined up one after the other over a length of 20 meters. They will catch particles that are emitted in about the direction of the incoming proton beam. Key components include the vertex locator (top), which tracks particles with a precision of 10 microns to identify their decays. A calorimeter (middle) measures the energy of the particles. The instrument consists of an iron structure interleaved with scintillating plastic plates, which light up when particles pass through them. The LHCb Ring Imaging Cherenkov detector system, which contains spherical high-precision mirrors, had to be assembled in a clean room (bottom). The mirrors will focus Cherenkov light, created by the charged particles passing through, onto a set of light-sensitive detectors.

Photos: CERN