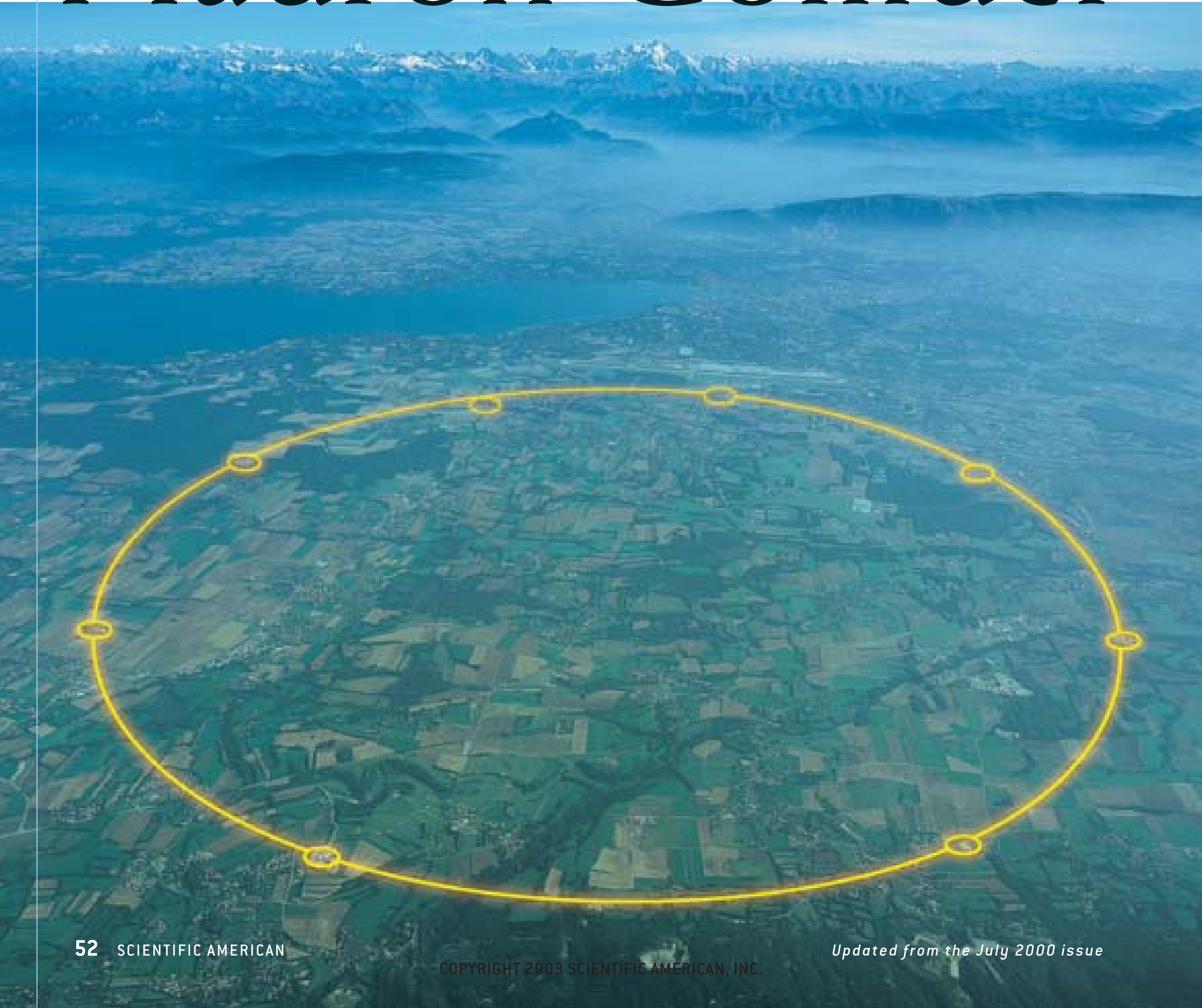
the Large Hadron Collider



Updated from the July 2000 issue

The Large Hadron Collider will be a particle accelerator of unprecedented energy and complexity, a global collaboration to uncover an exotic new layer of reality

By Chris Llewellyn Smith

When two protons traveling at 99.999999 percent of the speed of light collide head-on, the ensuing subatomic explosion provides nature with 14 trillion electron volts (TeV) of energy to play with. This energy, equal to 14,000 times that stored in the mass of a proton at rest, is shared among the smaller particles that make up each proton: quarks and the gluons that bind them together. In most collisions the energy is squandered when the individual quarks and gluons strike only glancing blows, setting off a tangential spray of familiar particles that physicists have long since catalogued and analyzed. On occasion, however, two of the quarks will themselves collide head-on with an energy as high as 2 TeV or more. Physicists are sure that nature has new tricks up her sleeve that must be revealed in those collisions—perhaps an exotic particle known as the Higgs boson, perhaps evidence of a miraculous effect called supersymmetry, or perhaps something unexpected that will turn theoretical particle physics on its head.

The last time that such violent collisions of quarks occurred in large numbers was billions of years ago, during the first picosecond of the big bang. They will start occurring again in 2007, in a circular tunnel under the Franco-Swiss countryside near Geneva. That's when thousands of scientists and engineers from dozens of countries expect to finish building the giant detectors for the Large Hadron Collider (LHC) and start experiments. This vast and technologically challenging project, coordinated by CERN (the European laboratory for particle physics), which is taking the major responsibility for constructing the accelerator, is already well under way.

The LHC will have about seven times the energy of the Tevatron collider based at Fermi National Accelerator Laboratory in Batavia, Ill., which discovered the long-sought "top" quark in experiments spanning from 1992 to 1995. The LHC will achieve its unprecedented energies despite being built within the confines of an existing 27-kilometer tunnel. That tunnel housed CERN's Large Electron-Positron Collider (LEP), which operated from 1989 to 2000 and was used to carry out precision tests of particle physics theory at about 1 percent of the LHC's energy. By using LEP's tunnel, the LHC avoids the problems and vast expense of siting and building a new, larger tunnel and constructing four smaller "injector" accelerators and supporting facilities. But bending the trajectories of the 7-TeV proton beams around the old tunnel's curves will require magnetic fields stronger than those any accelerator has used before. Those fields will be produced by 1,232 15-meter-long magnets installed around 85 percent of the tunnel's circumference. The magnets will be powered by superconducting cables carrying currents of 12,000 amps cooled by superfluid helium to –271 degrees Celsius, two degrees above the absolute zero of temperature.

STRADDLING THE FRANCO-SWISS BORDER, the location of the 27-kilometer tunnel that will house the Large Hadron Collider (LHC) 100 meters below the ground is indicated in gold. Smaller circles mark the positions of caverns that house detectors or ancillary equipment.

CERN

SUPERCONDUCTING MAGNET test string is laid out in the assembly hall; 1,232 large magnets will bend the trajectory of the two proton beams to follow the curve of the accelerator's tunnel.

To carry out productive physics experiments, one needs more than just high-energy protons. What counts is the energy of collisions between the protons' constituent quarks and gluons, which share a proton's energy in a fluctuating manner. The LHC will collide beams of protons of unprecedented intensity to increase the number of rare collisions between quarks and gluons carrying unusually large fractions of their parent protons' energy. The LHC's intensity, or luminosity, will be 100 times as great as that of previous colliders and 10 times that of the canceled Superconducting Super Collider (SSC). The SSC would have been a direct competitor to the LHC, colliding 20-TeV proton beams in an 87-kilometer-circumference tunnel around Waxahachie, Tex. The LHC's higher intensity will mostly compensate for the lower beam energy, but it will make the experiments much harder. Furthermore, such large intensities can provoke problems, such as chaos in the beam orbits, that must be overcome to keep the beams stable and well focused.

At four locations around the LHC's ring, a billion collisions will occur each second, each one producing about 100 secondary particles. Enormous detectors—the largest roughly the height of a six-story building—packed with thousands of sophisticated components will track all this debris. Elaborate computer algorithms will have to sift through this avalanche of data in real time to decide which cases (perhaps 10 to 100 per second) appear worthy of being recorded for full analysis later, off-line.

Unanswered Questions

AS WE STUDY nature with higher-energy probes, we are delving into the structure of matter at ever smaller scales. Experiments at existing accelerators have explored down to one billionth of one billionth of a meter (10^{-18} meter). The LHC's projectiles will penetrate even deeper into the heart of matter, down to 10^{-19} meter. This alone would be enough to whet scientific appetites, but pulses are really set racing by compelling arguments that the answers to major questions must lie in this new domain.

In the past 35 years, particle physicists have established a relatively compact picture—the Standard Model—that successfully describes the structure of matter down to 10^{-18} meter. The Standard Model [*see box on page 57*] succinctly characterizes all the known constituents of matter and three of the four forces that control their behavior. The constituents of matter are six particles called leptons and six called quarks. One of the forces, known as the strong force, acts on quarks, binding them together to form hundreds of particles known as hadrons. The proton and the neutron are hadrons, and a residual effect of the strong force binds them together to form atomic nuclei. The other two forces are electromagnetism and the weak force, which operates only at very short range but is responsible for radioactive beta decay and is essential for the sun's fuel cycle. The Standard Model elegantly accounts for these two forces as a "unified" electroweak force, which relates their properties despite their appearing very different.

More than 20 physicists have won Nobel Prizes for work that has contributed to the Standard Model, from the theory of quantum electrodynamics (the 1965 prize) to the discovery of the neutrino and the tau particle (1995) and the theoretical work of Gerardus 't Hooft and Martinus J. G. Veltman while at the University of Utrecht (1999). Nevertheless, although it is a great scientific achievement, confirmed by a plethora of detailed experiments, the Standard Model has a number of serious flaws.

First, it does not consistently include Albert Einstein's theory of the properties of spacetime and its interaction with matter. This theory, general relativity, provides a beautiful, experimentally very well verified description of the fourth force, gravity. The difficulty is that unlike general relativity, the Standard Model is a fully quantum-mechanical theory, and its predictions must therefore break down at very small scales (very far from the domain in which it has been tested). The absence of a quantum-mechanical description of gravity renders the Standard Model logically incomplete.

Second, although it successfully describes a huge range of data with simple underlying equations, the Standard Model contains many apparently arbitrary features. It is too byzantine to be the full story. For example, it does not indicate why there are six quarks and six leptons instead of, say, four. Nor does it explain why there are equal numbers of leptons and quarks—is this just a coincidence? On paper, we can construct theories that explain why there are deep connections between quarks and leptons, but we do not know if any of these theories is correct.

Third, the Standard Model has an unfinished, untested element. This is not some minor detail but a central component: a mechanism to generate the observed masses of the particles. Particle

THE AUTHOR

CHRIS LLEWELLYN SMITH is a senior research fellow in the physics department of the University of Oxford. He served as president and provost of University College London from 1999 to 2002. He spent periods at the Lebedev Institute in Moscow, at CERN near Geneva and at the Stanford Linear Accelerator Center in California before returning to Oxford for most of his career as a theoretical physicist. His 1994–98 term as director general of CERN saw the approval of the Large Hadron Collider project and the negotiation of new relations with nonmember countries, including Japan and the U.S., that will participate in the project.

LAURENT GUIRAUD *CERN*

masses are profoundly important—altering the mass of the electron, for example, would change all of chemistry, and the masses of neutrinos affect the expansion of the universe. (A neutrino's mass is at most a few millionths of an electron's mass, but recent experiments show that it is not zero. The scientists who led two pioneering experiments that made this discovery were awarded a share of the 2002 Nobel Prize for Physics.)

Higgs Mechanism

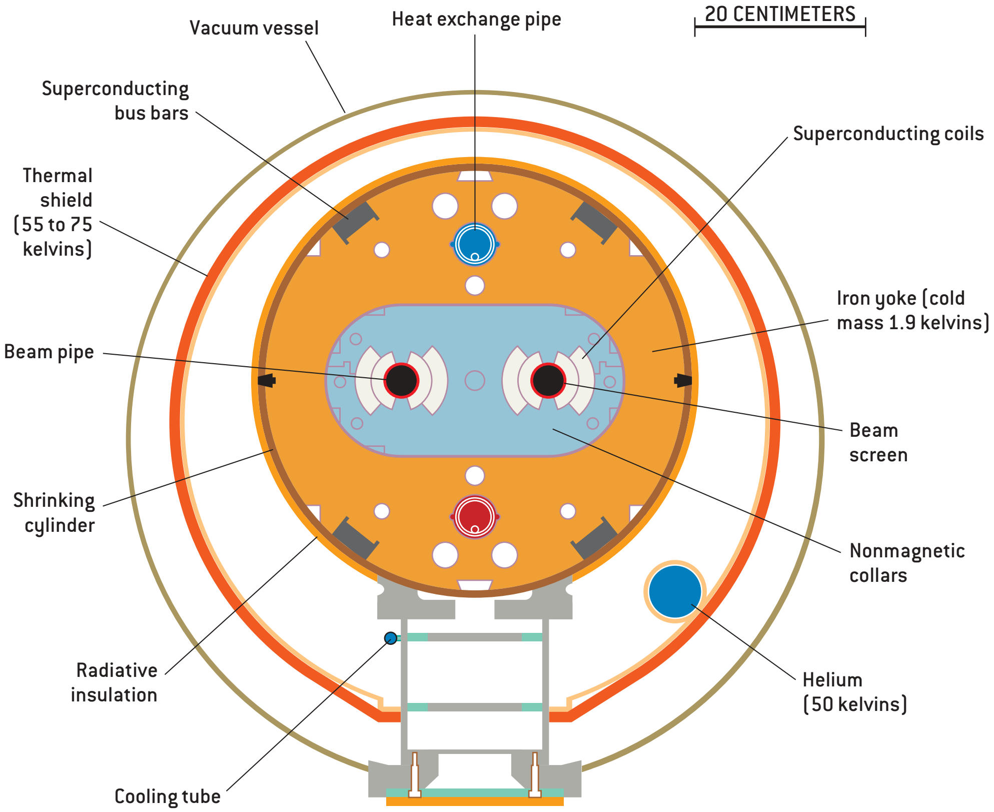
PHYSICISTS BELIEVE that particle masses are generated by interactions with a field that permeates the entire universe; the stronger a particle interacts with the field, the more massive it is [*see illustration on page 59*]. The nature of this field, however, remains unknown. It could be a new elementary field, called the Higgs field after British physicist Peter Higgs. Alternatively, it may be a composite object, made of new particles ("techniquarks") tightly bound together by a new force ("technicolor"). Even if it is an elementary field, there are many variations on the Higgs theme: How many Higgs fields are there, and what are their detailed properties?

Nevertheless, we know with virtually mathematical certainty that *whatever* mechanism is responsible, it must produce new phenomena in the LHC's energy range, such as observable Higgs particles (which would be a manifestation of ripples in the underlying field) or techniparticles. The principal design goal of the LHC is therefore to discover these phenomena and pin down the nature of the mass-generating mechanism.

The LHC experiments will also be sensitive to other new phenomena that could confirm one or another of the speculative theories that extend or complete the Standard Model. For example, it is widely thought that the more complete theory must incorporate a "super" symmetry. Supersymmetry would greatly increase the web of relations among the elementary particles and forces. Furthermore, so-called local supersymmetry automatically includes gravity; conversely, the only known theory (string theory) that could successfully combine general relativity and quantum mechanics requires supersymmetry. If supersymmetry is correct, physicists have very good reason to believe that the LHC can find the new particles that it predicts.

These new phenomena may be discovered before the LHC comes into operation by experiments at Fermilab's Tevatron, which started colliding beams of protons and antiprotons again in 2001 after a major upgrade. These experiments could find new phenomena beyond the range already explored by LEP. But even if they do "scoop" the LHC, they will reveal only the tip of a new iceberg, and the LHC will be where physicists make comprehensive studies of the new processes.

If the Tevatron does not observe these new phenomena, then the LHC will pick up the chase. The exploratory power of the LHC overlaps that of LEP and the Tevatron, leaving no gaps in which new physics could hide. Moreover, high-precision measurements made in the past decade at LEP, the Stanford Linear Accelerator Center and Fermilab have



ACCELERATOR MAGNET is shown in cross section. The superconducting coils carry 12,000 amps of current and must be kept cooled to below two kelvins. Each beam pipe carries one of the two countermoving proton beams. Other magnets focus the beams and bend them to cross at collision points within the detectors.

SLIM FILMS

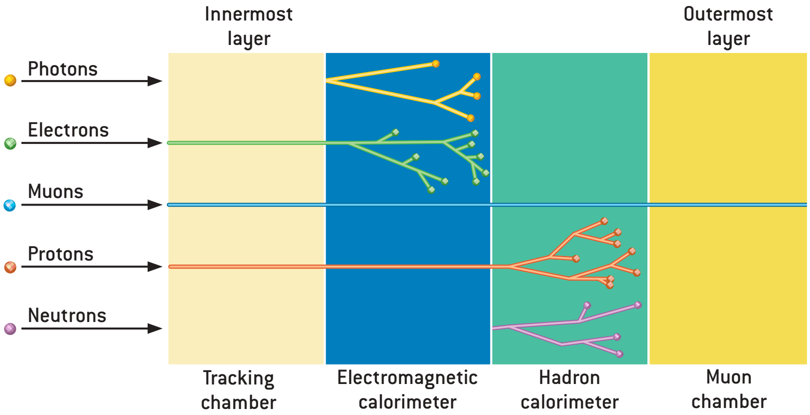
essentially eliminated worries that the Higgs boson might be out of reach of the LHC's energy range. It is now clear that either the Higgs boson or other new physics associated with the generation of mass will be found at the LHC.

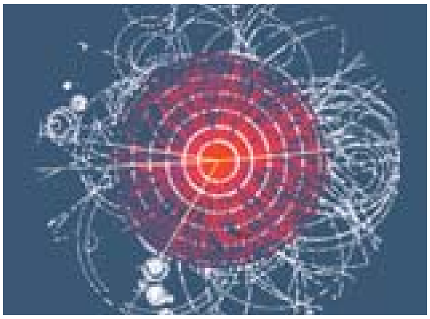
Emulating the Big Bang

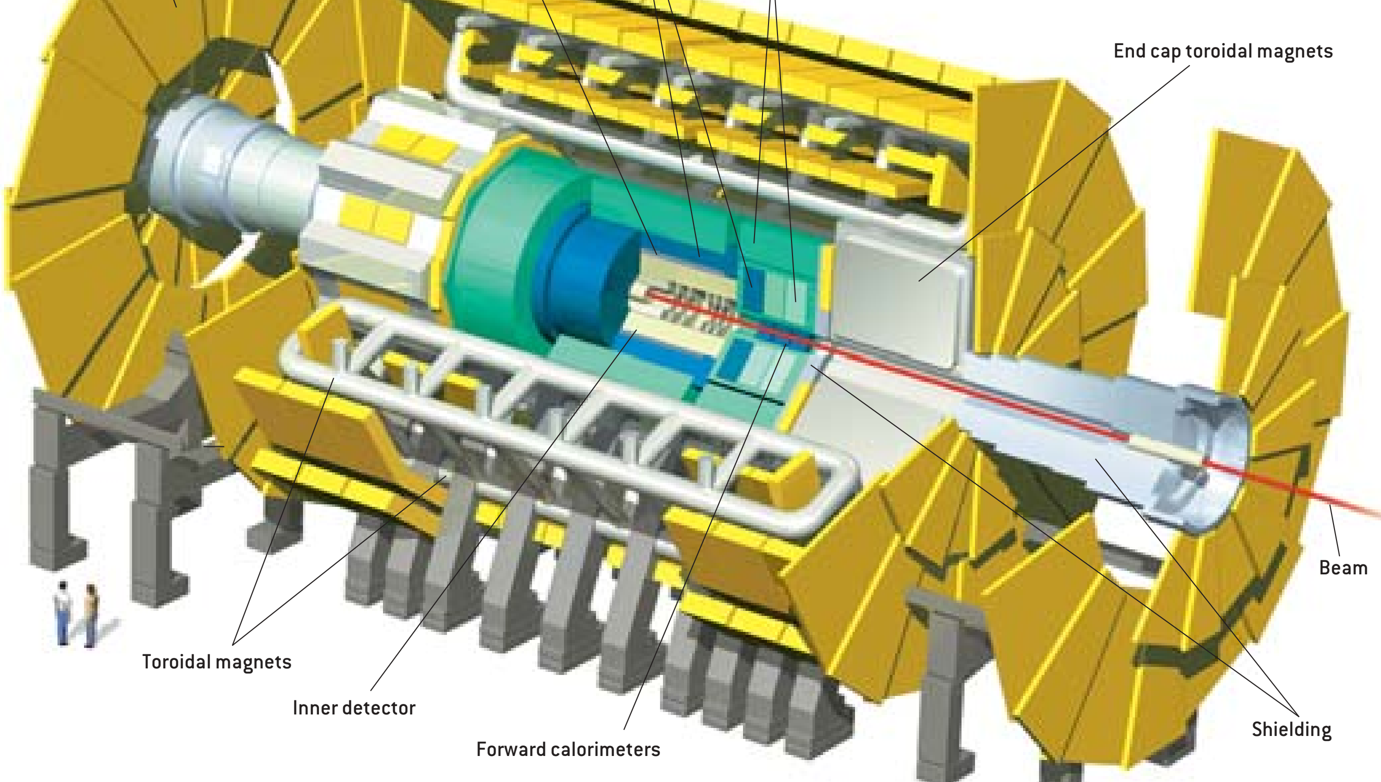
TO ADDRESS THIS kind of physics requires re-creating conditions that existed just a trillionth of a second after the big bang, a task that will push modern technologies to their limits and beyond. To hold the 7-TeV proton beams on course, magnets must sustain a magnetic field of 8.3 tesla, almost 100,000 times the earth's magnetic field and the highest ever used in an accelerator. They will rely on superconductivity: large currents flowing without resistance through thin superconducting wires, resulting in compact magnets that can generate magnetic-field strengths unobtainable with conventional magnets made with copper wires [*see illustration on preceding page*]. To maintain the superconductivity under operating conditions—with 12,000 amps of current—the magnets' cores must be held at –271 degrees C around 22.4 kilometers of the tunnel. Cryogenics on this scale has never before been attempted.

In December 1994 a full prototype section of the LHC was operated for 24

A TOROIDAL LHC APPARATUS (ATLAS) detector (*bottom*) uses a novel toroidal magnet system. Protons collide in the center, producing a spray of particles. The concentric layers of ATLAS detect different species of particles, some precisely tracking the particle trajectories, others ("calorimeters") measuring the energy carried. The simplified diagram (*below, left*) illustrates how such layers work. The toroidal magnets curve the tracks of charged particles, allowing their momenta to be measured. The image (*below, right*) shows simulated data of a collision in which a Higgs particle decays into four muons (*yellow tracks*).







SLIM FILMS (*bottom* and *top left*); CERN (*top right*)

hours, demonstrating that the key technical choices for the magnets are correct. Since then, tests on prototypes have simulated about 10 years of running the LHC. Magnets that surpass the design criteria are now being produced in industry and delivered to CERN for final testing and subsequent installation.

With the 1993 demise of the planned 40-TeV SSC, the 14-TeV LHC became the only accelerator project in the world that can support a diverse research program at the high-energy frontier. The LHC's intense beams present those designing the experiments with remarkable challenges of data acquisition. The beams will consist of proton bunches strung like beads on a chain, 25 billionths of a second apart. At each collision point, pairs of these bunches will sweep through each other 40 million times a second, each time producing about 20 proton-proton collisions. Collisions will happen so often that particles from one collision will still be flying through the detectors when the next one occurs!

Of these 800 million collisions a second, only about one in a billion will involve a head-on quark collision. To keep up with this furious pace, information from the detector will go into electronic pipelines that are long enough to hold the data from a few thousand collisions. This will give "downstream" electronics enough time to decide whether a collision is interesting and should be recorded before the data reach the end of the pipeline and are lost. LHC detectors will have tens of millions of readout channels. Matching up all the pipelined signals that originate from the same proton-proton collision will be a mind-boggling task.

When Quarks Collide

PARTICLE DETECTORS are the physicists' electronic eyes, diligently watching each collision for signs of interesting events. LHC will have four particle detectors. Two will be giants, each built like a Russian *matryoshka* doll, with modules fitting snugly inside modules and a beam collision point at the center. Each module, packed with state-of-the-art technology, is custom-built to perform specific observations before the particles fly out to the next layer. These general-purpose detectors, ATLAS and CMS, standing up to 22 meters high, will look for Higgs particles and supersymmetry and will be on the alert for the unexpected, recording as much as possible of the collision debris. Two smaller detectors, ALICE and LHCb, will concentrate on different specific areas of physics.

Both ATLAS and CMS are optimized to detect energetic muons, electrons and photons, whose presence could signal the production of new particles, including Higgs bosons. Yet they follow very different strategies. Years of computer simulations of their performance have shown that they are capable of detecting whatever new phenomena nature may exhibit. ATLAS (*a t*oroidal *LHC a*pparatu*s*) is based on an enormous toroidal magnet equipped with detectors designed to identify muons in air [*see illustration on opposite page*]. CMS (*c*ompact *m*uon *s*olenoid) follows the more traditional approach of using chambers inside the return yoke of a very powerful solenoidal magnet to detect muons [*see illustration on next page*].

Part of the CMS detector will consist of crystals that glow, or scintillate, when electrons and photons enter them. Such crystals are extremely difficult to make, and CMS benefits from the experience gained from a recent CERN experiment, L3, which also used crystals. (The L3 detector was one of four that operated from

THE STANDARD MODEL

THE STANDARD MODEL of particle physics encompasses our knowledge of the fundamental particles. It contains particles of matter and particles that transmit forces. For example, the electromagnetic force between a proton and an electron is generated by photons (particles of light) being passed back and forth between them.

The matter particles come in three families of four, each family differing only by mass. All the matter around us is made of particles from the lightest family. These are "up" quarks, "down" quarks, electrons and electron-neutrinos. The other two families of matter particles exist only ephemerally after being created in high-energy collisions (neutrinos, however, are long-lived).

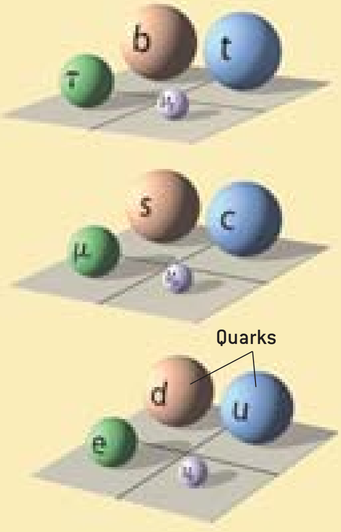
The quarks are stuck together by the strong force, carried by gluons, to form hadrons, which include the protons and neutrons that make atomic nuclei. Electrons, attracted to these nuclei by the electromagnetic force, orbit nuclei to form atoms and molecules. The weak interaction, carried by the *W* and *Z* particles, helps to fuel the sun and is responsible when an atomic nucleus decays and emits an electron and a neutrino.

Gravity, the weakest force, is most familiar to us because it acts on mass. Particles called gravitons are assumed to carry gravity, but they have not been detected, because the force is so weak. Also, gravitons are not yet properly incorporated into the Standard Model.

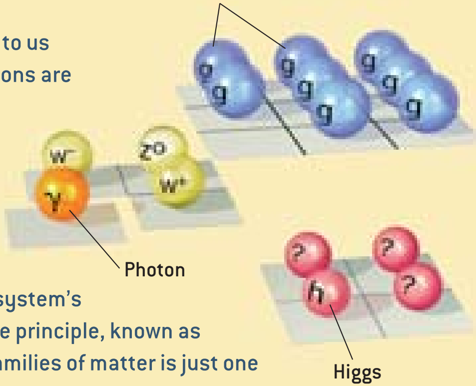
The entire system of matter and forces (except gravity) is encapsulated in a few simple equations derived from a function (the system's "Lagrangian") that is organized around one core principle, known as local gauge symmetry. Why nature has three families of matter is just one of many questions unanswered by the Standard Model. Considered one of the great intellectual triumphs of 20th-century science, the Standard Model can only be a stepping-stone to a more complete description of nature's forces.

—Graham P. Collins, staff writer

FERMIONS (MATTER)

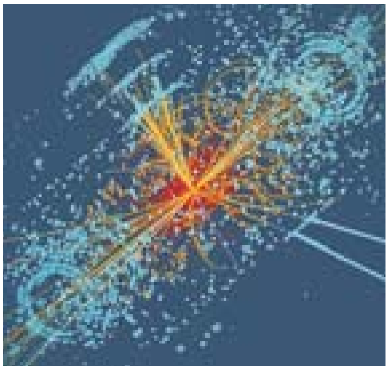


BOSONS (FORCES)



SLIM FILMS

1989 to 2000 at the LEP collider, performing precision studies of the weak force that told us that exactly three types of zero- or low-mass neutrino exist.) Before L3, such crystals had been made only in small quantities, but L3 needed 11,000 of them. Crystals of the type developed for L3 have been widely used in medical imaging devices. CMS needs more than seven times as many crystals made of a more robust material. In due course the superior CMS crystals are likely to have an even bigger effect on the medical field.

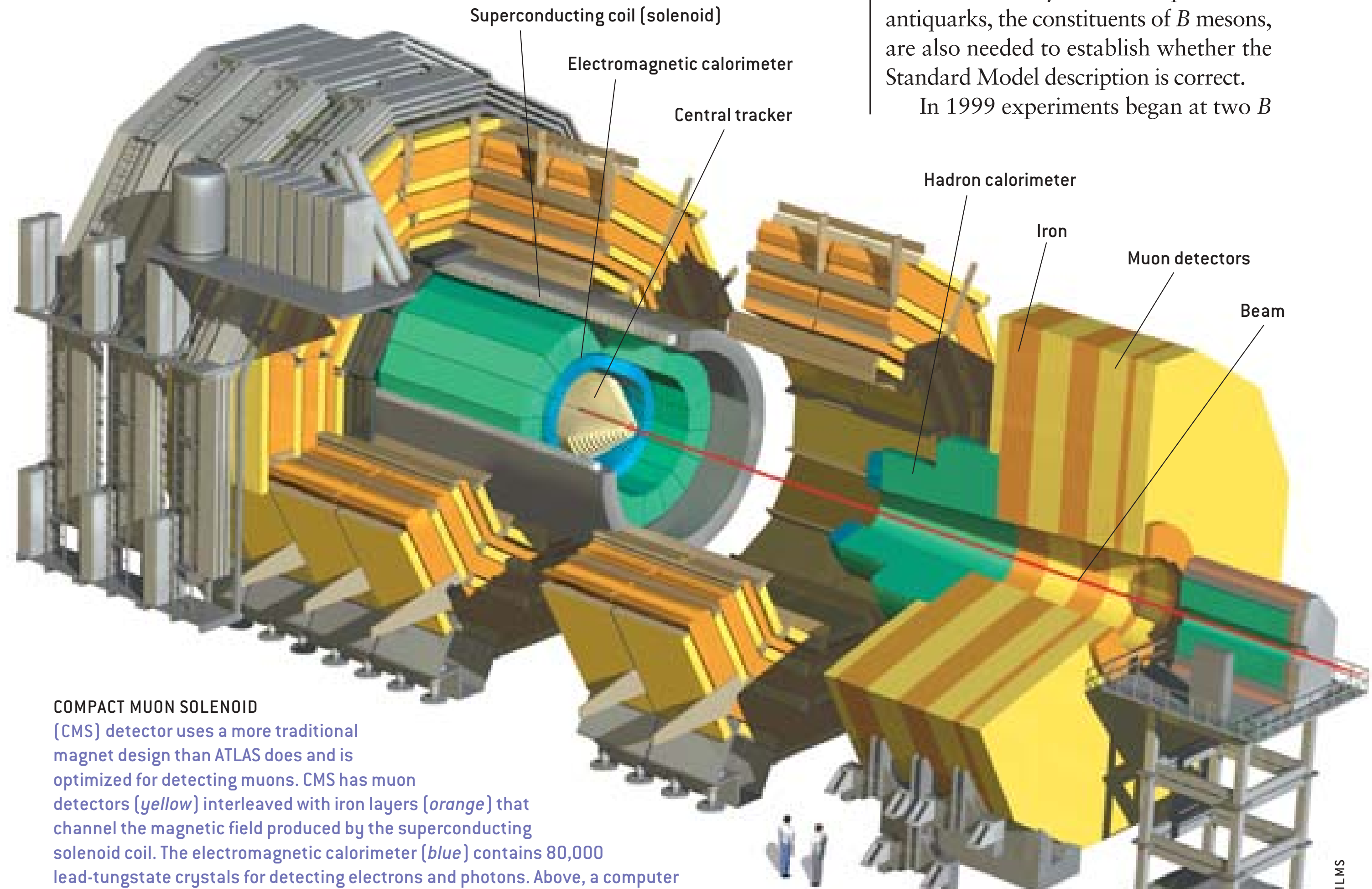

CERN

ALICE (*a* *l*arge *i*on *c*ollider *e*xperiment) is a more specialized experiment that will come into its own when the LHC collides nuclei of lead with the colossal energy of 1,150 TeV. That energy is expected to "melt" the more than 400 protons and neutrons in the colliding nuclei, releasing their quarks and gluons to form a globule of quark-gluon plasma (QGP), which dominated the universe about 10 microseconds after the big bang. ALICE is based around the magnet of the L3 experiment, with new detectors optimized for QGP studies.

There is good evidence that experiments at CERN have already created a quark-gluon plasma. Over the coming years, Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) has a good chance of studying QGP in detail by packing 10 times more energy per nucleon into its collisions than CERN does. The LHC will extend this by a further factor of 30. The higher energy at the LHC will complement the more varied range of experiments at RHIC, guaranteeing a thorough study of an important phase in the universe's early evolution.

B mesons, the subject of LHCb's investigations, could help tell us why the universe is made of matter instead of equal amounts of matter and antimatter. Such an imbalance can arise only if heavy quarks and antiquarks decay into their lighter cousins at different rates. The Standard Model can accommodate this phenomenon, called CP violation, but probably not enough of it to account completely for the dominance of matter in the universe. Physicists observed CP violation in the decay of strange quarks in the 1960s, but data on heavy "bottom" quarks and antiquarks, the constituents of *B* mesons, are also needed to establish whether the Standard Model description is correct.

In 1999 experiments began at two *B*



COMPACT MUON SOLENOID (CMS) detector uses a more traditional magnet design than ATLAS does and is optimized for detecting muons. CMS has muon detectors (*yellow*) interleaved with iron layers (*orange*) that channel the magnetic field produced by the superconducting solenoid coil. The electromagnetic calorimeter (*blue*) contains 80,000 lead-tungstate crystals for detecting electrons and photons. Above, a computer simulation shows a collision in which a Higgs particle decays into two muons (the tracks at about "4 o'clock") and two jets of hadrons (at about "11 o'clock").

SLIM FILMS

HOW THE HIGGS FIELD GENERATES MASS

“Empty” space, which is filled with the Higgs field, is like a roomful of people chatting quietly.

A particle crossing that region of space is like a celebrity arriving …

… and attracting a cluster of admirers who impede his progress—he acquires “mass.”

HOW HIGGS PARTICLES ARE CREATED

Energy from a particle collision can be like a rumor crossing the room …

… creating a similar cluster that is self-sustaining, analogous to a Higgs particle itself.

GEORGES BOIXADER *CERN*

factories in California and Japan that can produce tens of millions of *B* mesons a year. These experiments have observed the CP violation predicted by the Standard Model in one *B* meson decay mode. The high luminosity of the LHC beams can churn out a *trillion B* mesons a year for LHCb. This will allow much higher precision studies in a wider variety of circumstances and perhaps uncover crucial exotic decay modes too rare for the other factories to see clearly.

A Laboratory for the World

SCIENTIFIC EXPERIMENTS as ambitious as the LHC project are too expensive to be palatable for any one country. Of course, international collaboration has always played a role in particle physics, scientists being attracted to the facilities best suited to their research interests, wherever situated. As detectors have become larger and costlier, the size and geographic spread of the collaborations that built them have grown correspondingly. (It was the need to facilitate communication between the LEP collaborations that stimulated the invention of the World Wide Web by Tim Berners-Lee at CERN.)

The LHC accelerator originally had funding only from CERN’s (then) 19 European member states, with construction to occur in two phases on a painfully slow timetable—a poor plan scientifically and more expensive in toto than a faster, single-phase development. Fortunately, additional funds from other countries (which will provide some 40 percent of the LHC’s users) will speed up the project. Contributions of money or labor have been agreed to by Canada, India, Israel, Japan, Russia and the U.S. For example, Japan’s KEK laboratory will supply 16 special focusing magnets. The U.S., with more than 550 scientists already involved, will furnish the largest national group; accelerator components will be designed and fabricated by Brookhaven, Fermilab and Lawrence Berkeley National Laboratory.

Furthermore, 5,000 scientists and engineers in more than 300 universities and research institutes in 50 countries on six continents are building the ATLAS and CMS detectors. When possible, components will be built in the participating institutions, close to students (who get great training by working on such projects) and in collaboration with local industries. The data analysis will also be dispersed. It will be a formidable challenge to manage these projects, with their stringent technical requirements and tight schedules, while maintaining the democracy and freedom for scientific initiatives that are essential for research to flourish.

Until now, CERN has been primarily a European laboratory. With the LHC, it is set to become a laboratory for the world. Already its 7,000 scientific users amount to more than half the world’s experimental particle physicists. In 1994 John Peoples, Jr., then director of Fermilab, summed it up nicely: “For 40 years, CERN has given the world a living demonstration of the power of international cooperation for the advancement of human knowledge. May CERN’s next 40 years bring not only new understanding of our Universe, but new levels of understanding among nations.” SA

MORE TO EXPLORE

The Particle Century. Edited by Gordon Fraser. Institute of Physics, 1998.

Supersymmetry. Gordon Kane. Perseus Publishing, 2000.

Links to home pages for all four LHC experiments are on the CERN Web site at **www.cern.ch/CERN/Experiments.html**

Two other excellent sites are **http://pdg.lbl.gov/atlas/atlas.html** and **www.particleadventure.org**