

*Straddling the border between Switzerland and France, an immense particle collider, nearly 30 kilometres long, will soon make Europe the world leader in physics research.*



Aerial view of CERN site and the surrounding region in May 1991, with Lake Geneva in the background. The smallest white ring shows the underground position of the PS (Proton Synchrotron) tunnel, which went into operation in 1959. The middle ring indicates the SPS (Super Proton Synchrotron) tunnel, with a circumference of 7 kilometres, which entered service in 1976. The largest ring (27 kilometres) marks the LEP (Large Electron-Positron) tunnel, built in the 1980s and now being used to house the Large Hadron Collider.

LISA RANDALL

## Smashing Open the Universe

*Next year, some of the great questions that have puzzled physicists for centuries may begin to be answered. What happened at the birth of our universe? Why are the natural world's forces so different – from our exceedingly weak gravity to the immensely powerful nuclear forces? Are universes always three-dimensional? The unravelling of these tantalizing mysteries may well make physics front-page news in 2007.*

**N**EXT YEAR, we might be forced to revise radically our ideas about the underlying nature of matter and our conception of the universe. In 2007, the Large Hadron Collider (LHC) will begin operating at CERN (the European Organization for Nuclear Research) near Geneva, boosting particles to energy levels that have never before been produced on earth. Physicists will then combine results from the LHC experiments with insights from their theoretical investigations to explore phenomena whose effects are only detectable at small distances and high energies.

The theory known as the Standard Model of particle physics describes all known matter and the forces through which it interacts. Experiments have thoroughly tested the Standard Model, and its basic ingredients are almost certainly correct. But the Standard Model cannot be the final word: it leaves open important questions about the origin of elementary particle masses and puzzles such as the relative weakness of gravity. The LHC will help to resolve these mysteries, and scientists all over the globe are busily preparing experiments. Perhaps the most exciting proposal for extending and completing the Standard

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The huge calorimeter assembly of the ATLAS experiment detector, with technicians perched on its scaffolding, July 2006. Photo: Claudia Marcelloni.

Model involves additional hidden dimensions of space beyond the three dimensions with which we are all familiar: up-down, left-right, and forward-backward. As a theoretical physicist working on extra dimensions, I look to LHC experiments to guide my future investigations and my views about the universe.

The premise underlying particle physics is that elementary particles constitute the building blocks of matter. Peel away the layers, and inside you will always ultimately find elementary particles. Because of Einstein's  $E=mc^2$  equation, which states that energy ( $E$ ) is equal to mass ( $m$ ) multiplied by the square of the speed of light ( $c$ ), we need high energies to create particles with big masses. The LHC will produce enormous amounts of energy that can then be converted into particles we would never find in any other way. But matter is not a Russian doll, with the same elements repeated on smaller scales. At smaller distances, it is not only new elements of matter that should reveal themselves but new physical laws too.

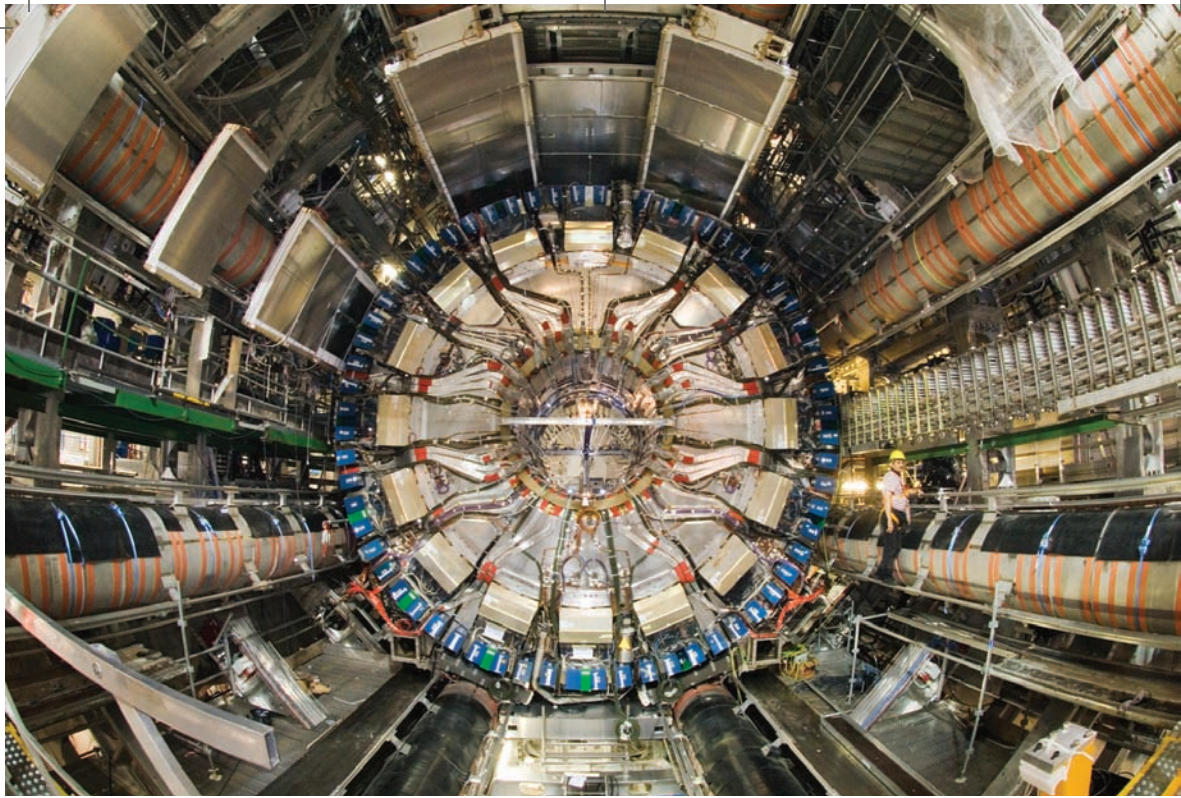
Admittedly, the experimental evidence for new phenomena that the LHC will provide will be somewhat indirect. But that is true of almost all recent discoveries in physics. As physics evolved in the twentieth century, it moved away from things that can be directly observed to things that can be “seen” only through measurements coupled with a train of theory.

For example, quarks – components of the proton and neutron that underlie the secondary school picture of the atom – never appear in isolation. We find them by following the trail of evidence they leave behind as they influence other particles. It is the same with the intriguing kinds of stuff known as dark energy and dark matter. We don’t know where most of the energy in the universe comes from, or the nature of most of the matter that the universe contains. Yet we know that dark matter and dark energy exist because they have effects on surrounding matter. We only “see” dark energy through the accelerating rate of expansion of the universe and through its influence on the universe’s cosmological background radiation.

We can indirectly discover these exotic phenomena because the laws of physics we know about apply over an enormous range. A proton or neutron inside an atom is about  $10^{-13}$  cm (a tenth of a thousandth of a billionth of a centimetre) in size. On the other hand, the visible universe is  $10^{28}$  cm (ten thousand trillion trillion centimetres) large.

Physical theories work over such an enormous range because, at any given scale, details that are too small to be measured can be ignored. Scientists often average over or ignore physical processes that occur on immeasurably small scales when formulating their theories or setting up their calculations. When you are exploring large scales, short-distance physical effects wash out, in much the same way that the detailed city grid is irrelevant to planning your route for a cross-country journey. In fact, it is essential to the way we do physics that we can neglect unmeasurable or irrelevant small-scale effects. Underlying structure is essentially invisible at lower energies. Quantum mechanics and the uncertainty principle tell us that we can only study very short distances by exploring very high energies. That is why we need particle colliders: only they can create the energies to study the small scales at which new phenomena should be revealed.

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The calorimeter insertion between toroids in the ATLAS experiment detector, July 2006. The technician standing to the right gives a sense of the scale and complexity of the equipment being assembled at CERN. Photo: Claudia Marcelloni.

## Particle Accelerators and Colliders

**F**OR the last 50 years, the most important experiments for probing matter's underlying nature have taken place in particle accelerators, in which particles are boosted to high energies through acceleration in a magnetic field, and then smashed into other matter. Such accelerator experiments have discovered quarks, among other things.

A particle accelerator is an elaborate construction. Electromagnetic fields accelerate particles around a vacuum chamber, which is a metal pipe with extremely low pressure located in a tunnel at least 50 metres underground. Amplifiers provide radio waves that are fed into resonating structures known as radio-frequency cavities. As particles pass through these cavities, they absorb some of the energy of the radio wave. The vacuum chambers (and the tunnels that enclose

them) are circular so that the particle beams can go through the same chambers many times. Magnetic fields accelerate the particle beams as they travel around this circular ring.

Because you need larger magnetic fields for more energetic particles, one of the chief technological challenges for the LHC was designing superconducting magnets that would work at LHC energies (superconductivity happens at very cold temperatures when all electrical resistance in conducting materials vanishes). In March 2005, the first of the 15-metre long, 35-tonne superconducting dipole magnets was installed in the tunnel, and half of the 1,232 magnets that will eventually be placed there were delivered. Over the next year, the remaining magnets will be put in place so that the machine will be ready to begin operating in 2007.

Particle accelerators create the most energy by bombarding two particle beams directly into each other: accelerators that do this are called colliders. In high-energy colliders, additional magnets focus two accelerated beams of particles into a small collision region. In the collision, particles annihilate each other and turn into a huge amount of energy. The energy that is created in the collision can be converted into heavy particles. These colliders are the only known places in which the heaviest known particles have appeared since the Big Bang, when the much hotter universe contained all particles in abundance. Important collider discoveries include the two heaviest known quarks, which were discovered at the Tevatron – a collider based in Batavia, Illinois – in 1977 and 1995, and the three force-communicating analogues of the photon that transmit the weak nuclear force, discovered in Geneva in 1983.

But the most exciting collider experiments will begin in 2007 at the LHC, where two beams of highly energetic protons will be collided together, with at least seven times the energy we have ever before produced. The LHC experiments will, among other things, try to explain the origin of elementary particles' masses. One explanation involves a hypothetical particle called the Higgs boson. The idea is that particles acquire mass through weak force interactions with a Higgs field that permeates space. According to this theory, particles that have the biggest interactions get the heaviest masses. If this Higgs field theory is right, the LHC will discover the particle it predicts – the Higgs boson. But a theory with a single Higgs boson is only one of many competing theories. In fact, the theory with a single Higgs boson is so problematic

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The Safety Team tests the fire extinguishing system in the CMS (Compact Muon Solenoid) underground cavern, 12 May 2006. Photo: Maximilien Brice.

that physicists are fairly certain that LHC energies will reveal even more exotic phenomena. Those phenomena could be evidence of “supersymmetry” – a hypothetical extension of the Standard Model and the symmetries of space and time in which every known particle has a heavier partner that has not yet been seen. The chief goal of LHC experiments will be to discover the Higgs boson, or whatever it is that serves its role.

The Large Hadron Collider – a hadron is a particle that experiences the strong nuclear force, like the proton and neutron – is presently taking shape at CERN. Founded in 1954, the laboratory was one of Europe’s first joint ventures. Its main site is located in the town of Meyrin, near Geneva. CERN is a truly international effort that now comprises 20 member states as well as many more with observer status.

The collider, which will cost around US\$5 billion to complete, will use the existing circular tunnel at CERN, where experiments to test the Standard Model have already been performed. The protons are accelerated around the circular tunnel, or ring, which has a circumference of 27 kilometres. (The ring has to be very big



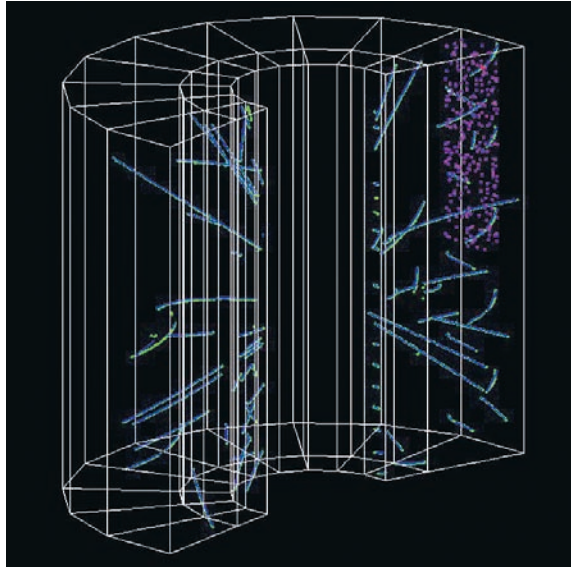
In less than two minutes the CMS cavern, 100 metres underground, is filled with 5,600 cubic metres of fire-suppressing foam. Photo: Maximilien Brice.

because protons accelerated in a smaller ring would lose too much energy to radiation.)

Because the energies of the colliding beams of protons will be much higher than ever before, collisions will occur far more frequently, leading to much more data. Exotic phenomena are more likely to be discovered if there are an enormous number of collisions.

Five separate LHC experiments will be carried out to detect the particles that proton collisions produce. The chief experiments investigating mass and the weakness of gravity are ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid). These will involve about 2,000 physicists from 35 countries.

The particle detectors, which monitor the results of the particle collisions, will be about the size of five-storey buildings. Working on the enormous detectors requires researchers to don climbing gear – safety harnesses and helmets (this equipment came in handy once when I went glacier-hiking close to CERN). Particles do not come with name tags: detectors must identify them by their distinguishing properties, such as their electric charge or the interactions in which they



The HLT (High Level Trigger) TPC (Time Projection Chamber) online display.

participate. This great number of properties requires a great number of components within the detector, which is built to capture a huge amount of information using its many sensors.

Once a detector registers a signal, it transmits it through an extensive array of wires and amplifiers, and records resulting data. Not everything that is detected is worth recording. The interesting particles are only rarely produced when protons collide, and not even CERN scientists can predict precisely when that will happen.

Reconstructing the result of a collision is a big task, one that has stretched people's ingenuity and is likely to lead to further data-processing advances in the years to come. In fact, once it is fully operational, the LHC will be the most data-intensive physics instrument in the world, producing more than 1,500 megabytes of data a second. These experiments, and this rate of acquiring information, should continue for at least ten years.

The need to process and share data from experiments like these has produced something all of us now use extensively: the World Wide Web. Tim Berners-Lee, a former CERN employee, came up with HTML (hypertext markup language) and HTTP (hypertext transfer protocol) so that experimenters across scattered nations could be instantly linked and data could be shared among many computers. The web is a notable example of the unforeseeable practical applications that can result from fundamental scientific research.

## What will we learn from the collider?

**T**HE LHC experiments should help to answer a number of questions. Why do we see the particular forces we see, and are there any more? What is the origin of the masses and properties of familiar particles, and why do those masses take the values that they do? And why is gravity so weak?

The fact that gravity is so much weaker than other forces is one of the central mysteries of particle physics. A tiny magnet can lift a paper clip, even though all the mass of the earth is pulling it in the opposite direction. Why is gravity so defenceless against the small tug of a tiny magnet?

My favourite explanation for this weakness is based on a theory my collaborators and I developed that assumes there is an additional dimension of space. Recent advances in physics suggest that extra dimensions, not yet experienced and not yet understood, might resolve some of the mysteries of our universe.

Within physics, one reason to consider extra dimensions is string theory, which postulates that particles are the oscillations of elementary strings. These strings – unlike, say, violin strings – are not made up of atoms, which are in turn made up of electrons and nucleons, which are in turn made up of quarks. Exactly the opposite is true. String theory's hypothesis is that the oscillation modes of strings correspond to particles. Each and every particle arises from the vibrations of fundamental underlying strings, and it is the character of that vibration that determines a particle's properties, such as mass and charge.

String theory was developed to address a famous disconnect between the physics of large and small scales. The development of quantum mechanics and general relativity at the beginning of the twentieth century meant we could understand both the physical laws inside the atom and the physical laws describing the expansion of the universe. Quantum mechanics works well on small scales and general relativity on large scales. But neither theory can be applied over all scales. String theory is the leading candidate for a theory that can consistently include them both.

Physicists still don't know whether string theory is right and, if it is, how it connects to our world. But a lot of research uses ideas from string theory to address questions about the observable universe.

For example, string theory does not naturally describe a world with three dimensions of space. It more naturally suggests a world with many more, perhaps nine or ten. String theorists do not ask whether extra dimensions exist; instead, they ask: “Where are they?” and “Why haven’t we seen them?” Not everyone is convinced by string theory, but recent research has provided a compelling argument for extra dimensions: a universe with these dimensions might contain answers to physics puzzles that have no convincing solutions without them.

My collaborator Raman Sundrum and I have shown why, in a world with one extra dimension of space, gravity would be so feeble. Our idea is based on “warped geometry,” a notion that arises from Einstein’s theory of general relativity. According to Einstein’s theory, space and time are integrated into a single spacetime fabric that gets distorted, or warped, by matter and energy. We applied this theory in an extra-dimensional context and found a configuration in which spacetime warps so severely that even if gravity were strong in one region of space, it would be feeble everywhere else. The universe of our proposal is in fact a multiverse, in which gravity is localized in one universe, and we are living in another universe, separated along a fourth spatial dimension.

## Extra dimensions and KK particles

EVIDENCE for our theory could include particles known as Kaluza-Klein (KK) particles, five-dimensional black holes and very light strings from string theory. KK particles travel in an extra dimension, but appear to us as ordinary particles in three-dimensional space. Any particle that travels in an extra dimension would have KK partners. This includes the graviton, a hypothetical particle thought to be responsible for gravity.

The graviton’s KK partners interact so strongly in our theory that any KK partner produced at the collider will not simply disappear. Instead, it will decay inside the detector into observable particles that can be used to reconstruct the KK particle from which they originated. The KK partners of the graviton, though visiting from higher-dimensional space, would be distinguishable, visible particles that will decay into known particles in the LHC detector. This is the conventional recipe for discovering new particles in collider experiments: study all the decay products and deduce the properties of what they came



In the LHC's immense underground tunnel, 1,232 dipole magnets have been delivered to CERN and are being installed. Photo: Maximilien Brice, 24 October 2005.

from. If what you find is not something you already know about, it must be something new. If the KK particles decay in the detector, the signal of extra dimensions should be very clear.

If we are lucky, in addition to the KK partners of the graviton, experiments might also produce an even richer set of KK particles. We might also see charged KK partners of quarks and leptons and gauge bosons. Those particles could ultimately give us even more information about the higher-dimensional world. In addition to KK particles, other signals of extra dimensions could turn up. Although the effects of five-dimensional gravity are minuscule at ordinary energies, five-dimensional gravity will become significant when colliders create high-energy particles. In fact, at the energies reached by the LHC, the effects of five-dimensional gravity could be enormous. Five-dimensional black holes could be produced (don't worry – they will decay immediately), as well as five-dimensional strings. Furthermore, at high energies, particles will interact very strongly with other particles. Such strong interactions among all known particles and gravity would not occur in a four-dimensional scenario (three spatial dimensions plus time): they would be a definite signal of something new.

Finally, strings from string theory might show up if spacetime is warped in the way that we suggest.

I am most excited about extra dimensions, but that is not all that the LHC might discover. If supersymmetry is correct, experiments at the LHC will discover a slew of particles with all the charges and interactions of the Standard Model particles we know. These charged heavy particles that are not part of the Standard Model will be very hard to miss and would be a very significant discovery.

Recent discoveries have shown many remarkable possibilities. Extra dimensions might have many shapes and sizes. And extra dimensions might house exotic phenomena, such as multiverses containing parallel worlds, on which forces and chemistry are entirely different from ours. With my collaborators, I have discovered that there can be extra dimensions that extend infinitely far, yet remain unseen. And we have found theories that allow for pockets of four-dimensional gravity residing in a universe that looks higher-dimensional everywhere else. Such theoretical investigations will make us rethink our place in the order of things.

**N**OT ALL these ideas will be immediately tested by experiments. But we know that some of them will be: no matter what is out there, the questions about mass and the weakness of gravity tell us we will soon learn more about the fundamental nature of matter. In a few years, the universe will be prised open and the secrets of the cosmos will begin to unravel. I, for one, can't wait.





Peter Glassel, technical coordinator for the ALICE Time Projection Chamber, sits in the middle of the completed TPC, during the commissioning phase in June 2006. Photo: Maximilien Brice, Claudia Marcelloni.