KENN BROWN AND CHRIS WREN/MONDOLITHIC STUDIOS

# POWER UP

After years dreaming of what the biggest atom smasher ever built will produce, the time has come to find out, says **Matthew Chalmers**

"I WILL probably cry when we see the first collision," says Bilge Demirköz. After spending the best part of a decade designing detectors and writing computer code for them, the 28-year-old physicist is yet to get her hands on real data. That's about to change. In a matter of weeks, the Large Hadron Collider at the CERN laboratory near Geneva, Switzerland, will begin amassing enough data to keep physicists off the streets for decades.

It's an emotional time for Demirköz and thousands of others who have devoted the past few years of their lives to a machine that will change our understanding of reality. The LHC is the daddy of all particle accelerators. Its collisions will generate seven times the energy of its most powerful rival, the Tevatron at Fermilab in Batavia, Illinois. By smashing together protons travelling just shy of the speed of light, the LHC will generate the largest concentration of energy ever seen in the lab – albeit in a region just billionths of the width of a speck of dust.

Smashing particles together is a tried-and-tested way of revealing what matter is ultimately made from, and what holds it together. Ernest Rutherford scored the first success nearly 100 years ago when he revealed the structure of the atom. Since then, physicists have been using accelerators to whip particles up to ever higher energies to explore even deeper into matter. At the highest energies, matter is smashed to smithereens, leaving behind fragments and energy that transform themselves into types of particles never seen before.

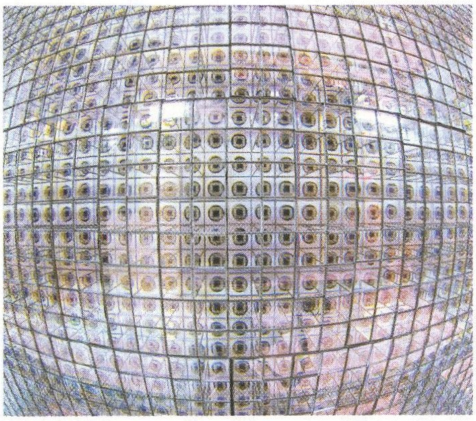
The LHC's microscopic fireball is the closest we can get to recreating conditions last seen less than a trillionth of a second after the big bang, when the particles and forces that shape today's universe began to emerge. The higher the collision energy, the more massive the particles created in the debris. So a host of hitherto unseen particles could materialise from the firestorm, providing physicists with important new leads in the quest to unite all the forces of nature, including gravity, into one "theory of everything".

The LHC might help us to finally crack what are arguably the biggest mysteries in physics, starting with the origin of mass and the disappearance of antimatter. It could reveal what makes up the majority of matter in the universe, the so-called dark matter that is invisible to our telescopes. And it might tell us about the very nature of space-time itself. Do extra dimensions of space exist in addition to the three we live in? Are there mini-black holes? The LHC is more than a machine. It is the intellectual quest of our age.

On 10 September the protons are set to make the first of the 11,000 or so laps they'll complete each second around the LHC's 27-kilometre ring (see diagram, page 29). Eventually proton beams travelling in the opposite direction will meet them head-on at four points in the ring where giant detectors – ATLAS, CMS, ALICE and LHCb – have been built to pore over the particle wreckage.

The universe won't be giving up its secrets ▶

MAXIMILIEN BRICE/CERN



MAXIMILIEN BRICE/CERN

**The CMS experiment (left) is designed to spot all kinds of particles. ALICE (above) will study a state called the quark gluon plasma when the LHC swaps its protons for lead ions at the end of 2009**

to the LHC straight away, however. For a start, it will take two months just to get the proton beams colliding. Then, depending on how optimistic you are, physicists potentially face a five to 10-year slog before they know for sure whether the effort has paid off.

If nature is kind, and possibly a bit weird, the LHC will create particles we have never seen before within minutes of smashing its first protons. Finding those particles, however, is a different story. Most elementary particles fleet in and out of existence in less than a trillionth of a second, while some can pass through tens of metres of detector as if it wasn't there.

To be sure that what they're seeing is something new and not some familiar particle that blazes a similar trail, physicists will have to search the LHC's collisions for as many copies as possible. And that will take time.

In fact it could take years for CERN to announce a major discovery, especially when it comes to the Higgs boson – the earthly face of the mechanism thought to give particles their mass, and the main motivation for building the LHC in the first place. With luck, however, today's physics textbooks will start to look out of date by the end of 2009.

From day one, researchers will be scouring their detectors for distinctive patterns of energy and charge that scream "new physics". Realistically, though, they won't collect enough data in the first few months to be able to claim a discovery. What's more, no sensible scientist is going to announce a discovery until they are confident that they understand every last millimetre of their massively complex detectors.

Instead they will use this year's data – taken with a "warm-up" collision energy of 10 teraelectronvolts (TeV) – to calibrate their detectors. Then, after the machine has shut down over the New Year, they will be ready by March 2009 to pack even more protons into the beams and ramp them up to the maximum collision energy of 14 TeV.

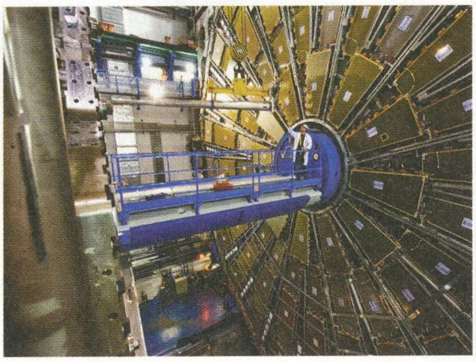
The LHC is exploring uncharted waters and no one knows what it will throw up first. Studies suggest that the first major discovery could be confirmation of a theory called supersymmetry (SUSY), theorists' best hope for building a deeper fundamental theory of particles and forces.

SUSY predicts that all known particles have a heavier "superpartner", and that's what physicists will be hunting for in their data. "Finding evidence for SUSY would be a great intellectual triumph, given that these ideas were conceived of 30 years ago for their intrinsic theoretical beauty," says Albert De Roeck, who leads the search for new physics at the CMS experiment. What's more, the lightest of the proposed supersymmetric particles is a candidate for dark matter – an invisible entity that appears to outweigh normal matter by a factor of five.

If superpartners exist and weigh less than about 1 TeV, as the simplest versions of supersymmetry predict, then the LHC should produce them by the hundred next year. "It's a damn difficult analysis, but if SUSY exists then claiming a discovery in 2009 is absolutely our target," says Oliver Buchmüller of the CMS experiment. "If you've built a $10 billion machine you're allowed to be optimistic."

Optimism is an apt word, because researchers hunting for supersymmetric particles will be looking for the invisible. The lightest supersymmetric particle, into which the heavier ones decay, interacts so weakly with matter that it will fly straight out of the detectors, carrying energy and momentum with it. Physicists will look for this missing energy as a possible sign of supersymmetry. Yet things aren't even that simple. Tiny gaps between the thousands of segments in the giant detectors or a few broken electronic connections could conjure the illusion of a Nobel prize-worthy discovery. ▶

**ATLAS (right) is the biggest detector ever built at a particle collider. LHCb (far right) is designed to measure particles called B mesons and it could make the first surprise discovery at the LHC**



MAXIMILIEN BRICE/CERN

CLAUDIA MARCELLONI/CERN

# LHC - THE BIG TURN ON

**The Large Hadron Collider will accelerate two beams of protons (and later lead ions) in opposite directions and collide them head-on at four locations where huge detectors will analyse the debris**


**Before the protons or ions enter the main LHC ring, they travel through a series of machines that accelerate them to increasingly higher energies**

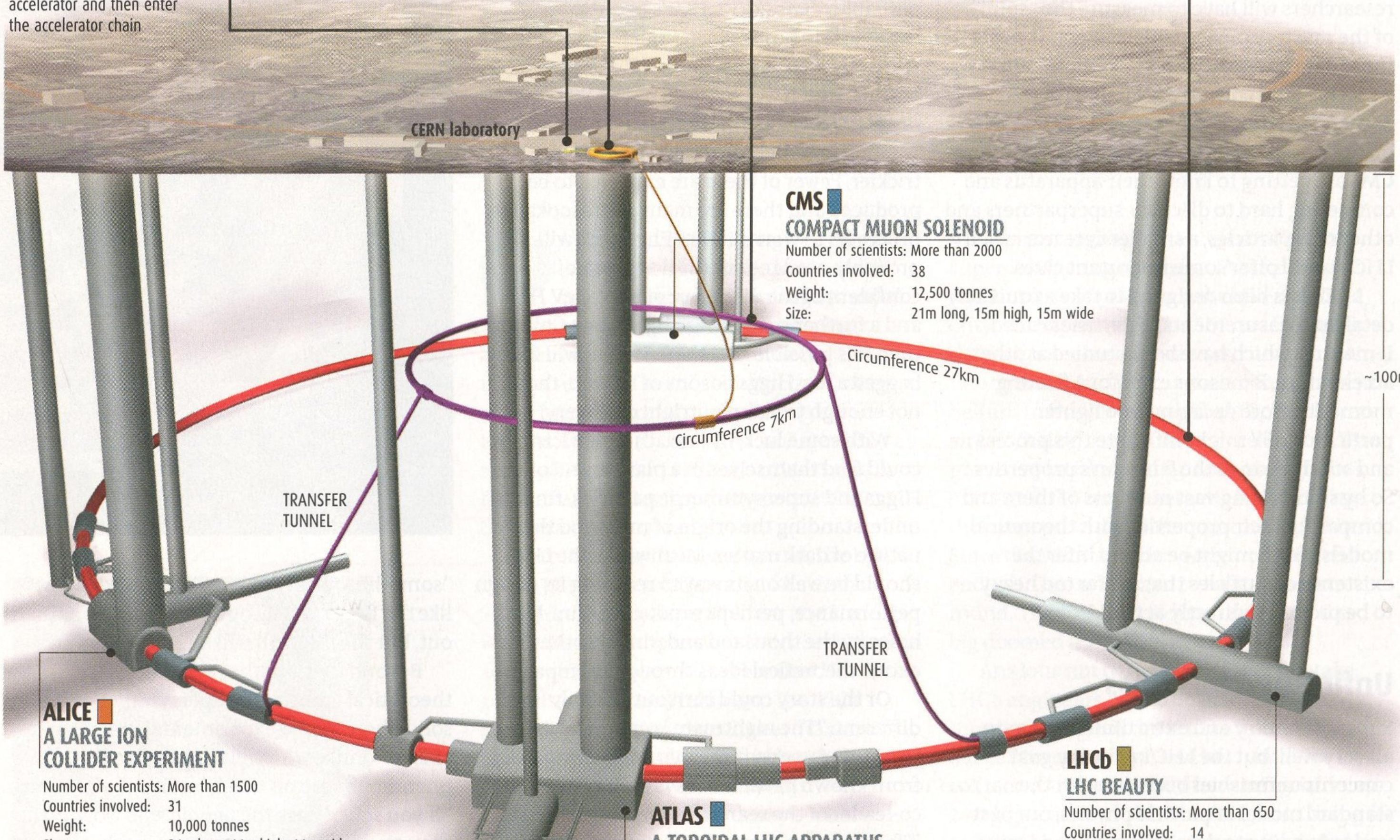
**THE FIRST STEP**
starts above ground and involves stripping electrons from atoms of hydrogen gas to make protons. These are sped up to 31.4% of the speed of light in a linear accelerator and then enter the accelerator chain

**BOOSTER RING**
Accelerates the protons to 91.6% of the speed of light and feeds them into the 200-metre-diameter Proton Synchrotron machine

**PROTON SYNCHROTRON**
Almost 50 years old, this machine accelerates protons to 99.93% of the speed of light (25 GeV in energy). For several weeks, starting in late 2009, it will also accelerate lead ions for the ALICE experiment

**SUPER PROTON SYNCHROTRON**
Located 40 metres underground, the SPS accelerates protons to 99.9998% of the speed of light (450 GeV in energy). It feeds protons both clockwise and anticlockwise into the LHC

**LARGE HADRON COLLIDER (LHC)**
Designed to accelerate protons to 99.9999991% of the speed of light (7 TeV in energy). The beams will be made to collide in four experimental areas




**CMS**
**COMPACT MUON SOLENOID**

| | |
|---|---|
| Number of scientists: | More than 2000 |
| Countries involved: | 38 |
| Weight: | 12,500 tonnes |
| Size: | 21m long, 15m high, 15m wide |

**ALICE**
**A LARGE ION COLLIDER EXPERIMENT**

| | |
|---|---|
| Number of scientists: | More than 1500 |
| Countries involved: | 31 |
| Weight: | 10,000 tonnes |
| Size: | 26m long, 16m high, 16m wide |

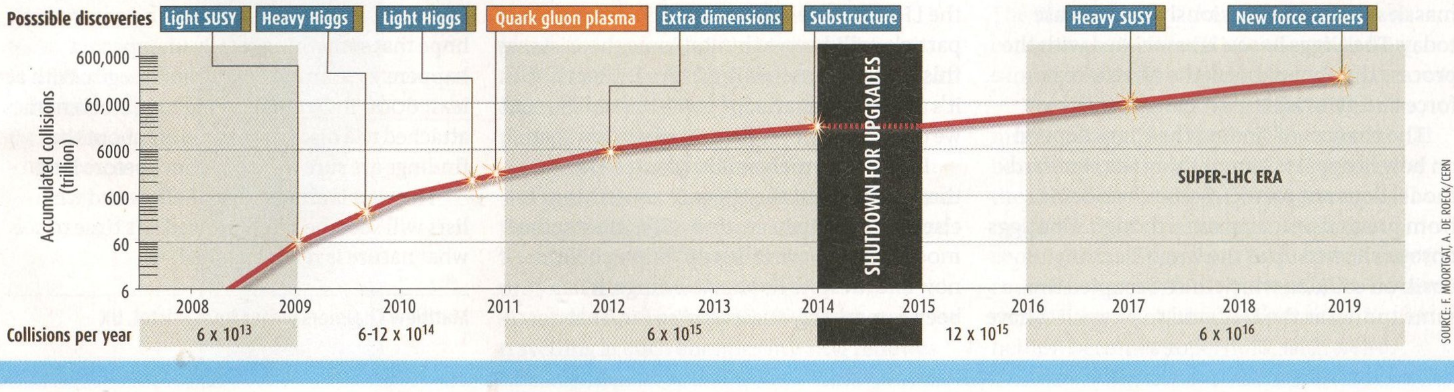
**ATLAS**
**A TOROIDAL LHC APPARATUS**

| | |
|---|---|
| Number of scientists: | More than 1900 |
| Countries involved: | 35 |
| Weight: | 7000 tonnes |
| Size: | 46m long, 25m high, 25m wide |

**LHCb**
**LHC BEAUTY**

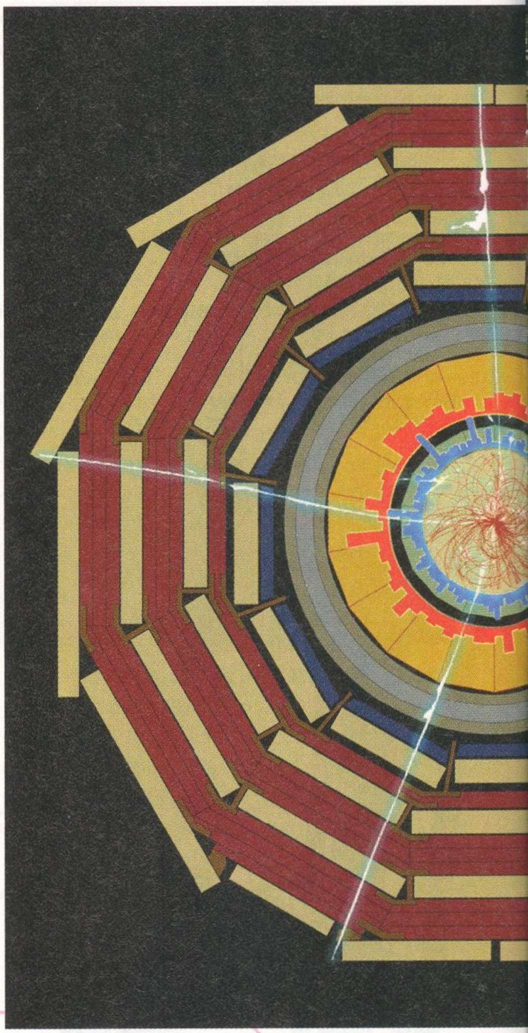
| | |
|---|---|
| Number of scientists: | More than 650 |
| Countries involved: | 14 |
| Weight: | 5600 tonnes |
| Size: | 21m long, 10m high, 13m wide |

**TIMELINE FOR DISCOVERY**
**Assuming the LHC runs according to design, the first discoveries could be made as early as 2009**




SOURCE: F. MOORTGAT, A. DE ROECK/CERN

"If you've built a $10 billion machine you are allowed to be a little optimistic"



Even if missing energy is genuinely detected, there will be no guarantee that it is due to supersymmetry. Missing energy could also be a sign that a particle has disappeared into an extra dimension, taking its energy with it. To tell these scenarios apart, researchers will have to measure the "spin" of the mystery object, which will require yet more data and further painstaking analysis.

Help could come from an unexpected corner. This time next year, just as researchers on the multi-purpose experiments ATLAS and CMS are getting to know their apparatus and competing hard to discover superpartners and other new particles, a smaller detector called LHCb could offer some important clues.

LHCb has been designed to take exquisitely detailed measurements of particles called B mesons, which have been studied at other accelerators. B mesons exist for a fleeting moment before decaying into lighter particles. SUSY might infiltrate this process and subtly change the B meson's properties. So by scrutinising vast numbers of them and comparing their properties with theoretical models, LHCb might be able to infer the existence of particles that are far too heavy to be produced directly at the LHC.

## Unfinished business

Supersymmetry and extra dimensions are all very well, but the LHC's primary goal concerns unfinished business with the standard model of particle physics, our best understanding to date of matter and forces. The theory is built on the well-tested idea that the electromagnetic and weak forces are united at high energies, as they were in the very early universe as the electroweak force. But this only holds if all particles are massless – which is obviously not the case today. The Higgs boson is associated with the process thought to break the electroweak force and give rise to particle masses.

The chances of finding the Higgs depend on how heavy it is – something the standard model does not predict. Some clues come from previous experiments, though. No Higgs bosons showed up at the Large Electron Positron collider, which once occupied the same tunnel as the LHC, and so physicists have ruled out a Higgs weighing less than 114 gigaelectronvolts (GeV). And earlier this month, researchers at the Tevatron excluded a Higgs with a mass of exactly 170 GeV.

A heavy Higgs in the range 140 to 500 GeV could turn up sooner than a lighter one – perhaps by late 2009. That's because a hefty Higgs would be heavy enough to decay into relatively massive particles called W and Z bosons, which would stand out against the profusion of other particles.

Spotting a lighter Higgs would be much trickier. Fewer of them are expected to be produced and there are many more lookalike processes to worry about. Physicists will probably need to wait until 2011 to be confident of the discovery of a 120 GeV Higgs, and a further year if it's as light as 115 GeV. By then it is possible that the Tevatron will have bagged a few Higgs bosons of its own, though not enough to claim outright discovery.

With some luck, by late 2010 physicists could find themselves in a playground of Higgs and supersymmetric particles, finally understanding the origin of mass and the nature of dark matter. Meanwhile, the LHC should be well on its way to reaching its design performance, perhaps producing mini-black holes by the thousand and putting other exotic theoretical ideas through their paces.

Or the story could turn out horribly different. "The nightmare scenario is no Higgs, no supersymmetry, no anything apart from known particles," says Chiara Mariotti, co-leader of the search for the Higgs on CMS. "That would mean rethinking everything from scratch." It would also turn a planned LHC upgrade in 2012 – which will allow 10 times as many collisions and enable particles with masses up to about 6 TeV to be discovered – into a desperate last bid to stop the LHC from being the last high-energy particle collider ever built. "Some theorists say this would be interesting," says De Roeck. "But it's a horror scenario for experimentalists and we'd probably never listen to theorists again."

It's an extremely unlikely outcome, though. Without the Higgs or something else new kicking in around 1 TeV, the standard model would have fallen apart long before now and, despite its shortcomings, it has been remarkably successful so far. That "something else" may not be a crowd pleaser like the Higgs and it could take years to fathom out, but the LHC will still have done its job.

Beyond that, anything is a bonus. While the theoretical ground for supersymmetry is rock solid, there are no experimental hints that it exists – unlike with the Higgs. Other phenomena are on much weaker foundations. "If you soberly ask the people who work on it, they say that they would be astounded if baby black holes or extra dimensions ever showed up," says theorist Ben Allanach at the University of Cambridge.

Particle physicists are about to enter the unknown using the most complex instrument ever built. Despite their sales talk, most secretly hope that something totally unexpected happens as soon as the collisions begin. With at least 6000 individuals vying to get their names attached to a discovery, rumours about the findings are sure to be headlines before long.

The wait is almost over. Beliefs and wish-lists will soon be safely stowed. It's time to see what nature is really made of. ●

**Matthew Chalmers writes from Bristol, UK**