Science & Technology Facilities Council

# Particle Physics: Hot Topics

## Recreating the Big Bang

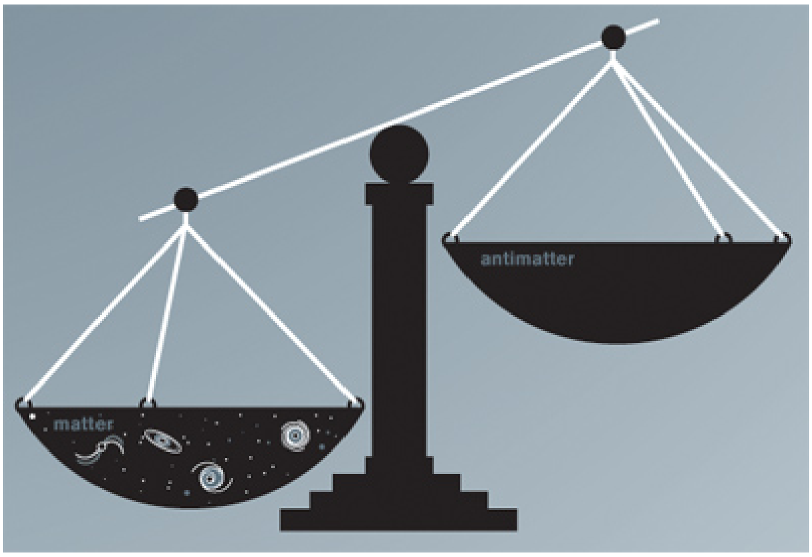
The Large Hadron Collider will allow scientists to reproduce at will the conditions of the Universe within a billionth of a second after the beginning of time (the Big Bang). By colliding beams of energetic particles and studying the debris of particles and energy that sprays in all directions, they will be able to understand more about how our Universe formed. In this way they hope to unravel the relationships between these fundamental building blocks, perhaps eventually developing a unified Theory of Everything; that accounts for all the fundamental characteristics of matter and energy.

Astronomical observations suggest that the Universe started about 14 billion years ago in the Big Bang. This was an ‘explosion’ of energy and matter, particularly rapid in the first fraction of a second as an intense fireball of matter and energy which expanded and cooled to form the Universe as we know it. During this first moment of time, the particles and forces that shape everything in the universe, including the world around us - and the rest of the cosmos - came into existence. Many of the particles created in the earliest moments of creation rapidly decayed and it is only recently what physicists have been able to create them at will in experiments. The programme at the LHC will feature the highest-energy experiments of this type and so will be able to probe the conditions of the Universe at an unprecedentedly early time. One detector at the LHC, called ALICE will investigate the elementary soup seen just after the Big Bang – a hot and dense mixture of particles called the quark-gluon plasma.

## Angels and Demons or ‘Can you blow up the Vatican with anti-matter?’

Author of the Da Vinci Code, Dan Brown, turned his attention to CERN as the setting for his page-turner Angels and Demons. In the story, anti-matter is stolen from CERN and placed under the Vatican in a plot to destroy the Catholic Church. As the clock starts ticking on the bomb, Robert Langdon is asked to investigate, teaming up with the beautiful scientist daughter of the murdered physicist who created the anti-matter.

But what is fact and what is fiction in Angels and Demons? CERN was the first laboratory in the world to create atoms of anti-matter in the form of anti-hydrogen. Anti-matter instantly annihilates on contact with ordinary matter (such as air) releasing a massive charge of energy in the form of high-energy light.




However, creating anti-matter is extremely difficult and requires a huge amount of energy. So whilst Dan Brown describes it both as a potential bomb and also as a clean source of energy, neither of these is possible – it takes far more energy to create anti-matter than you get released when it annihilates and storing anti-matter is extremely difficult so you can only store a few particles at a time.

More information go to the ‘Angels and Demons’ pages on the [CERN website](#) .

CERN produces and studies anti-matter in order to learn how it is different from ordinary matter. In the Big Bang, almost exactly equal amounts of matter and anti-matter were created and they annihilated each other – leaving a slight excess of matter! Something took place at this time that meant some matter remained (only one particle in every billion!), to make up the Universe we know. Scientists at CERN want to understand the differences that mean matter survived but anti-matter didn’t. Experiments so far have revealed small differences in the way particles and their anti-particles behave but more sensitive detectors are needed to chase down this minute difference. CERN’s LHCb detector is the most sensitive experiment in the world designed specifically to do this.

## Supersymmetry

Supersymmetry is a proposed property of the universe. Supersymmetry requires every type of particle to have an associated supersymmetric particle, called its superpartner. The superpartner is a heavy replica of a particle, with one other significant difference. All fundamental particles (such as electrons and photons) are classed as either fermions or bosons. A particle belonging to one class has a superpartner in the other, thereby "balancing the books" and making nature more symmetric. For example, the superpartner of an electron (a fermion) is called a selectron (a boson).

Supersymmetry describes a grand dance of particles through the universe, but we can currently see only one partner from each pair. The unseen particles might be the source of the mysterious "dark matter" in galaxies (see below). Although superpartners have not yet been observed in nature, scientists will be looking for them at the LHC. A group of theories called String Theory are all dependent on supersymmetry existing, so finding supersymmetric particles will be evidence that these theories are valid. On the other hand, if the experimenters at the LHC do not find supersymmetry it will be a sensation.

## Strings and the Theory of Everything

Ultimately, theorists want to develop a theory that unifies all the forces including gravity. The problem has been that gravity is a much weaker force, which appears to play no part in particle physics phenomena. It is described by a very different theory, Einstein's general theory of relativity. Early attempts to introduce gravity into quantum theory produced unsatisfactory results.

However, one approach, string theory, overcomes many of the problems. In string theory, particles, instead of being thought of as point-like objects, are regarded as one-dimensional strings vibrating in different modes, like a skipping rope. String theory combines well with supersymmetry to give 'superstring' theory, which incorporates gravity.

Superstring theory also relies on another significant idea - that there exist more dimensions than the three of space and one of time. Superstrings live in a 10-dimensional world in which six of the dimensions are rolled up tightly in minute circles. The only snag with this concept is that it happens at miniscule scales around 20 orders of magnitude smaller than a proton. This means we can never see them, and thus test the theory directly.

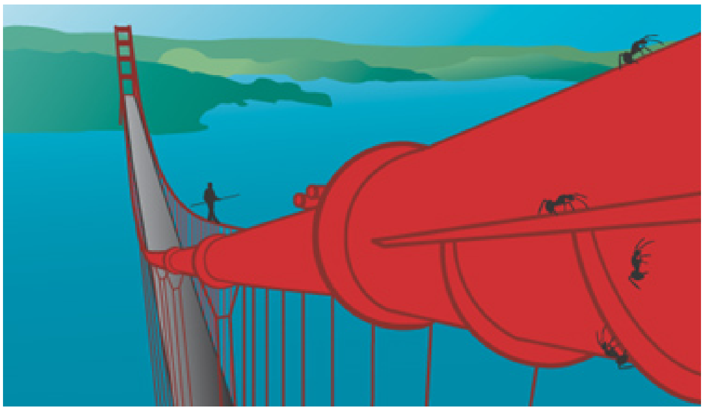
A further mathematical idea that has added an extra dimension to superstrings is that of 'branes'. Objects like zero-dimensional particles are considered to live on a one-dimensional brane; one-dimensional objects would live on a two-dimensional brane and so on. This idea has turned out to be profitable in developing a promising new theory that could be tested experimentally at the LHC. One key piece of evidence will be detecting supersymmetry particles that enable such theories.

## Extra dimensions – not just science fiction, they could be real!

It seems obvious, when we look around, that the world has only four dimensions: three of space – up and down, left and right, backwards and forwards – plus one of time. But many theories that attempt to explain the behaviour of the smallest particles of matter work only if there are more dimensions than this – 10 or even more! Whilst such theories sound like science fiction – the LHC offers a real opportunity to find out if they are true!

Einstein's general theory of relativity tells us that space-time is curved: roughly speaking, mass tells space-time how to curve, and space-time tells matter how to move. If one direction were to contract down to an extremely tiny size, trillions of times smaller than an atom, it would be hidden from our view. If we could observe on small enough scales, that hidden dimension might just become visible. That is how today's experimentalists hope one day to find evidence for the predicted 'higher dimensions'

Imagine a balancing act in which a daredevil walks the cable of a suspension bridge, only able to move backward and forward, not left and right, nor up and down. The daredevil experiences only one dimension, but things that live on a smaller scale, such as ants, can move about in an extra dimension - circularly around the cable, in this analogy.



One possibility is that our 4-D world is linked to another by a fifth dimension of almost infinitesimal size: a million, million, million times smaller than an atomic nucleus. This extra dimension cannot be seen, because ordinary matter cannot travel along it. The extra dimension also warps space, so that an object which moved from our space to the other side of the fifth dimension would shrink by a factor of one hundred, million, million. The world on the far side is therefore very hot and dense, filled with the fields of the unified theory long discussed by theorists. These are exactly the conditions that existed at the time of the Big Bang. The warping of space can explain why the underlying workings of the universe appear to be explained by four very different forces: gravity, electromagnetic, and two nuclear forces rather than just a single field. The hope is that one day; all the underlying forces will be understood in terms of single unified field theory.

Today, the best candidate for a unified theory is 'string theory'. According to this theory, the universe is ultimately made not from point-like particles but from unimaginably short pieces of strings that exist in higher dimensions. The LHC can search for evidence of these extra dimensions by looking for evidence of missing energy after the particle collisions within a detector – caused for example by gravitons escaping from the system.

## Gravitons?

Gravity is the only force that can penetrate into the fifth dimension. The gravitational field can resonate along the fifth dimension like the air in an organ pipe, giving 'notes' at particular frequencies called graviton resonances. Because the extra dimension is so small, a lot of energy is needed to make it vibrate. The Large Hadron Collider is providing the highest energy particle collisions ever seen in a laboratory. It is possible that pairs of particles will be seen in the LHC with energies characteristic of the graviton resonances which create them. This would provide the first glimpse into a truly new world.

## Creating Baby Black Holes

If higher dimensions do exist, they have a fascinating consequence – it might be possible to make miniature black holes in the LHC! Scientists will be watching closely for signs of these because if they exist, they should quickly 'pop' spraying out particles – known as Hawking radiation. Predicted by Stephen Hawking, this has not yet been observed and so would provide us with new insights into matter in the universe.

Whilst large black holes absorb more material than they emit, small black holes radiate more and vaporise in a shower of particles. Einstein's famous equation $E=mc^2$ determines the mass of black hole that can be created. E is the energy that is put in by CERN, m is the mass of the resulting black hole and c is the speed of light in a vacuum. The energies CERN can produce can only create baby black holes that will simply fizzle away. In fact the energies at CERN, whilst a new frontier for humans, are feeble compared with what Nature can manage. Cosmic rays regularly hit the Earth's atmosphere at much higher energy than anything CERN will produce (by a factor of about a billion). Baby black holes do not pose a risk as some fictional works have suggested. If found at the LHC, they will offer very exciting insights into the physics of the Universe.

## Why does anything have mass? The Higgs Mechanism

Whilst mass is a very every day concept to most people, to physicists it is something of mystery as they don't yet know why anything – including people - has mass. Some particles, like the proton, neutron and the electron that make up ordinary matter, have mass. Others like the photon (the particle form of light) are insubstantial. But why are they different? Its rather embarrassing for physicists to admit that they can't explain such a fundamental property that everyone encounters in every moment of their lives.

Peter Higgs of Edinburgh University suggested a mechanism by which particles acquire mass by interacting with a new field (like a gravitational field) filling all of space. Heavier particles interact more strongly, whereas photons (which have no mass) don't interact at all. The field is manifest as a new particle called the Higgs boson, and this is now part of the Standard Model – the basic theory that describes the fundamental interactions between all the fundamental particles. It is this particle that is largely responsible for large scale-matter's having mass: without the Higgs, everything would be as insubstantial as light!

Searching for the Higgs Boson is one of the major aims of the LHC and both the ATLAS and the CMS detector search for evidence of its existence. If it is not found, it will force a profound rethink of particle physics – not to mention cause a number of scientists to lose the bets they have placed!

## Dark Matter – the missing 90% of the Universe!

Much of the matter of the Universe is missing, nicknamed 'dark matter' as we cannot observe it directly. The LHC could find this unusual matter and tell us about its properties.

Astronomers studying the rates at which galaxies rotate discovered that they were moving too fast to be held together only by the gravitational forces of the material that could be observed – by a factor of about ten!
If current theories of gravity are correct, then the difference must be due to material that we can not see – called 'dark matter'. There are a number of candidates for types of particles that might be dark matter but none has yet been detected in sufficient numbers to account for all the missing material.

One candidate for dark matter is known as Weakly Interacting Massive Particles – or WIMPs for short. Several theories in particle physics, including supersymmetry suggest that different types of WIMPs could be made in the LHC. One example is the neutralino –- which has no charge but is very heavy in comparison. If it is created in the LHC it will pass straight through the detector but the fact that it was created can be deduced by looking at the other particles. The neutralino will carry off energy and the absence of that energy can be seen in the momenta of the particles that remain.

Depending on the exact nature and mass of the WIMPs, the LHC could produce 10,000 WIMP particles a year – and tell us a lot about the material that dominates the Universe!

## Dark Energy

More worrying for scientists than the possibility of dark matter they can not see, has been the recent idea that the Universe is also filled with vast amounts of 'dark energy'. In fact, it is possible that there is more dark energy than there is of everything else! Dark energy is believed to be the driving force making the Universe expand – but no one is sure what it is. So little is known about dark energy, that it is difficult to know yet whether the LHC can shed light on its mystery. Some senior theorists at CERN believe it will – dark energy must exist through out empty space and the Higgs field also permeates space. If the Higgs field could carry this energy then the mechanisms might be related. The only drawback with this model is that at the moment, the theoretical numbers for the Higgs field suggest it would carry more energy than is needed! So the LHC results on the search for the Higgs will help to refine such models.

## Quantum Mechanics & Relativity

The twin theories of relativity and quantum mechanics are the foundations of particle physics as they describe the behaviour of things that are moving very fast and are very small, like the particles in the LHC. The beams of particles at the LHC move so fast that they have to take account of the effects of general relativity to control them. Whilst these are exotic theories in everyday experience, they are part of the everyday language of particle physicists, who have to study nature at its extremes to uncover its deepest secrets.

Images courtesy Symmetry Magazine
Angels and Demons ambigram courtesy John Langdon
Spiral Galaxy Copyright ESO