A hundred metres below ground, under the border between France and Switzerland near Geneva, scientists are building a new machine to study how things were in the first fractions of a second after the beginning of the Universe. The scientists - particle physicists - would like to find out how the primordial stuff of the Universe developed into the building blocks that form everything we see today, from stars and galaxies to ourselves and the world about us.

Modern particle physicists have joined forces with astronomers in exploring the origins of the Universe and, in particular, the origins of matter. Astronomers have discovered that the Universe is still expanding from an infinitely dense and energetic state, some 13 billion years ago. But how did the matter of the present-day Universe evolve from this primordial state? Particle physics may provide the answer.

High energy collisions of subatomic particles can recreate forms of matter that probably existed in the first fractions of a second after the big bang. A new machine, to produce higher energy particle collisions than ever before, is under construction at CERN, the European centre for particle physics, near Geneva. The machine is called the Large Hadron Collider, or LHC. The physicists who use it - many from the UK - will be like explorers going back in time to answer one of the most fundamental of questions: Where do we come from?
What is matter?

Each element consists of building blocks - atoms - unique to the element, but the different atoms can combine to form an enormous variety of compounds from simple water to complex proteins. Yet, as scientists first discovered towards the end of the 19th century, atoms are not the simplest building bricks of matter.

We now know that most of the mass of an atom is concentrated in a small, dense, positively-charged nucleus. A cloud of tiny negatively-charged electrons envelopes the nucleus, but at a relatively large distance, so that much of the volume of an atom is empty space.

In most atoms the nucleus contains two types of particle of almost equal mass: positively-charged protons and electrically neutral neutrons. To make the atom neutral overall, the number of protons exactly balances the number of electrons.

This picture of the atom stems largely from pioneering work at the Universities of Cambridge and Manchester. At Cambridge in the 1890s, two physicists began unwittingly to probe the world within the atom. In 1897, J.J. Thomson discovered the first subatomic particle, the electron, and one of his students, Ernest Rutherford, started to explore the new phenomena of radioactivity, in which atoms change from one kind to another. This was to lead Rutherford to the discovery of the atomic nucleus, in work with Hans Geiger (of Geiger counter fame) and Ernest Marsden at Manchester in 1909-10.

Continuing his work at Manchester, Rutherford found that atoms contain positively-charged particles, identical to the nucleus of hydrogen. He called the particles protons. And at Cambridge in 1932, James Chadwick showed that the nucleus also contains neutrons. By this time Rutherford and his colleagues had established much of the modern picture of the atom.

During the past 200 years, scientists have made great progress in understanding what things are made of. First came the realisation that matter consists of basic substances, or elements, with well-defined physical and chemical properties. These elements range from hydrogen, the lightest, through to uranium and beyond.

A pageant of particles

The collisions of high energy cosmic rays with atoms in the atmosphere pried open the nucleus to reveal new kinds of short-lived particles that could be seen only through tracks left in sensitive detectors.

There were particles such as the muon, which behaves like an electron, but is 200 times heavier; the pion, which is just a little heavier than the muon; the kaon at little more than half the proton’s mass; and the lambda, which is about 20 percent heavier than the proton.

One particularly intriguing particle, discovered in 1932 by Carl Anderson at the California Institute of Technology, is the positron - as light as an electron, but with positive charge. By existence, at first a puzzle, was soon explained in a theory due to P.A.M. Dirac at Cambridge University.

Enter antimatter

According to Dirac’s theory, the positron is a particle with exactly opposite properties to an electron - an anti-electron. The theory showed how an electron and a positron can merge together from pure energy, provided the energy is sufficient to supply the total mass of the two particles, in accordance with Einstein’s equation, E=mc2.

If they collide, the particle and antiparticle disappear to leave only energy - an act of mutual destruction called annihilation. Experiments have since demonstrated that most other particles - protons, neutrons, muons and so on - have antiparticles.

Cosmic mimics

Work in the early 1930s by John Cockcroft and Ernest Walton at Cambridge, and by Ernest Lawrence and Stanley Livingston at Berkeley in California, had provided the first artificially accelerated protons. Their pioneering ideas gave birth in the 1950s and 60s to large machines capable of producing millions of protons, electrons, pions or kaons each second. With the invention of more sophisticated detectors to complement the accelerators, physicists now have the tools to study the many varieties of particle in detail.
By probing matter more energetically at accelerators, particle physicists have discovered a deeper layer to matter. Like atoms before them, protons, neutrons, pions, kaons, lambda and many other subatomic particles have proved to be complex structures based on only a few, more basic particles - the quarks.

Basic building blocks

There are six kinds of quark and six corresponding antiquarks. The quarks are known as up, down, charm, strange, top and bottom. They combine in groups of three to form the baryons - particles such as the proton, neutron, and lambda. The quarks can also bind with antiquarks to make particles such as pions and kaons, which are collectively known as mesons.

Just as important as the quarks and leptons - the building blocks of matter - are the forces that act between the particles and would them into the structures we observe, from atoms to galaxies. There appear to be five basic forces at work - gravity, the electromagnetic force, the weak force and the strong force.

The electron and muon, on the other hand, are not made from quarks but appear to be indivisible. They belong to a separate family of particles called leptons. These also include: a third, slightly heavier charged particle, the tau, as well as neutrinos - particles that are almost massless, electrically neutral and difficult to detect.

Facts about forces

Gravity is the weakest, but acts over great distances, binding stars and galaxies together. The electromagnetic force is stronger and holds atoms and molecules together. As with gravity, its range is infinite.

The weak force and the strong force, by contrast, operate only within the dimensions typical of an atomic nucleus.

The weak force causes certain forms of radioactivity and underlies the nuclear reactions that fuel the Sun. Last but not least, the strong force - the strongest we know of - binds quarks and antiquarks together within the particles we observe. The strong force seems to act in such a way that quarks are always forced inside these more complex particles, so that we have never observed a single free quark.

One of the challenges for particle physics in the 21st century is to discover whether the particles known as Higgs bosons really exist. In the late 1960s, Peter Higgs and others proposed a mechanism that would endow particles with mass, even though they appeared originally in a theory - and possibly in the Universe - with no mass at all.

The basic idea is that all particles acquire their mass through interactions with an all-pervading field called the Higgs field, which is carried by the Higgs bosons. This mechanism is an important part of the Standard Model of particles and forces, for it explains the masses of the carriers of the weak force, responsible for beta-decay and for nuclear reactions that fuel the Sun.

Credit: Peter Tuffy, Edinburgh University.

The theories that describe the quarks and leptons, and their interactions through the strong and electroweak forces, form the Standard Model of particle physics. Although the strong force is not yet fully united with the other two forces, it is described by a similar type of theory. Gravity alone remains outside the Standard Model.

There is a different gauge boson for each force. Photons (the particles of light) carry the electromagnetic force; gluons carry the strong force; charged particles, W+ and W-, and neutral particles, Z0, carry the weak force. A particle called the graviton - not yet observed - is believed to be responsible for gravity.

In the 1960s and 70s, particle physicists discovered that the weak and electromagnetic forces behave as different aspects of a single electroweak force. The main difference is that photons,

In the Standard Model, particles acquire their masses by interacting with another particle, the Higgs boson, named after Peter Higgs of Edinburgh University. The strength of this interaction gives rise to what we call mass. As yet there is no definite direct experimental evidence for the Higgs boson, so searching for it is a top priority in particle physics.
Nowadays many particle physicists from Europe and beyond work together at CERN, Europe’s laboratory for particle physics, on the outskirts of Geneva, straddling the French/Swiss border. CERN is probably the best example of European co-operation in any field, not only in science. It was founded in 1954, at a time when many European physicists began to realise that co-operation provided the only way forward for a project as complex as a large particle accelerator.

The CERN Laboratory

The UK was one of the founder states, along with Belgium, Denmark, France, Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland and Yugoslavia. Since 1954, CERN has grown in size, until today it houses several accelerators, which serve a community of some 6,500 scientists - half the world’s particle physicists! The number of member states now stands at 20, with Austria, Bulgaria, the Czech Republic, Finland, Hungary, Poland, Portugal, the Slovak Republic and Spain adding to the original list, while Yugoslavia has left. Physics from countries outside CERN, such as China, Japan, India, the Russian Federation and the USA, also participate by contributing to new experiments and accelerators.

Since its beginning, CERN has built several accelerators. In 1989 LEP - the Large Electron Positron Collider - became the world’s largest particle accelerator. It closed down in 2000 to make way for CERN’s new machine, the Large Hadron Collider, which is being built in the tunnel that was constructed for LEP. LEP began to realise that co-operation provided the only way forward for a project as complex as a large particle accelerator.

The Large Electron Positron Collider - LEP

LEP, which ran from 1989 to 2000, occupied a tunnel forming a circle 27 km in circumference - as big as the Circle Line on the London Underground. As in all large circular accelerators it had a ring of magnets to guide the bunches of particles on their path, so that they would pass repeatedly through regions where they were given small accelerating boosts. In LEP, bunches of positrons and electrons travelled in opposite directions around the ring. Once the particles had reached maximum energy, their paths were allowed to cross at four points so that some of the electrons and positrons could annihilate.

LEP was big to keep the electrons and positrons on a gently curving path, to reduce energy losses through “synchrotron radiation”. Electrons (and positrons) easily radiate energy as they change direction, which happens continuously when a particle travels round in a circle. The phenomenon is known as “synchrotron radiation” after the circular accelerators (“synchrotrons”) in which it occurs. The smaller the radius, the greater the curvature, and the more energy that is lost in this way, so LEP was built with as large a radius as possible.

From 1989 to 1995, LEP accelerated the electrons and positrons to an energy of 50 giga electronvolts (50 GeV). This is equivalent to accelerating the particles through a potential of 50 thousand million volts (50 giga volts). Later the energy was gradually increased to double this.
Detective work at LEP

Four huge experiments – named ALEPH, DELPHI, L3 and OPAL – studied the electron-positron annihilations in LEP. Each used a variety of detectors that could identify different particles and measure their energies. These detectors were wrapped in layers around the beam pipe in separate assemblies at four points where electrons and positrons collided.

Each assembly formed a huge structure about the size of a house – typically 10-12 m high, wide and long – and weighing several thousand tonnes. Each was built and run by a team of 200-300 physicists and engineers from around the world, with components coming from many different countries, including the UK.

The detector assemblies all followed a similar basic design. The first layers, closest to the beam, revealed the tracks of the charged particles (tracks of charged particles do not leave vacancies in the detector). The next layer measured the energy of the particles, and the third layer measured the energy of the hadrons (particles built from quarks and antiquarks) by stopping them in iron that also formed part of the electromagnetic calorimeter.

Layers of detectors

The next layer - the electromagnetic calorimeter - stopped electrons, positrons and photons and measured their energies as they plunged into a dense material such as lead. The third layer - the hadron calorimeter - measured the energy of the hadrons (particles built from quarks and antiquarks) by stopping them in iron that also formed part of the electromagnetic calorimeter.

The final, outer layer registered muons, the only charged particles that could penetrate so far. Only neutrinos could escape the apparatus without direct detection. But they could be sensed by the “missing” energy and momentum that they took away.

Crucial circuitry

Electronics and computing played crucial roles in the LEP experiments. All the detectors produced electrical signals, which electronic circuits converted into a form that could be fed into computers and stored on magnetic or optical media. Other sophisticated circuits were necessary to process signals and make fast decisions as to whether the information from an annihilation was worth recording. This electronic “trigger” would set off the whole complex chain for recording data from the experiment.

The UK at LEP

Physicists and engineers from 25 British universities, as well as from the Rutherford Appleton Laboratory (RAL), were involved in three of the experiments at LEP - ALEPH, DELPHI and OPAL. They contributed at all stages, from the design of the apparatus to the final analysis of the data.

For the DELPHI experiment, the world’s largest superconducting solenoid was designed and built at RAL. UK groups also contributed to the innermost tracking layer, made of silicon, and to the muon detectors that formed DELPHI’s outermost layer.

For OPAL, UK groups were again involved in the initial measurement of tracks emerging from the beam pipe, providing silicon tracking detectors and trigger electronics. In addition, the end-caps for the lead-glass electromagnetic calorimeter and the muon detectors were built in the UK, together with components to track particles emerging close to the path of the electron and positron beam.

The giant DELPHI superconducting solenoid was designed and constructed at the Rutherford Appleton Laboratory in Oxfordshire, and then transported to CERN.

A computer display of the decay of a Z° particle seen in ALEPH echoes the segmented structure of the detector.
From the time of the first collisions in 1989, LEP provided a wealth of new data for the research teams to analyse. The earliest results contained vital information on the number of types of neutrinos. When the beams in LEP were tuned to the correct energy, the annihilations produced $Z^0$ particles - the neutral gauge bosons of the weak force. These would decay instantly to particle-antiparticle pairs, including neutrino-antineutrino pairs.

**Results from LEP**

When the physicists compared the data from LEP with the predictions of the Standard Model, they found agreement only if there are three types of neutrino - no less, and importantly, no more. This indicates that we already knew all the neutrinos that exist. Moreover, the six types of quark and six types of lepton (including the three neutrinos) already known appear to be related in pairs, as the diagram on page 5 indicates. This implies that as there can be no more types of light neutrino, there are no further quarks or leptons to find. The result from LEP also helped to confirm theories of the formation of elements in the big bang, as observations of the amount of primordial helium in the Universe today indicate that there should be no more than four types of neutrino. This is one example of the relationship between particle physics and astronomy.

**Precision measurements**

The experiments at LEP tested the Standard Model in precise detail. From the start in 1989 to 1995, the experiments recorded the decays of 17 million $Z^0$ particles. This enabled the physicists to measure the mass of the $Z^0$ – which is about 100 times as heavy as a proton – to 0.001%, which is like knowing your weight to better than 1 gm. Such precise measurements test predictions of the Standard Model and help to pin down the mass of as yet undetected particles, such as the Higgs boson (see page 5).

By 2000 the energy of the beams had been more than doubled, as new accelerating cavities (see page 7) were installed. With the higher beam energies, the physicists at LEP could make detailed studies of the W particles – the charged partners of the $Z^0$. Because the $Z^0$ has no charge, then an electron and a positron can annihilate to make a single $Z$; provided they have enough energy. However, the annihilations must make the charged W particles in pairs – $W^+$ and $W^-$, which was possible once the total energy of LEP had doubled.

**Pairs of W particles**

Just before LEP shut down at the beginning of November 2000, at the highest energies possible, the four experiments observed a few collisions that produced patterns of particles like those predicted for the decay of the Higgs boson. There were too few examples to confirm that these were indeed due to Higgs bosons, so physicists working at CERN now eagerly await the higher energies of the Large Hadron Collider, which is to replace LEP.

**Higgs hints**

Detailed analysis of the data collected by the detectors at LEP at last brings the physicists the reward for their hard work – the results!
Towards further unification

Although today we create such high energy conditions artificially, it seems probable that early in the history of the Universe all matter was in a state of high energy. We know that the weak and electromagnetic forces behaved as one electroweak force at energies that would have prevailed less than a billionth of a second after the big bang. But what happened before then, when the Universe was even hotter and more energetic? Was there an original state in which all forces behaved as one?

Attempts to develop a grand unified theory that brings together the electroweak and strong forces, suggest that there must be a symmetry between particles and forces, which physicists call supersymmetry. Supersymmetry links the matter particles (quarks and leptons) with the force particles (gauge bosons). In so doing it predicts that additional "superparticles" are needed to complete the symmetry. The lightest of these particles should be around ten times heavier than the heaviest particles observed so far – the top quark and the W and Z gauge bosons.

The discovery of supersymmetric particles could help to solve one of the important puzzles in cosmology. Astronomers have found that 90% of the Universe is dark matter, which is apparently very different at low energies. The Standard Model unifies the electromagnetic and weak forces at energies above 100 GeV, and attributes the low energy divergence to the so-called symmetry breaking Higgs mechanism.

The Large Hadron Collider - LHC

The LHC will be the world’s highest energy particle collider, reaching an energy of 7 tera electronvolts (7 TeV, or 7000 GeV). This energy will mean that it is well placed to investigate new phenomena such as the Higgs boson and supersymmetry, as well as heavy quarks and the difference between matter and antimatter. It will also have great potential to make new, unexpected discoveries.

The new machine will replace LEP in the 27km circular tunnel at CERN. It can reach much higher energies than LEP because the protons are 2000 times heavier than electrons and positrons and do not lose energy through synchrotron radiation so easily (see page 7). However the high energies of the LHC require very strong magnetic fields to bend the protons in a circle, even with a circumference of 27 km. The LHC magnets will produce fields of 8 tesla, the strongest ever used in a particle accelerator. To do this, experts at CERN have designed innovative superconducting magnets. These will guide the two proton beams in opposite directions in separate magnetic channels within the same mechanical structure, which will be cooled to 1.9 degrees above absolute zero - colder than outer space!
Four large composite detectors are being built to study the high-energy collisions in the LHC. Although they share some basic similarities, they complement each other by having different strengths or different purposes.

The ATLAS and CMS experiments involve “general purpose” detectors, designed to explore the new high-energy frontier thoroughly. Like the LEP experiments they are multilayered detector assemblies that aim to detect as many of the particles produced in a collision as possible.

The ATLAS detector will be the size of a five-storey building and weigh 7000 tonnes. It will consist of four major components to track particles, measure their energies, provide a magnetic field for momentum measurement, and detect muons. By contrast the CMS (Compact Muon Solenoid) will be about half the size of ATLAS but will weigh 12500 tonnes. It is designed in particular to give excellent detection of muons. They provide important clues in identifying short-lived particles, such as top and bottom quarks, which are observed only through their decays.

These two experiments together involve around 4000 physicists from countries in six continents, including many UK teams. Every UK university that does research in experimental particle physics has people working on either ATLAS or CMS. Four universities own ATLAS and four on CMS, together with members of the Rutherford Appleton Laboratory. These UK teams are contributing to the silicon central tracking detector for ATLAS, and to the electromagnetic calorimeter for CMS, as well as to the trigger electronics, data acquisition, and preparation for the all-important data analysis for both experiments.

Such an asymmetry between matter and antimatter could have a deep significance for cosmology, for although matter and antimatter should have been created in equal quantities in the initial bang, the Universe now is predominantly matter. Eight UK institutes are working on LHC-b (the Universities of Bristol, Cambridge, Edinburgh, Glasgow, Liverpool and Oxford; Imperial College, London; and the Rutherford Appleton Laboratory). These teams are building detectors to identify different particles, and developing the trigger system that will pick out collisions containing particles built from b quarks.

The LHC will not always accelerate proton beams: on some occasions it will instead accelerate beams of lead ions – lead atoms with all their individual protons and neutrons within the nucleus should merge to form a state of matter known as quark-gluon plasma. This should have existed in the very early Universe, when conditions were too hot and energetic for quarks to cluster into individual protons and neutrons. ALICE (A Large Ion Collider Experiment) will search for evidence for the formation of quark-gluon plasma in collisions of lead-ions at the LHC. The University of Birmingham is contributing to the trigger design and electronics for the experiment.

The other two LHC experiments, called ALICE and LHC-b, will investigate particular phenomena. The collisions at the LHC will produce large numbers of particles made from heavier quarks, and the LHC-b experiment will look specifically for particles containing the b quark, to search for small differences between the particles and their antiparticles.
Particle Physics and you

British physicist J.J. Thomson discovered the electron just over 100 years ago. Today the applications of the electron feature in all our lives, in areas ranging from electronics to chemistry, in products from washing machines to mobile phones. Modern particle physics brings benefits too, as these pages illustrate - and also provides people with skills to work in technology, commerce and industry.

Beyond the World Wide Web

In late 1990, Tim Berners-Lee, a computer scientist working at CERN, invented the World Wide Web, so that the large groups of particle physicists that work on experiments at CERN could easily and instantaneously share information while they were working in their different institutes and laboratories in many countries. Today the web has millions of users in commerce, industry and homes around the world. Particle physicists at CERN and in the UK are now contributing to a bigger concept - known as the GRID - which will share the processing of data on computers around the world.

Techniques developed initially for research in particle physics have for many years found their way into other subjects, particularly in medicine. For example, both Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) nowadays involve technology invented for particle physics. Thousands of these systems for imaging inside the body can be found in hospitals around the world.

Particle Physics and you

In PET, pairs of detectors on opposite sides of the head register gamma rays produced when positrons from radioactive sugar annihilate with electrons in the brain.
BIG BANG SCIENCE
exploring the origins of matter