The European strategy for particle physics

CERN Council

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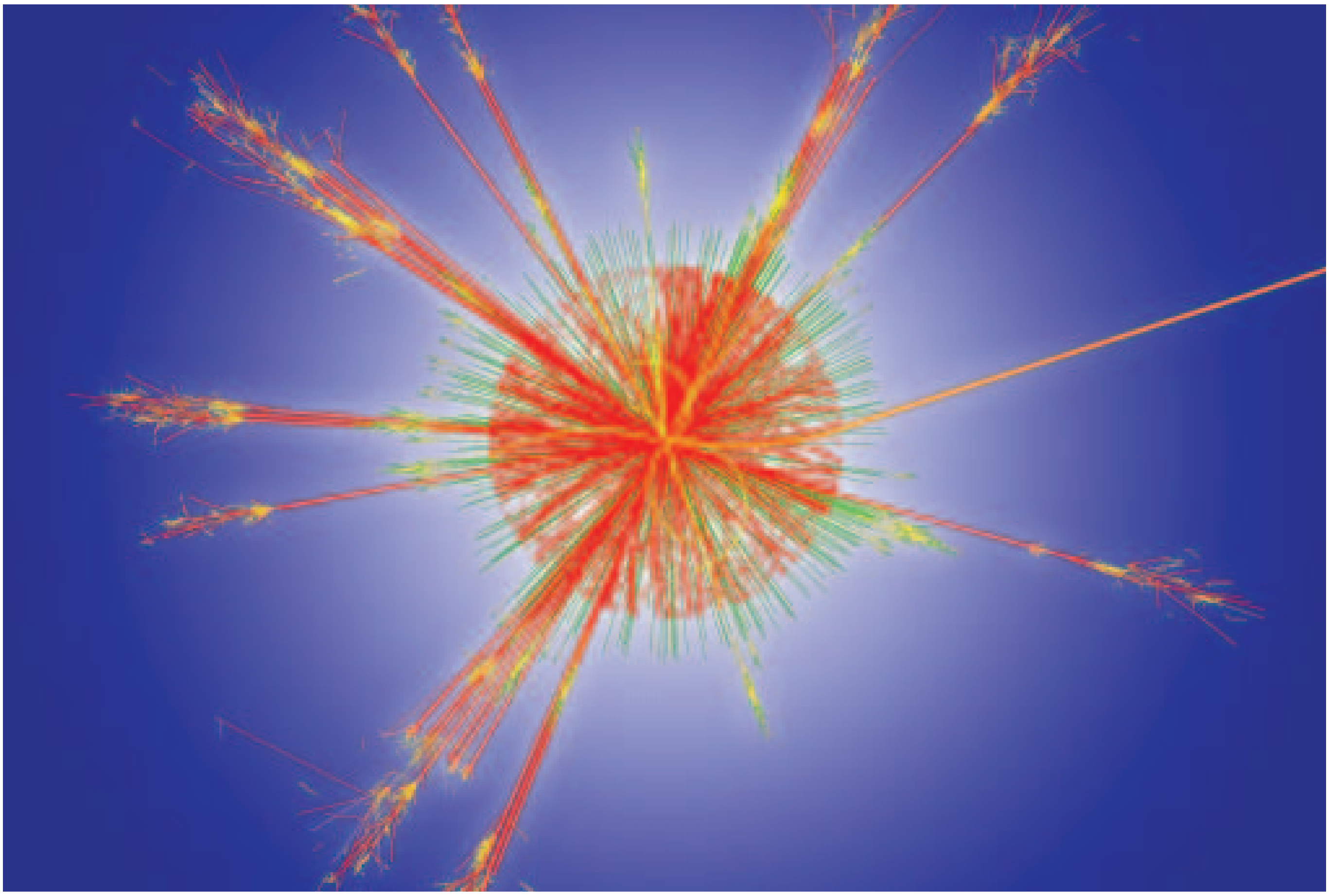


Particle physics a cornerstone of European scientific strategy

Particle physics – the study of the structure of the Universe at its most fundamental level – stands on the threshold of a new era of discovery and insight. As the scale of the experimental and theoretical challenges increases, European particle physicists need a strategy to ensure that Europe can continue to lead the exploration of this exciting domain within an increasingly global framework.

The extraordinary Universe

The modern science of particle physics is the direct descendant of ancient Greek philosophical tradition. It faces the challenge of identifying the fundamental constituents of matter and the basic rules governing their behaviour. It aims to explain how these constituents and rules relate to all physical phenomena we observe in the Universe today. We now understand a great deal about the ordinary matter from which we, and all the stars and planets, are made. We are able to predict with amazing precision the results of experiments, using a beautiful mathematical description of the fundamental particles and the way they interact, called the Standard Model. This is built upon the twin foundations of quantum mechanics and special relativity, revolutionary scientific concepts developed in Europe during the first half of the 20th century. During the second half of the 20th century, many of the key discoveries that led to the subsequent development of the Standard Model were also made in Europe. Today the Standard Model ranks alongside remarkable advances in biology, medicine, the environment, cosmology and other physical sciences as one of the greatest scientific achievements of the 20th century.

But there is much more to learn in all domains, and particle physics is no exception. Although we understand the composition of ordinary matter at its most fundamental level, we now know that it accounts for only about 4% of the total mass and energy of the Universe. The remaining 96% is made up of some new component – usually called dark matter and dark energy – about which we know very little, although we are immersed in an invisible sea of it. This missing component does not shine or reflect light, and its presence has been exposed through its effects on the gravitational forces shaping the Universe. Understanding the nature of dark matter and dark energy is just one of the big challenges for particle physics today, as we try to fill the gaps in our knowledge of the ordinary and the extraordinary.

A global endeavour

Particle physics is big science. It requires the development of huge scientific instruments that push technology to the limit. It demands concentration of facilities and intellect, and has long been organised on an international scale. In the Europe of the 1950s, 12 countries chose to combine their strengths and create a European Organization for Nuclear Research. For more than 50 years, this Organization has operated a major laboratory, CERN, near Geneva. Its Member States have grown to 20, each with a thriving domestic programme, including a number of world-class national laboratories. In addition, the particle physics community has long set an example of global collaboration, with scientists from all over the world sharing their knowledge and experience in the pursuit of common goals. It is no accident that particle physics gave rise to the World Wide Web.

A new adventure

Over the next few decades, particle physics experiments should complete our knowledge of ordinary matter, and begin to explore the extraordinary Universe of dark matter and energy. The next step on this voyage of discovery will be taken by the Large Hadron Collider accelerator at CERN. After a decade in the making, this machine, 27 kilometres in circumference, and its four mammoth particle detectors, will begin commissioning in 2007, and should soon start answering some of the most pressing questions. It will also light up the way ahead to a more complete theory and make clear which new facilities, such as the International Linear Collider, will be needed to explore and verify it.

Towards the strategy

A European strategy for particle physics is needed to meet the challenges posed by the increasingly global nature of frontier facilities. In 2005, the CERN Council formed an ad hoc scientific group to propose such a strategy. European particle physics is founded on strong national institutes, universities and laboratories, as well as CERN. In taking particle physics forward, Europe must build on the leadership it has established in the field, while at the same time engaging even more fully with the global particle physics community.

Developing the strategy

The CERN Council decided in June 2005 to set up a scientific advisory group, the strategy group, to propose a strategy for European particle physics in the decade to come. The resulting strategy document was approved by Council at a special meeting in Lisbon on 14 July 2006.

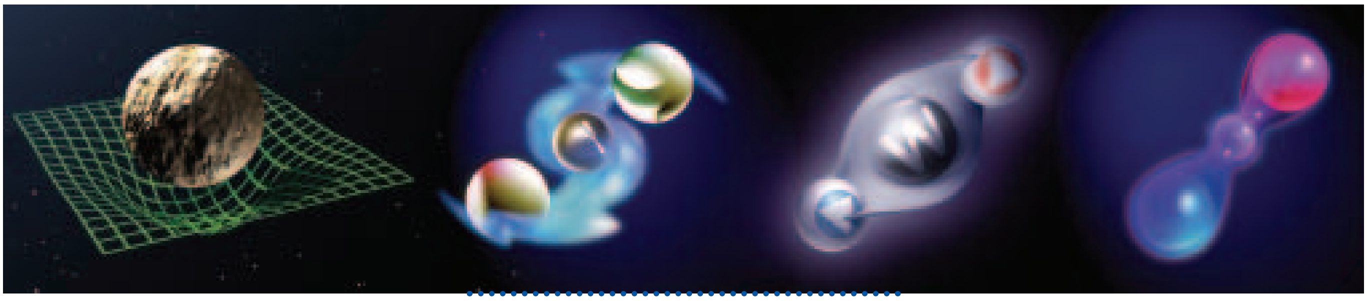
The strategy addresses:
- accelerator based particle physics
- non-accelerator based particle physics
- R&D for novel accelerator and detector technologies

It is the result of a bottom-up approach with the following key phases:
- an open symposium in Orsay in January 2006
- a strategy group meeting in Zeuthen, Berlin, in March 2006
- a dedicated meeting of CERN Council in Lisbon in July 2006

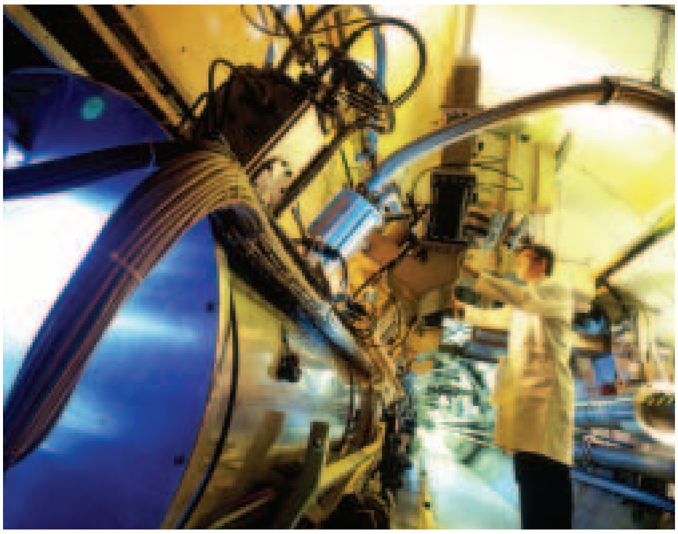
All relevant documents concerning this work are available at:
http://cern.ch/council-strategygroup/

Opening a gateway to the Universe

The giant new experiment in Geneva will soon begin to reveal more of the still well guarded secrets of the Universe. For particle physicists from the Atlantic to the Black Sea, from the Arctic to the Mediterranean, the discoveries will be a new beginning in the search for answers to fundamental questions. Why does matter have mass? Where did all the antimatter go? And what is the mystery of the missing 96% of the mass and energy of the Universe?



The Standard Model is a triumph of 20th century science. It describes the particles that make up our Universe and the forces acting between them. However, it does not explain why there are three families of matter particles, nor why there are four apparently distinct forces acting between them.



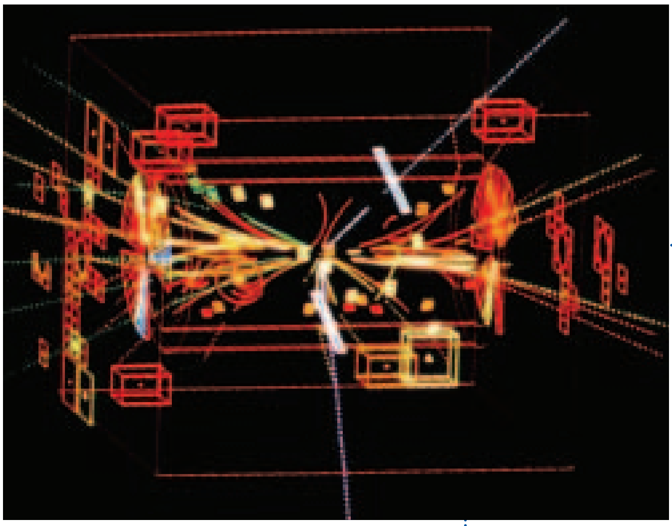
Two facilities that put the Standard Model to a gruelling test through the 1990s. Left, the European Large Electron Positron collider (LEP), which demonstrated incontrovertibly that there are three families of matter particles. Right, the SLD detector at the Stanford Linear Accelerator Center in the US.

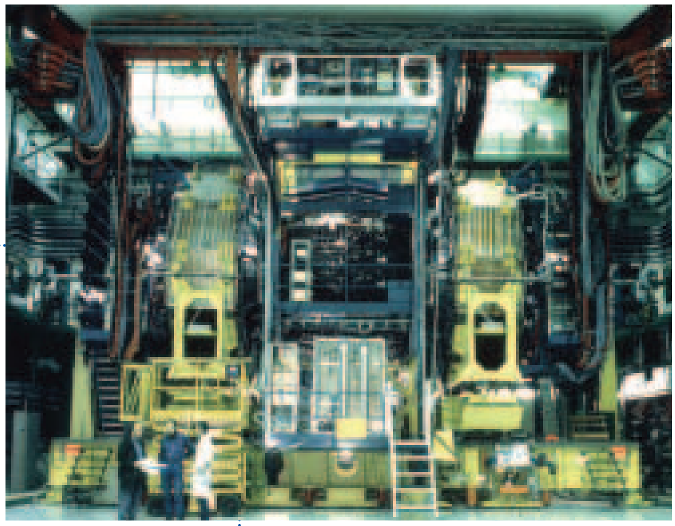
Throughout recorded history, humans have sought to understand what the Universe contains, what it is made of, and how it came to be. This search for an understanding of the matter in and around us has progressed through many stages, and particle physics is its cutting edge. The objective of particle physics is to discover the fundamental laws of Nature that govern the behaviour of the Universe: to explore the frontiers of matter, energy, space and time.

Particles and forces

The ancient Greeks and their successors went from qualitative ideas about a handful of fundamental constituents of matter – earth, air, fire and water - to the atomic theory that was finally confirmed just over a century ago. In quick succession, the discoveries of the electron, radioactivity and nuclei revealed that atoms were not fundamental. Later 20th-century experiments revealed that nuclei are themselves composed of protons and neutrons, and that these are in turn composed of yet more fundamental entities called quarks. A picture emerged, called the Standard Model, in which all physical phenomena can be reduced to a small set of indivisible particles and the forces that govern their interactions. The particles are the quarks of which protons and neutrons are composed, along with others, such as electrons, which are collectively known as leptons. Their interactions explain how the particles stick together, how they decay and how they form complex structures from the microscopic to the macroscopic scale. Modern particle physics aims to understand this framework, its origins and its implications, in greater depth.

Essential to an understanding of the components of particles are the fundamental forces that hold them together and cause many of them to decay. Electricity, magnetism and gravity are forces felt in everyday life. Inside the atom, a strong force confines quarks within protons and neutrons, which are in turn combined into nuclei, while a weak force causes the radioactive decays of some nuclei.





Left: Tracks betraying the presence of a Z particle in the UA1 detector at CERN.

Right: The UA2 detector.

The discovery of W and Z particles at CERN in the 1980s brought verification of the theory that unifies two of Nature's forces.

Together, these forces explain how the Sun shines and provides the sources of energy on which our civilization and its technologies are based.

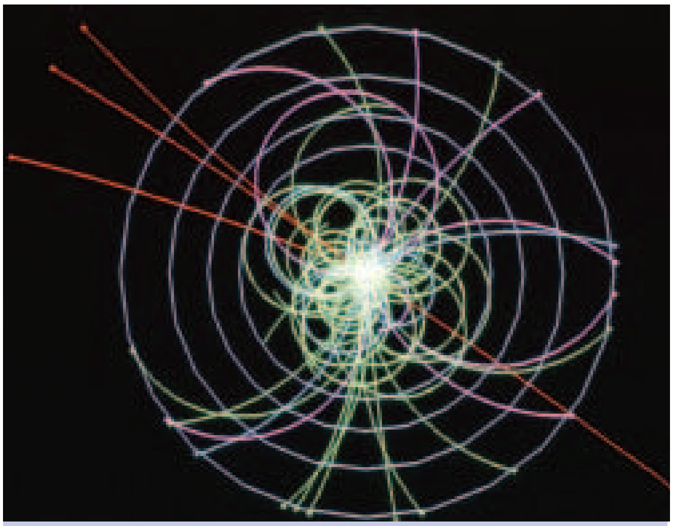
Most of our understanding of particle physics derives from experiments performed with particle accelerators. Accelerating particles to velocities close to the speed of light and bringing them into collision at very high energy allows us to exploit Einstein's equation $E=mc^2$ and to convert this energy into new particles. The higher the energy, the heavier the particles that can be produced, making it possible to explore states of matter that, while playing no apparent role in our daily life, were nevertheless present in the early instants of the Universe, when the prevalent high energy made their production possible. The study of the properties of such particles in experiments at today's large accelerators allows us, among other things, to establish how they contributed to the evolution of the Universe into what we observe today. The Standard Model accounts with extraordinary precision for the results of these experiments. It provides the mathematical instrument with which to calculate the behaviour of matter one tenth of a billionth of a second after the Big Bang, when the energy density of the Universe matched the energies achievable in today's experiments, and to extrapolate the Universe's subsequent evolution.

The Standard Model extends and generalizes the combined theory of electricity and magnetism that was developed in the 19th century, and which was revolutionized by quantum mechanics and special relativity. It includes a successful theory of the strong nuclear force and it predicted the properties of the weak force later discovered in experiments in the 1970s and 1980s. In the last decade of the 20th century, precise measurements of the properties of the weak force put the Standard Model on a very solid experimental foundation.

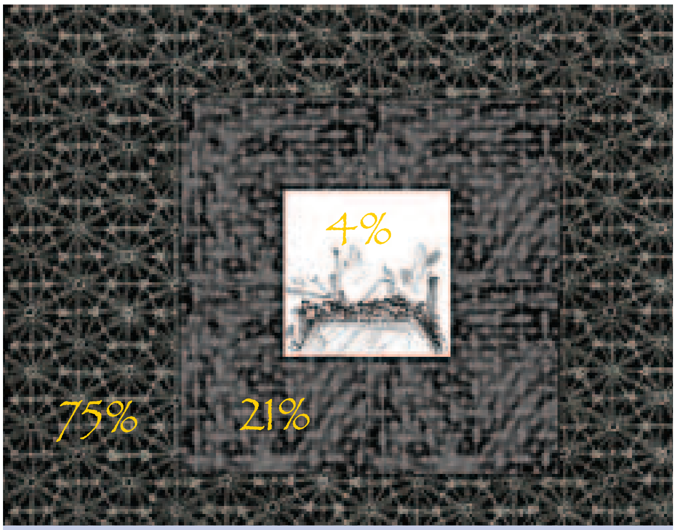
Weighty questions

The Standard Model is a triumph of human ingenuity, patience and painstaking research. It is the most accurately tested and verified theory in the history of science.

Nevertheless, the successes of the Standard Model raise deeper questions, the solutions to which are the current objectives of particle physics. We know that matter has weight. Newton taught us that weight is proportional to mass. Einstein in turn demonstrated the equivalence of mass and energy. However, nei-



Particle tracks hold the key to understanding new phenomena. In this simulation of a collision at the LHC, the red tracks originate from the decay of a Higgs particle, whose discovery would help to explain the mystery of mass.



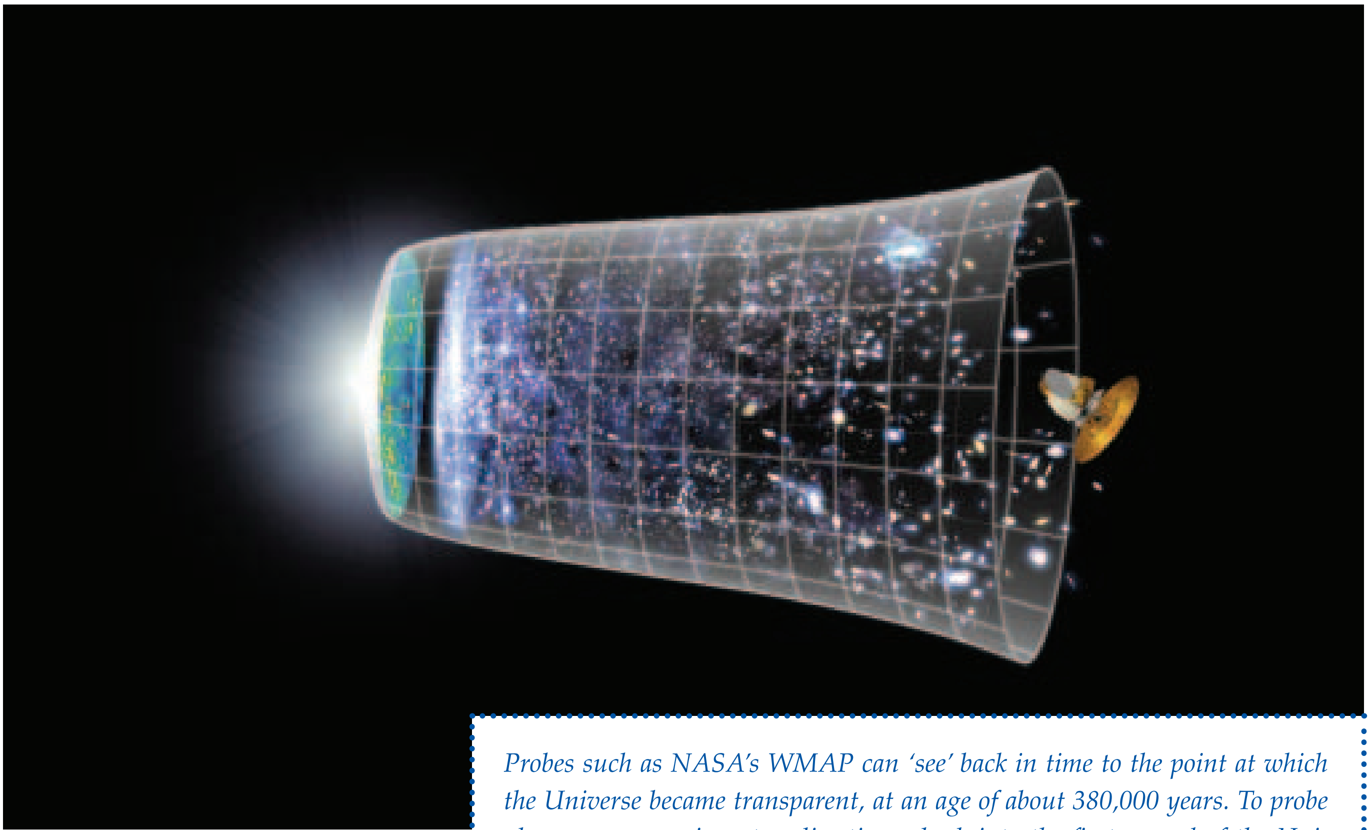
Ordinary matter accounts for just 4% of the mass and energy of the known, visible, Universe. The remaining 96% makes its presence felt through gravitational effects. Some 21% is thought to be dark matter, with the rest being dark energy.

ther Newton nor Einstein explained the origin of mass itself, or why some particles are very heavy whilst others have no mass at all. Since the mass of the electron determines the sizes of atoms, and since radioactivity is relatively uncommon because the carrier of the weak force – the W boson, a particle discovered at CERN – weighs as much as a medium-sized nucleus, understanding the origin of mass will unlock some of the most profound mysteries of the Universe.

Whatever the explanation for particle masses, it requires new physics to manifest itself at some infinitesimally small distance, only slightly smaller than that already probed by particle accelerators. This new physics is necessary to explain the great success of the Standard Model, and will be explored with the next generation of particle accelerators.

The Standard Model provides a possible mechanism to explain particle masses, known as the Higgs mechanism. This idea envisages a Universe permeated with a medium, in addition to the familiar gravitational, electric and magnetic fields, whose interactions with elementary particles provide their masses. Fluctuations in this new field should appear as a new particle, which has been named the Higgs particle. Its mass is so large and it is so rarely produced that it has escaped detection at particle accelerators until now, but the Standard Model predicts that, if it exists, it must be within the reach of the LHC experiments.

Testing this idea, and discovering the Higgs particle, is a top priority for the new generation of particle physics experiments. However, while the Higgs mechanism provides a possible way to explain the masses of particles, it does not pro-



Probes such as NASA's WMAP can 'see' back in time to the point at which the Universe became transparent, at an age of about 380,000 years. To probe phenomena occuring at earlier times, back into the first second of the Universe's life, requires particle accelerators. WMAP will soon be joined by the European Planck probe, which will further refine our understanding of the early Universe.

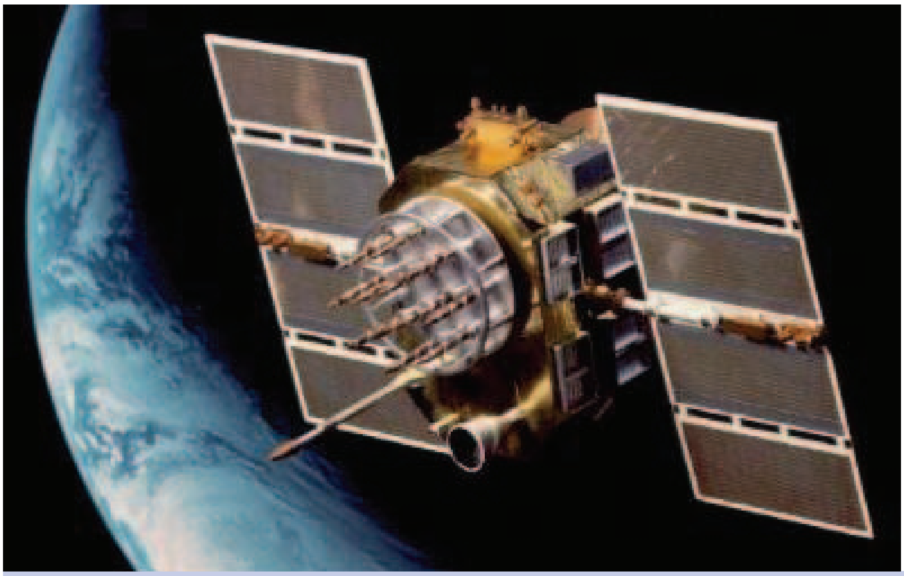
vide a satisfactory understanding of the origin of mass itself. Particle physicists expect that this understanding lies in some extension of the Standard Model, an extension that would not only provide a conclusive answer to the question of mass, but also unveil the existence of new particles and link the acquisition of mass to other mysteries of the Universe. For example, in some of the alternative proposals new particles exist in addition to the Higgs particle. The lightest of these might provide the dark matter that no telescope can detect but which must exist to explain the fabric of the Universe and the formation of structures, such as galaxies, within it. Other proposals postulate the existence of new dimensions of space that would be discernible to the next generation of accelerators.

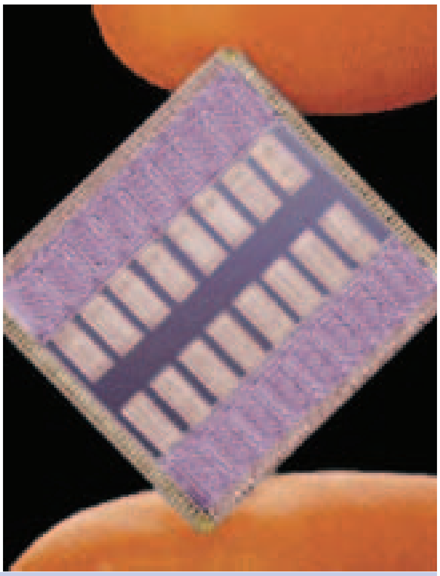
The understanding of mass is the last missing ingredient of the Standard Model. It is nevertheless likely that, as we probe at higher and higher energies, new phenomena will appear.

The extraordinary Universe

We know that only 4% of the Universe is made up of what we think of as ordinary matter. The remaining 96% is extraordinary – dark matter and energy that is all around us but invisible to us. The next generation of accelerator experiments will take the first steps into this extraordinary world.

The Universe is expanding at an accelerating rate, and must have been very hot and dense when it was young. The conditions a fraction of a second after the Big Bang are similar to those created by colliding particles together at very high energies using powerful accelerators. If we want to push the understanding of the primordial Universe to times earlier than a tenth of a billionth of a second, the time ruled by Standard Model physics, we need to push further the frontier of high-energy accelerators. This is necessary to clarify the origin of dark mat-





Left: Satellite-based global positioning systems rely on general relativity for their pinpoint accuracy. Right: The humble transistor - a quantum machine at the heart of all modern electronic devices. We rely on quantum mechanics and general relativity every day, yet the two theories remain to be reconciled.

ter and energy, and to find an explanation for the dominance of matter over antimatter in today's Universe. Going to higher energies will allow us to peer beyond the Standard Model, uncovering new phenomena and gaining a greater understanding of the workings of our Universe.

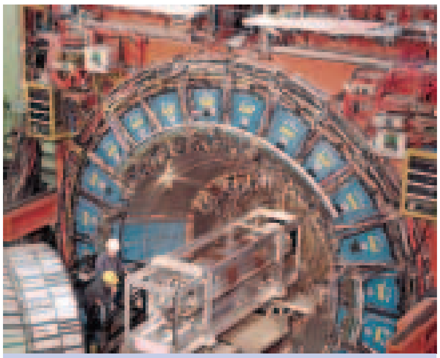
Probes such as NASA's WMAP can 'see' back in time to the point at which the Universe became transparent, at an age of about 380,000 years. To go back further, right into the first second of the Universe's life, requires particle accelerators.

In search of the superforce

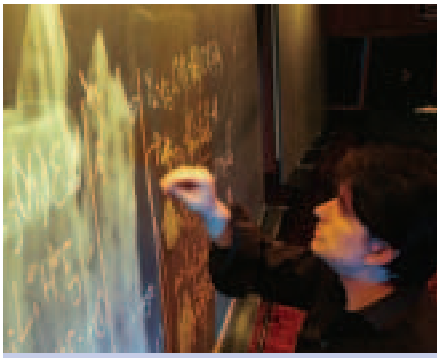
The intellectual achievement of the Standard Model is to have successfully identified a common framework describing all particles and their interactions by a unique and concise set of rules. This is underscored by the unification of two among the fundamental forces – electromagnetic and weak – and by the elegant structure within which the elementary matter particles are organized.

Three different 'families' of matter particles exist, one that makes up the ordinary stable matter composed of protons, neutrons and electrons, and two heavier families that have been revealed in cosmic rays and accelerator experiments. The particles in the extra families are unstable and, once produced, decay to the particles of the first family after a tiny fraction of a second. They play no part in the ordinary matter from which we are made. The Standard Model does not explain why there are three families of matter particles. However, they played a crucial role in the processes taking place in the early Universe. Their presence may have helped create the conditions that removed all antimatter and let the matter we are made of survive, and they may have determined the relative abundance of the light nuclei that continue to fuel the stars.

Electron-proton collisions at the HERA accelerator are probing more deeply than ever into the structure of the proton and neutron at the DESY laboratory in Germany.



CDF is one of two experiments that are currently exploring the high-energy frontier at Fermilab in the US, home to the Tevatron proton-antiproton collider.



Theoretical physicists have come up with many ideas for what lies at the high energy frontier. Experiment is about to put them to the test.

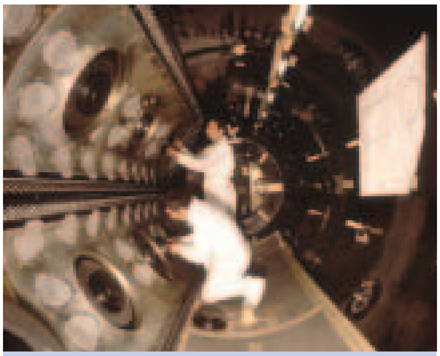
Today, we see four distinct forces at work. The mathematical framework of the Standard Model shows a strong underlying similarity between the electromagnetic, weak and strong forces. This suggests that these forces could be joined together at some very high energy scale; there is even a possibility that, at some still higher energy scale, they could be joined by gravity in a single "superforce". Experiments at accelerators, and on neutrinos produced by cosmic rays and the Sun, reinforce this idea, offering hints as to how the fundamental forces might be unified at high energies and in the very early Universe. Among the consequences of the unification of forces is the unification of matter particles, leading to the transformation of quarks into leptons, and ultimately to the possible decay of a proton into an antielectron and pure energy. If confirmed by experiments, proton decay would provide an unequivocal proof of force unification, and demonstrate matter's ultimate instability. However, although the Standard Model seems capable of describing the unification of the forces, it does not explain why they have such evidently different characteristics when we examine them at work today.

A question of scale

The deepest quandary in fundamental physics may be how to reconcile two fundamental pillars of 20th century science, quantum mechanics and the general theory of relativity. Both theories work, and we put them to use in everyday life.

Quantum mechanics underpins our understanding of the microworld – the workings of atoms and the fundamental particles. Without it, there would be no transistors and no consumer electronics. General relativity is a theory of gravity. It governs the large-scale behaviour of the Universe, and is taken into account in achieving pinpoint accuracy in global positioning systems.

Direct evidence for gluons, carriers of the strong force that binds quarks together, was first seen at DESY in 1979 in patterns of tracks like this in the TASSO detector.



Inside the Gargamelle bubble chamber at CERN, which in 1973 found the first evidence for particle interactions predicted by the theory that unifies the electromagnetic and weak forces.

OPAL, one of four detectors at CERN that measured the number of families of fundamental particles, and which put the Standard Model to a gruelling experimental test.

Quantum mechanics and the general theory of relativity were the greatest achievements in fundamental physics in the first half of the 20th century, yet the two seem to be mutually incompatible. Any reconciliation is likely to require new insights into the natures of space and time themselves.

Through the energy frontier

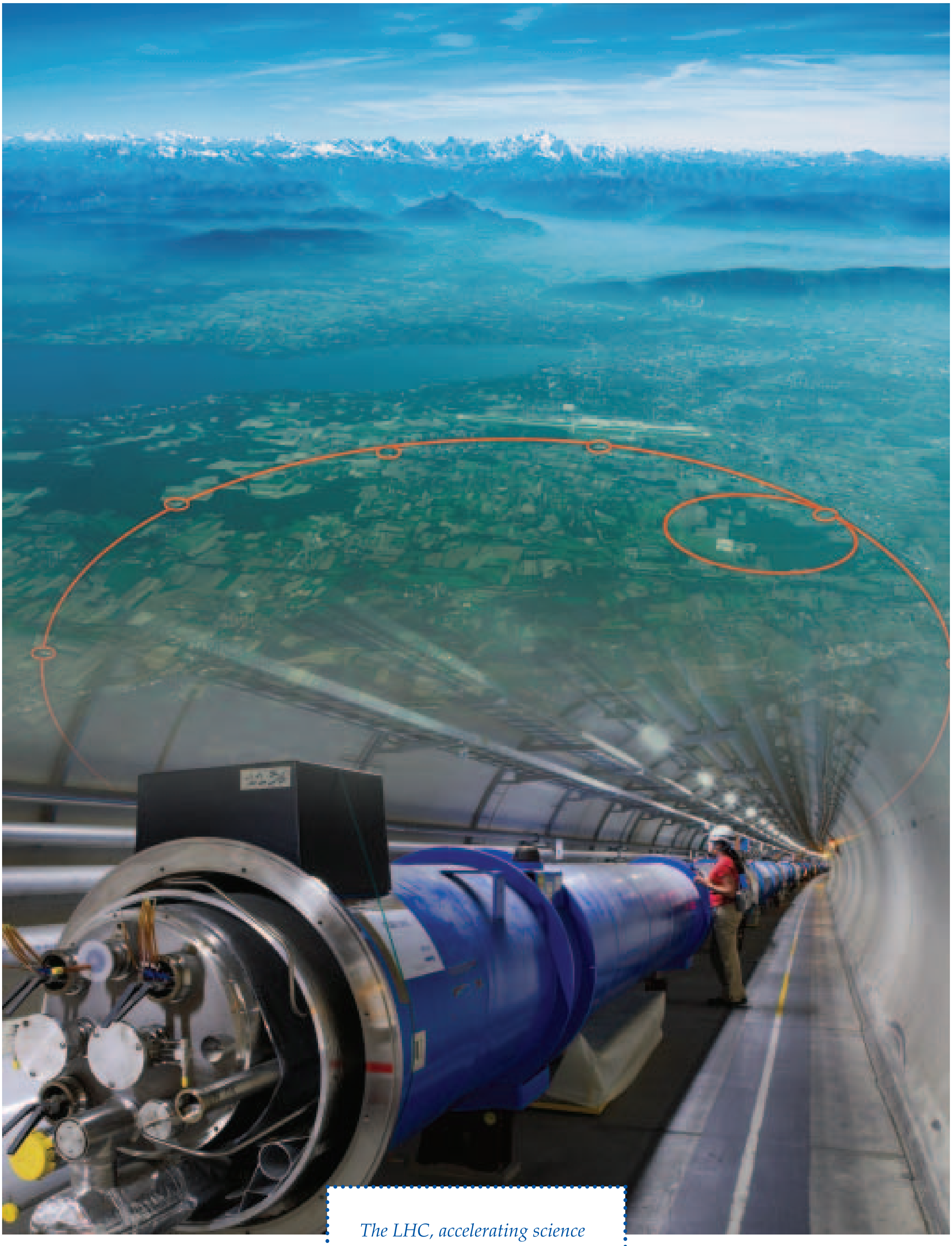
We will not know which, if any, of these theories has been endorsed by Nature until the next generation of accelerators starts to provide experimental results. The Large Hadron Collider (LHC) currently nearing completion at the CERN laboratory near Geneva will provide first direct information on physics at the next distance or energy scale. Its findings will guide scientists towards the answers to many of the questions discussed here, and will undoubtedly trigger new ones. Making sense of the new scenarios unveiled by the LHC, through the development of new theories and by designing and performing new experiments, will be a great challenge to physicists worldwide.

If the LHC discovers a candidate for the Higgs particle, will it have all the properties required for its role as mass donor to all the elementary particles? If the LHC finds some new particles not predicted by the Standard Model, could they provide all the dark matter in the Universe? If the LHC finds new dimensions of space, how many will there be, how large, and of what shape? Will the new physics cast light on the problems of force unification or the reconciliation of quantum mechanics and gravity? Could it also be probed in non-accelerator experiments?

Finding the answers to these questions requires a worldwide effort, within which Europe should play a leading role, defining a strategy assembled from several complementary scientific elements. New experiments at the high-energy frontier are central to this strategy, but other tactics may be useful. Lower-energy accelerators with high-intensity beams, for example, may have a role to play.

What new accelerators will we need to unravel fully the problems of mass and unification? Are the technologies needed to build these accelerators and their accompanying detectors already in hand, or do they require further development? Do we need higher-precision tests of the Standard Model and better understanding of the forces and particles it contains? What are the roles for future non-accelerator experiments? What are the roles for theoretical physics in guiding and interpreting future experiments?

The LHC will soon revolutionize our understanding of matter, forces and space. Now is the time to get ready to exploit the scientific opportunities it will reveal.



The LHC, accelerating science

Illuminating the high energy frontier

The Large Hadron Collider will generate billions of collisions every second. It will amass mountains of data every year. It will illuminate a new landscape of physics and trigger a new age of discovery. It could even reveal extra dimensions of spacetime.

Particle physics is a voyage of exploration, and like any such adventure it passes through alternating cycles of discovery and understanding. With the Large Hadron Collider (LHC), currently under construction at CERN, we are about to enter a new era.

Physicists have been painstakingly putting the Standard Model together for four decades, in great detail. They are now ready to explore what lies beyond. Although there are many theories as to what that might be, we are essentially in the dark. The beam that will throw a searching light on a new landscape of physics beyond the Standard Model is the LHC.

The LHC will be the world's most powerful particle accelerator. When running at full energy, it will collide protons at a combined energy of 14 TeV (see box), giving access to physics at an energy scale about ten times higher than has been open to exploration so far.

Frontier science

Particle physicists are very excited by the LHC. There are very strong reasons to believe that the energy frontier it will reach is crucial. For example, the mechanism that governs particle masses should become visible. This mechanism may announce itself through the production of one or more so-called Higgs particles, so a major theme for the LHC is to search for and study these.

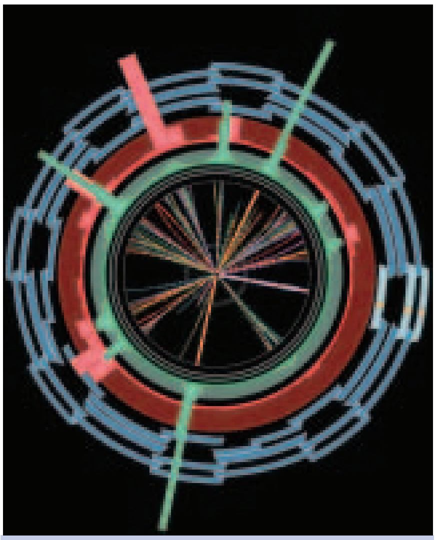
The Standard Model requires Higgs particles so that it can continue to describe Nature at the energies that will be probed by the LHC. If the Higgs mechanism is the correct hypothesis, then our calculations and measurements tell us that Higgs particles must be produced at the LHC. And if there are no Higgs particles? Then it seems unavoidable that something else must emerge from the shadows as an alternative to the Higgs mechanism.

Theorists speculate as to what might happen at the LHC and at high energies, where the Standard Model is no longer enough. By far the most popular extension of the Standard Model is called supersymmetry. This provides a way for the strengths of the electromagnetic, weak and strong forces to converge naturally to the same value at very high energy, leading to unification of these forces. Supersymmetry also predicts a range of so-far unobserved particles and so provides a possible explanation for the enigmatic cosmic dark matter. If supersymmetry is right, the lightest supersymmetric particles could be produced at the LHC.

Another possible road beyond the Standard Model requires the introduction of extra dimensions of space. These would

What is a TeV?

A TeV is a unit of energy used in physics. One TeV is roughly equivalent to the energy of motion carried by a mosquito. What makes the LHC special is that it concentrates fourteen times this energy into a space a trillion times smaller than a mosquito.



Particle fireworks. Each collision gives rise to a spray of new particles such as these, simulated in the ATLAS detector. This pattern shows what the detector would see if a mini black hole were produced and immediately decayed.

With its extremely demanding computing and networking needs, it is no accident that particle physics attracts the IT industry. The CERN openlab for datagrid applications, for example, brings cutting edge science and industry together to the benefit of both.

be invisible to us much as a third dimension would be beyond the experience of an ant crawling on a flat sheet of paper. If extra dimensions exist, they could produce measurable effects in the energy region to be explored by the LHC. This would allow the LHC to enter the domain of quantum gravity, providing experimental data that will help us to understand how to reconcile quantum mechanics and gravity.

Frontier technology

The LHC is a machine of superlatives. It is the world's largest superconducting installation. Its interior is colder than outer space. It contains a vacuum more perfect than anywhere between the Earth and the Moon. It will produce billions of proton-proton collisions per second. All this makes it not only a machine for frontier physics, but also a machine for frontier technology.

Housed in a 27 km long circular tunnel, the LHC is a true giant. It is the most complex scientific instrument ever constructed. At its heart are superconducting magnets based on coils made from niobium-titanium wire that conducts electricity without resistance at low temperature. The LHC magnets will operate at 1.9 degrees above absolute zero (about -271 C), and they are cooled by superfluid helium.

A major feature of these magnets is their two-in-one design. To provide opposite magnetic fields for the two beams travelling around the machine in opposite directions, two coils are embedded within a single structure. The LHC uses 1232 dipole magnets to guide the beam, together with a few thousand additional magnets to focus the beams and fine-tune the orbits. Altogether, they use enough superconducting filament to stretch to the Sun and back five times, with enough left over for a few trips to the Moon.

The high intensity of the LHC beams,

The concentric structure of the CMS detector is clearly visible during its assembly. When the LHC is running protons will collide head on at the centre, and the various layers will measure different particle properties, building up a complete picture of each collision recorded.

Assembly of a ring-imaging Cherenkov detector for the LHCb detector is carried out under extremely clean conditions.

which gives rise to the enormous collision rate, poses its own challenges. For example, at full intensity there will be enough energy in each beam to melt about 500 kg of copper. This is 200 times more than the highest stored energies achieved in any previous accelerator.

Each time protons collide inside a particle detector, between 100 and 1000 particles will emerge. Since there will be up to six hundred million collisions per second in each detector, this adds up to an enormous amount of data. Powerful electronic systems will select the interesting collisions, reject those that are uninteresting, and record the remaining data. Even after rigorous selection, the volume of data to be recorded by each experiment would fill some 100 thousand DVDs every year.

Two detectors called ATLAS and CMS have been designed to see anything that the LHC will reveal. Each surrounds a point at which protons collide, and measures the energies and trajectories of the emerging particles. Each has been prepared by a collaboration of around 2000 researchers from around the world, a prime example of different cultures working towards a common goal. Top of their priority lists are Higgs particles and supersymmetry.

Two other detectors, ALICE and LHCb are also under construction. ALICE will study matter as it was in the first instants of the Universe, in an attempt to understand how it evolved into matter as we know it today. LHCb will focus on nature's preference for matter over antimatter.

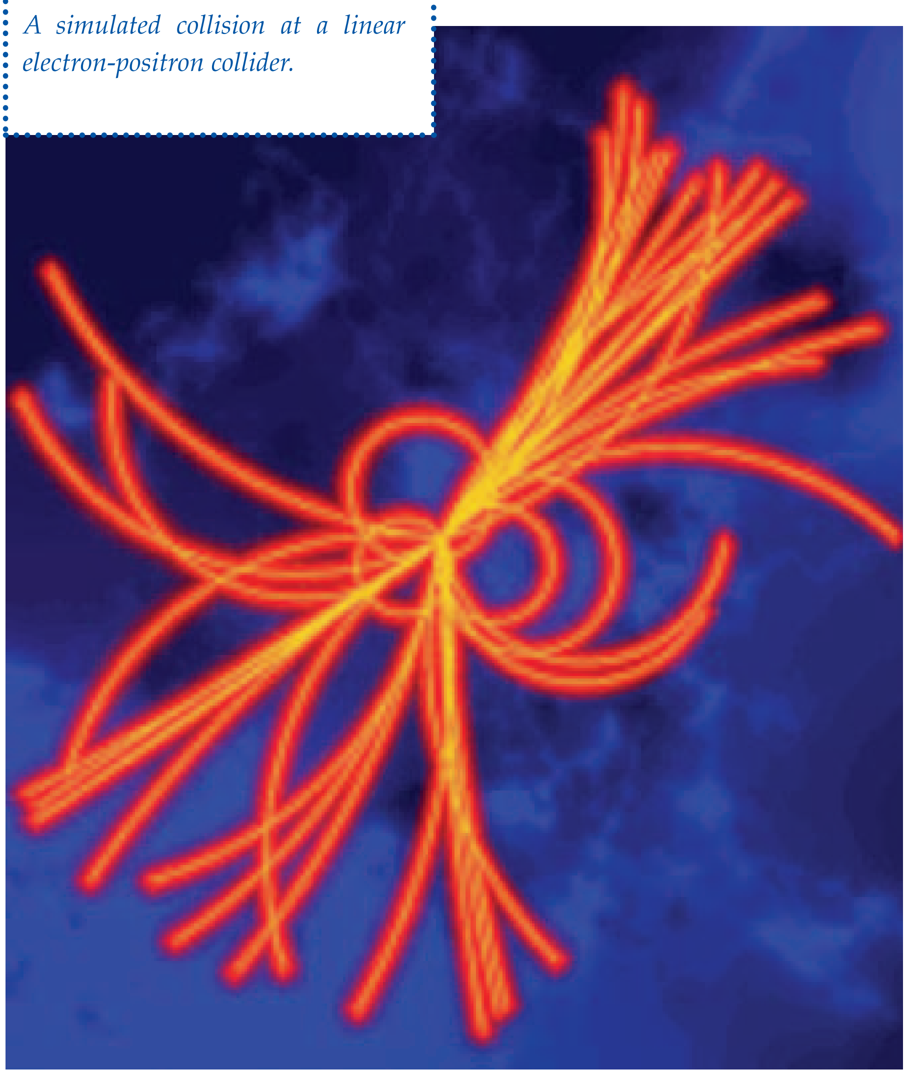
Frontier thinking

Conceived in the 1980s, approved in the 1990s, and scheduled to start commissioning in 2007, the LHC is a huge investment and a long-term project. In its first phase of operation it is set to illuminate a vast new terrain of physics for exploration, and set a course for the future. What new facilities that future will demand remains to be seen, but the LHC will operate for at least a decade at the forefront of science. Beyond that, the LHC could itself become part of the future landscape, through upgrades to push the number of collisions higher, or to increase their energy beyond the current frontier.

Zooming in on new discoveries

Turn on, tune in and see what drops out: discoveries by the new LHC could lead straight to a new and even more challenging research tool. That is because it is one thing to see a new horizon, quite another to explore it.

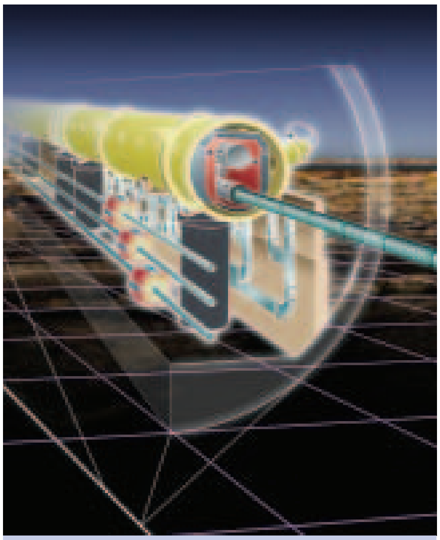
A simulated collision at a linear electron-positron collider.



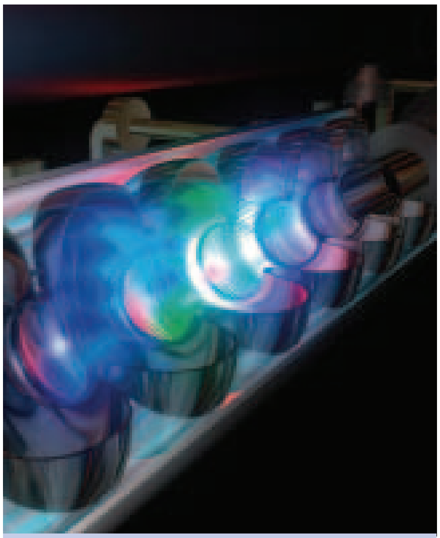
If a searchlight is the best way to illuminate a large area of terrain, then a powerful spotlight is the best tool for exploring the detail. Electron-positron colliders are the spotlights of particle physics, and their finely focused beams will probe the smallest features.

Circular proton colliders such as the LHC are the instruments of choice for discovery in particle physics. They can cover a broad spectrum of energy, so they illuminate vast new landscapes, and bring anything new into sharp relief. However, what is a strength for discovery is a weakness for precision investigation where the ability to tune the energy precisely is needed, and this is what electron-positron machines do best.

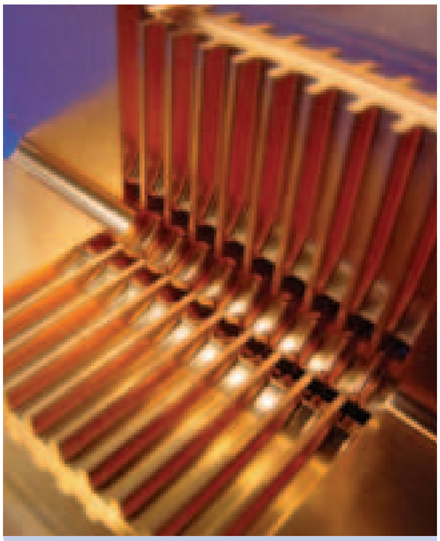
The basic difference between the two is the nature of the collided particles. Protons are composite particles made up of smaller entities called quarks and gluons, which share the total energy in a random way. Since the interesting physics comes from collisions between these smaller entities, proton machines produce collisions with a broad range of energy.



An artist's impression of a possible international linear collider.



A simulation of the field inside superconducting cavities developed by the DESY laboratory for a future linear collider. Cavities such as this are also powering DESY's free electron laser facility (pp26-27).



A prototype copper accelerating structure for the Compact Linear Collider study, which is investigating novel accelerating technology.

Going straight

Electrons and positrons are fundamental particles so the energy of a beam can be precisely tuned to home in on whatever energy the physicists need. But electron and positron beams do not like to be steered around corners. They lose energy as they curve round, making it harder to reach the highest energies. The machine that will zoom in on the LHC's discoveries is therefore likely to be straight instead of circular.

A linear electron-positron collider would deliver precise data to build on the discoveries of the LHC, it would completely measure features of particles discovered at the LHC that are within its reach, perhaps describing Higgs particles and the supersymmetric particle that could explain the nature of the dark matter and energy in the Universe.

Universities and laboratories from all over the world are already working on a detailed design for an International Linear Collider (ILC). Physicists and engineers with decades of experience have teamed up with young scientists to figure out the best way to build this extremely challenging machine. For the first time, this effort is being coordinated from the outset on a global scale, because wherever such a machine is built it will be a facility for the world. European scientists, working closely with researchers from other continents, lead the field in many areas of this research.

Parallel lines

They plan to smash electrons and positrons together in two 20-kilometre superconducting linear accelerators, initially producing collisions at energies of 0.5 TeV. This is within the energy range to be explored by the LHC. In parallel, a European initiative in novel acceleration technology, known as the Compact Linear Collider (CLIC) study, could deliver energies up to several TeV, should the LHC's discoveries point to the need for higher energy.

By the end of the decade, the ILC technical design will be complete, the LHC will have illuminated the features of the new TeV-scale landscape, and the CLIC study will have demonstrated whether the new technology is viable. These three results will help the global particle physics community to take an informed decision on the shape of experiments to come.

Whatever that decision may be, an overlap in operating time between the LHC and a linear collider would allow the data from one machine to influence investigations at the other. The spotlight and the searchlight will work in tandem. Rather than seeing double, particle physicists will see in depth and gain new perspectives.

Matter and antimatter
a question of balance

We exist because antimatter does not – at least, not in lethal quantities. But what happened to the missing half of all substance? Why does the Universe seem to favour one subatomic twin, rather than the other? To answer such questions, particle physicists must go back to the beginning.

The wire chamber of the KLOE detector at Italy's Frascati laboratory makes a beautiful sight. KLOE is engaged in research to understand matter-antimatter asymmetry.

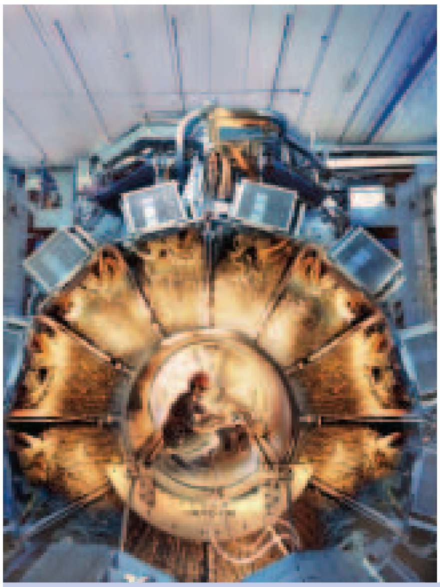
Antimatter is described by theory, it is created by cosmic rays in collisions with the atmosphere and it is studied in laboratories. Scientists believe that it must have existed in huge quantities a few moments after the Big Bang when matter was also created. But no significant amount of antimatter has so far been found in our Universe. If the same amounts of matter and antimatter were present at the beginning, where has all the antimatter gone?

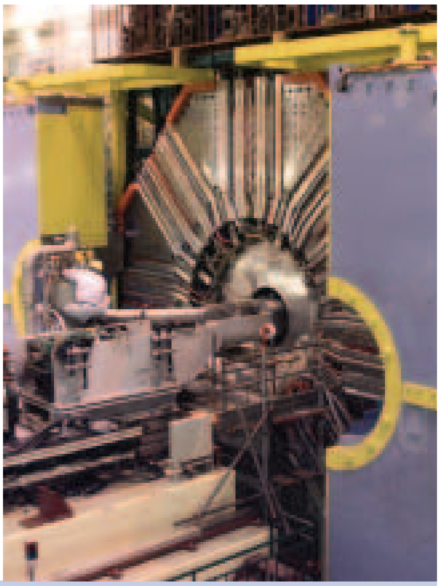
The theory of antimatter, developed in the 1930s, says that for every type of matter particle, there exists an equivalent particle of antimatter. Antimatter particles have the same mass, but opposite charge to their matter equivalents. In 1932, the discovery in cosmic rays of the positron, the antimatter counterpart of the electron, provided the first experimental confirmation that antimatter was more than just a theory.

With the discovery of antiparticles, interest shifted to studies of their properties. If we really do live in a Universe of matter, then something must have happened to the antimatter. Nature must have a preference. The quest to understand this preference takes place at the level of the particles and antiparticles themselves.

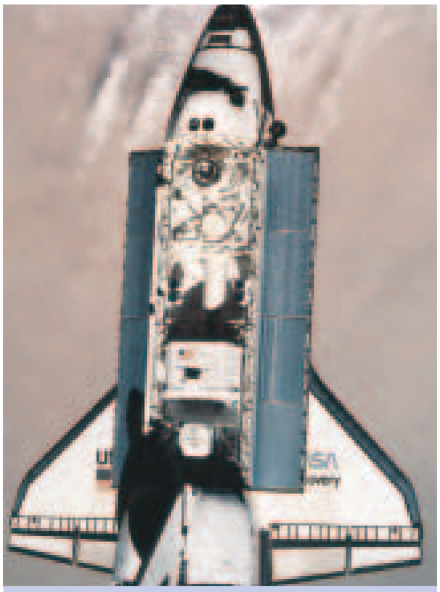
Broken symmetry

In 1964 physicists working with particles called neutral kaons showed that the labels matter and antimatter are more than just convention. There really is a difference. Neutral kaons break the so-called CP symmetry (see box), which would be a perfect symmetry if Nature were even handed. Many years after this first hint





The US BaBar detector (left) and the Japanese Belle detector have made precise measurements of matter-antimatter asymmetry in B mesons.



The small payload at the back of the space shuttle is the Alpha Magnetic Spectrometer, AMS, an experiment that flew on the shuttle in 1998 to look for antimatter in space.

of Nature's bias, experiments were able to reveal more. The rate of disintegration into two pions of a neutral kaon and of a neutral anti-kaon is not the same, a process called direct CP-violation, a phenomenon that truly distinguishes particles from antiparticles.

This result was not entirely unexpected. CP-symmetry breaking is one of the conditions necessary to develop an imbalance between matter and antimatter in the Universe. Kaons provided the first evidence, but frustratingly the amount of CP-symmetry breaking seen was not nearly enough to account for the observed matter-antimatter imbalance in the Universe. More recently, experiments have confirmed that CP-symmetry is also broken in particles called B mesons, but here too the amount is not enough to account for the apparent bias towards matter across the Universe.

Perhaps there is another explanation for the apparent absence of antimatter. Experiments have been sent into space, or high into the atmosphere, to look for evidence of antimatter in the cosmos. If these were to detect a single complex nucleus made entirely of antiparticles - anti-helium or anti-carbon, for example - that would be powerful evidence that somewhere in space large amounts of antimatter exist in the form of anti-stars, or anti-galaxies. So far, however, not a single anti-nucleus has been seen.

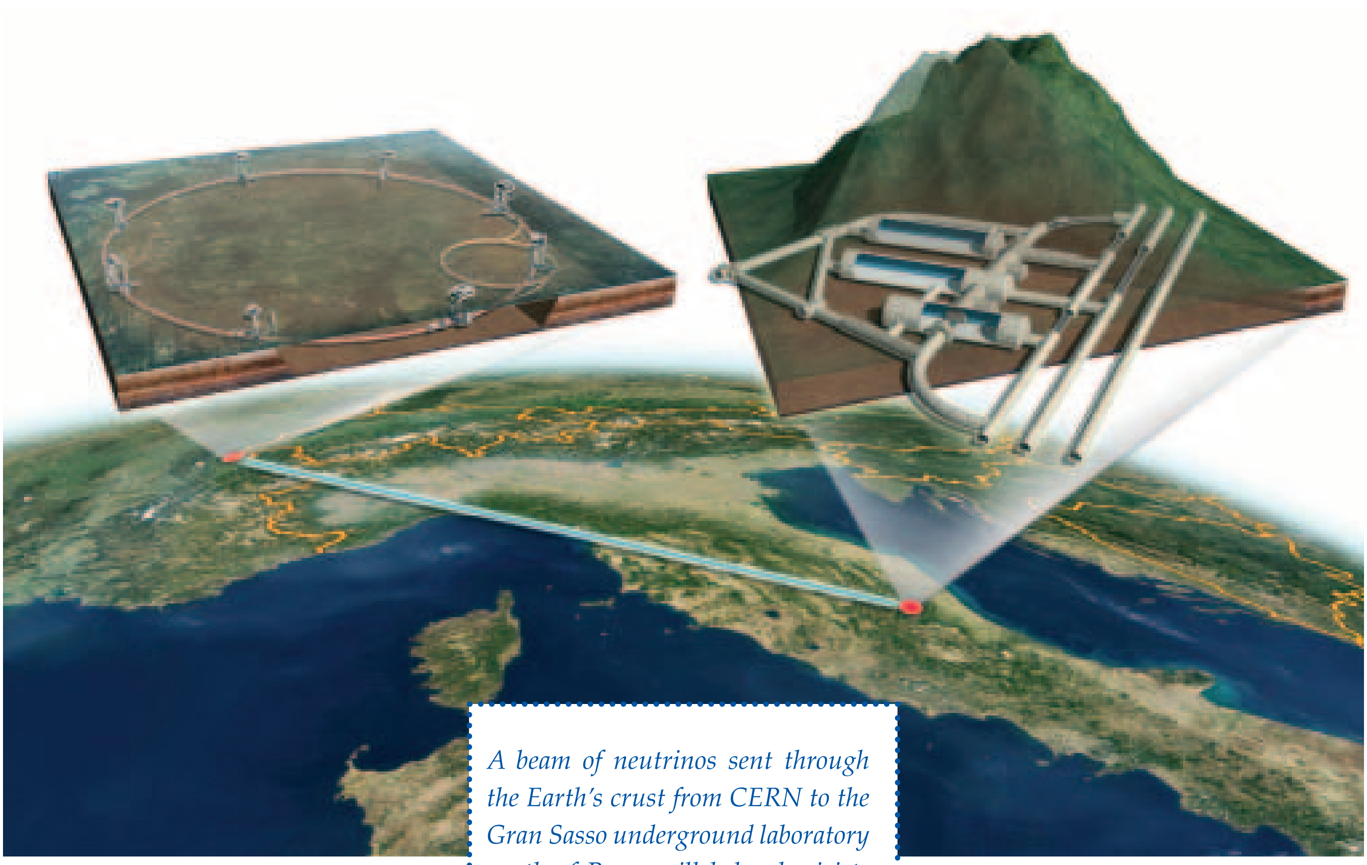
The quest to understand the matter-antimatter imbalance continues in laboratories such as CERN where anti-hydrogen atoms can be produced and studied. Preparations have begun to compare the properties of atoms of anti-hydrogen with those of hydrogen, the simplest and most precisely known atoms. It is too early to say what such comparisons will bring, but one thing is for certain: neither searches for antimatter in space, nor existing measurements of matter-antimatter asymmetry in the laboratory, can explain Nature's observed preference for matter. Some as yet unknown phenomenon must be responsible and the challenge for particle physics is to find it.

CP – the imperfect mirror

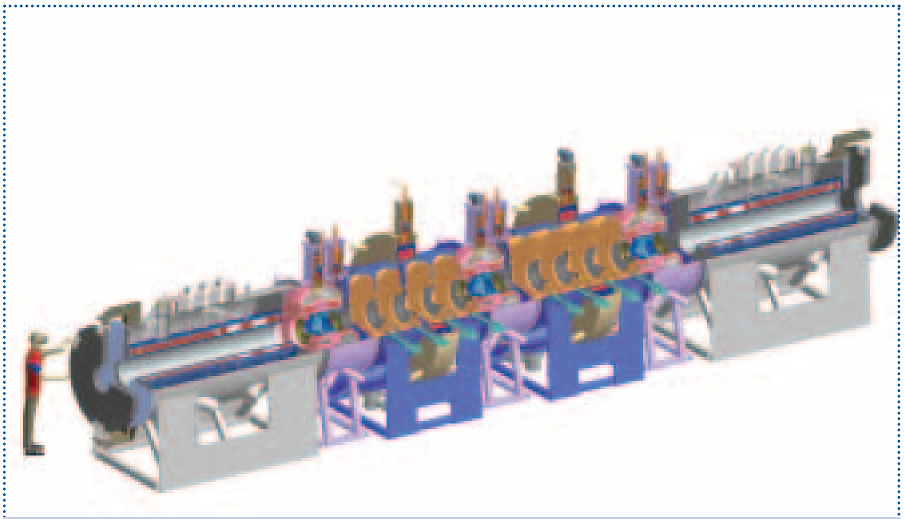
Each of C and P are symmetries that are conserved in most particle interactions. C represents swapping the charges of all the particles in an interaction. If the interaction looks the same before and after, then C symmetry is said to be conserved. If not, C is a broken symmetry. P is called parity and it corresponds to a mirror vision that reverses all three spatial co-ordinates. Physicists once thought that each of these symmetries was conserved in particle interactions, but then in 1956 experiments demonstrated that P could be broken. At the time the CP combination was thought to be conserved, but this too proved not to be the case.

Three neutrinos that made our world

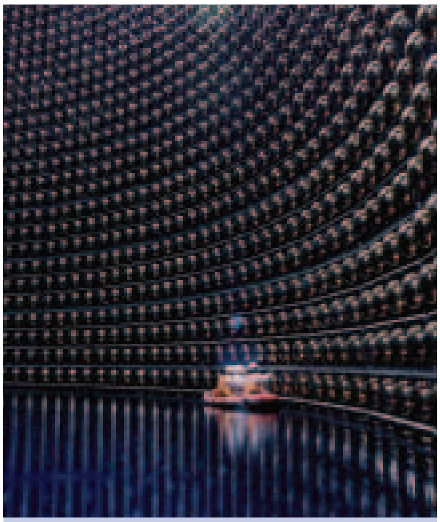
Don't make light of them. These ghostly particles can pass through planets as if they were not there but somehow the neutrinos know how to throw their weight around. Tiny particles that began as notional units of subatomic profit and loss are now credited with a role in shaping the Universe.



A beam of neutrinos sent through the Earth's crust from CERN to the Gran Sasso underground laboratory north of Rome will help physicists to understand neutrinos better.



An engineering drawing of the Muon Ionisation Cooling Experiment (MICE) at the CCLRC Rutherford Appleton Laboratory in the UK. This experiment is an essential step in R&D towards the realization of a neutrino "factory".



The giant Super-Kamiokande detector in Japan found the first evidence for neutrino oscillation in 1998.

Neutrinos: almost massless, they could pass through 50 light years of lead without interacting, yet in the first billionths of a second after the Big Bang they could have determined the shape of the Universe today. As particle physics shifts its emphasis towards why things are the way they are, new tools will allow us to study these mysterious particles, and determine the role they played when the Universe was born.

Neutrinos were proposed in 1930, to solve an accountancy puzzle in experimental physics. When certain atoms decay, emitting an electron, something else is needed to balance the energy budget. That something else is a neutrino. In the 1970s, neutrinos helped provide the experimental foundation of modern particle physics. Three and only three types of neutrinos have been discovered, and the Standard Model, in which neutrinos bear no mass, has become a powerful and consistent theory for almost all phenomena observed in particle physics today.

But not quite all, for neutrinos have also become the first heralds of physics from beyond the Standard Model. So-called neutrino oscillations, in which the tiny particles can change from one type to another, were observed in neutrinos emitted by the Sun and in cosmic rays, and then confirmed by experiments with neutrinos produced in nuclear reactors and particle accelerators. Neutrino oscillations are clear evidence that there is physics beyond the Standard Model, because these oscillations can only happen if neutrinos have mass.

Massive consequences

The fact that neutrinos have mass has profound consequences. Having mass but no charge, neutrinos could be their own antiparticles, a property possessed by no other fundamental particles. And the existence of three types of neutrinos could lead to antineutrinos with different properties from neutrinos. Neither of these phenomena has yet been observed, but if both were true, neutrinos would hold the key to one of the longest standing mysteries of the Universe.

We imagine the Big Bang as the transformation of a world of pure energy into a world of particles, with large and equal numbers of particles and antiparticles. Since matter and antimatter annihilate on contact, it is a mystery that only matter seems to remain. A small transition of some of the antimatter into matter would have allowed matter to remain to build our Universe, a possibility that massive neutrinos could offer.

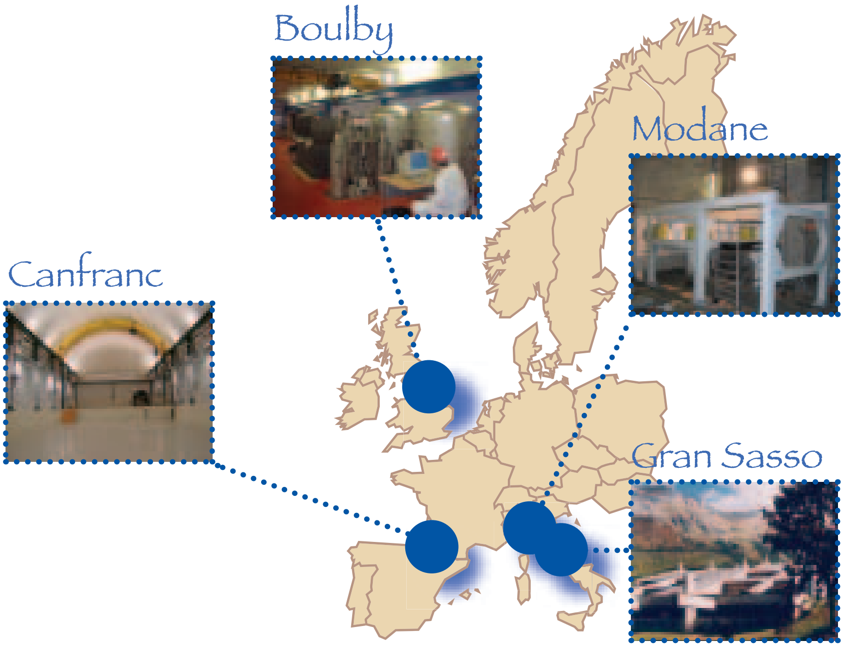
The discovery that neutrinos have mass has stimulated the emergence of a growing community of particle physicists in pursuit of these questions, with new experiments around the world. In Europe, a neutrino beam is being sent from CERN to the Gran Sasso laboratory 730 kilometres away. In Japan and the US similar programmes exist or are planned in the near future.

But neutrinos are slippery subjects. They hardly ever interact – they pass through other matter as if it wasn't there – and it is difficult to produce them in a pure state. Detailed studies will require more precise instruments and more intense beams than any available today. New detectors, weighing up to a million tons, are being discussed, together with very intense and pure neutrino beams produced from the storage of unstable nuclei or from unstable particles like muons. In Europe, physicists have begun to test these new techniques, preparing to discover just how these elusive particles may have shaped our Universe.

Underground physics

exploring rare phenomena

Somewhere in the subatomic world, a neutrino hits the spot, a WIMP shows its dark side and a proton gives up the ghost. These vanishingly rare events could never be detected on the irradiated and bombarded surface of the Earth. So particle physics has gone deep underground, to add new meaning to research in depth.



Europe has four world-class deep underground laboratories, where experiments are looking for rare phenomena that could help us answer questions about matter instability, antimatter, dark matter and dark energy.

Laboratories deep underground, shielded by the Earth's crust from the confusion of particles that rain down on the surface in the form of cosmic rays, provide an ideal location for exploring rare phenomena. They complement and reinforce research programmes at accelerator laboratories. Europe has four world-class deep underground laboratories: three close to road or rail tunnels under mountains in France, Italy and Spain, and one deep in a mine in the United Kingdom. They study neutrinos, search for dark matter and watch for proton decay.

Ghostly particles

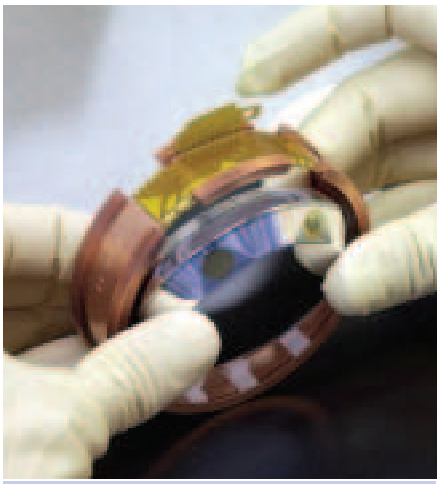
Neutrinos are difficult to study: they interact with matter so rarely. For this reason underground facilities are good places to study them. Whether looking for the rare interactions of neutrinos from space, or in a beam from an accelerator on Earth, deep underground laboratories provide the isolation that will maximise the chance of seeing something interesting. Although we know that neutrinos have mass, we still do not know what that mass is. And although we know that they oscillate between one kind and another, we have yet to understand fully the oscillation process.

Experiments at underground laboratories could also help us find out whether neutrinos are their own antiparticles or not, a question that may be linked to the apparent imbalance between matter and antimatter in the Universe. If neutrinos are their own antiparticles, then certain nuclei should decay by emitting two electrons and no neutrinos in a process called neutrinoless double beta decay. With neutrinos or not: the answer has profound consequences, because it would provide an answer to the mystery of the missing antimatter. Deep underground laboratories are also used for studies of neutrinos sent from accelerator laboratories far away (see pp 22-23).

Dark matter

Dark matter accounts for about 21% of the Universe. Ordinary matter adds another 4% or so and dark energy accounts for everything else. Dark energy is largely in the realm of cosmology, but dark

This experiment at Gran Sasso is patiently looking for the phenomenon of neutrinoless double beta decay, which could help us to understand the apparent absence of antimatter in the Universe.



The Edelweiss experiment in the underground laboratory at Modane in France searches for particles known as WIMPs with detectors made from germanium.

At work in the apparently contradictory environment of a clean room within a mine. The UK's Boulby mine hosts a research programme looking for dark matter.

matter should be acessible to particle physics. It could be made of so-far undetected particles, relics from the Big Bang that have been roaming the Universe ever since, making their presence known only through their gravitational influence. Whatever they are, the fact that we have never detected any makes deep underground laboratories, with their quiet conditions, good places to look.

The first indication of dark matter came more than 70 years ago from observations on galaxies and on clusters of galaxies. For example, close inspection showed that the speeds at which galaxies moved within a cluster was very different from what would be expected if visible matter were all that was needed to hold the cluster together. Later, the phenomenon was confirmed through studies of the rotation of spiral galaxies. The results suggested that the apparently flat-looking spiral galaxies must be embedded in an invisible spherical halo of dark matter.

Cosmologists and particle physicists have begun to move towards the same conclusion: dark matter must be made of things that are massive but undetectable, the so-called weakly interacting massive particles, or WIMPs. In particle physics, studies of the fundamental particles have led to the development of supersymmetry, a theory that provides a more complete picture of the particle world than the Standard Model, and predicts a range of extra particles. Could some of these extra particles be cosmology's WIMPs? Over the coming years, researchers at underground laboratories will work closely with their cousins at accelerator laboratories to find out.

At accelerator laboratories, researchers try to make the new particles and then observe their decays. In underground laboratories there are two approaches. One is to search for WIMPs indirectly, by looking for particles such as neutrinos that would emerge from WIMP annihilations in high-density places like the Sun. The other is to look for signals that a WIMP has slammed into a nucleus inside a sensitive detector. Because WIMPs lead a sort of double existence, mixed up with our Universe though hardly interacting with it, these events would be rare: nobody expects to detect more than a few events per year in the most ambitious detector currently conceivable.

The big picture

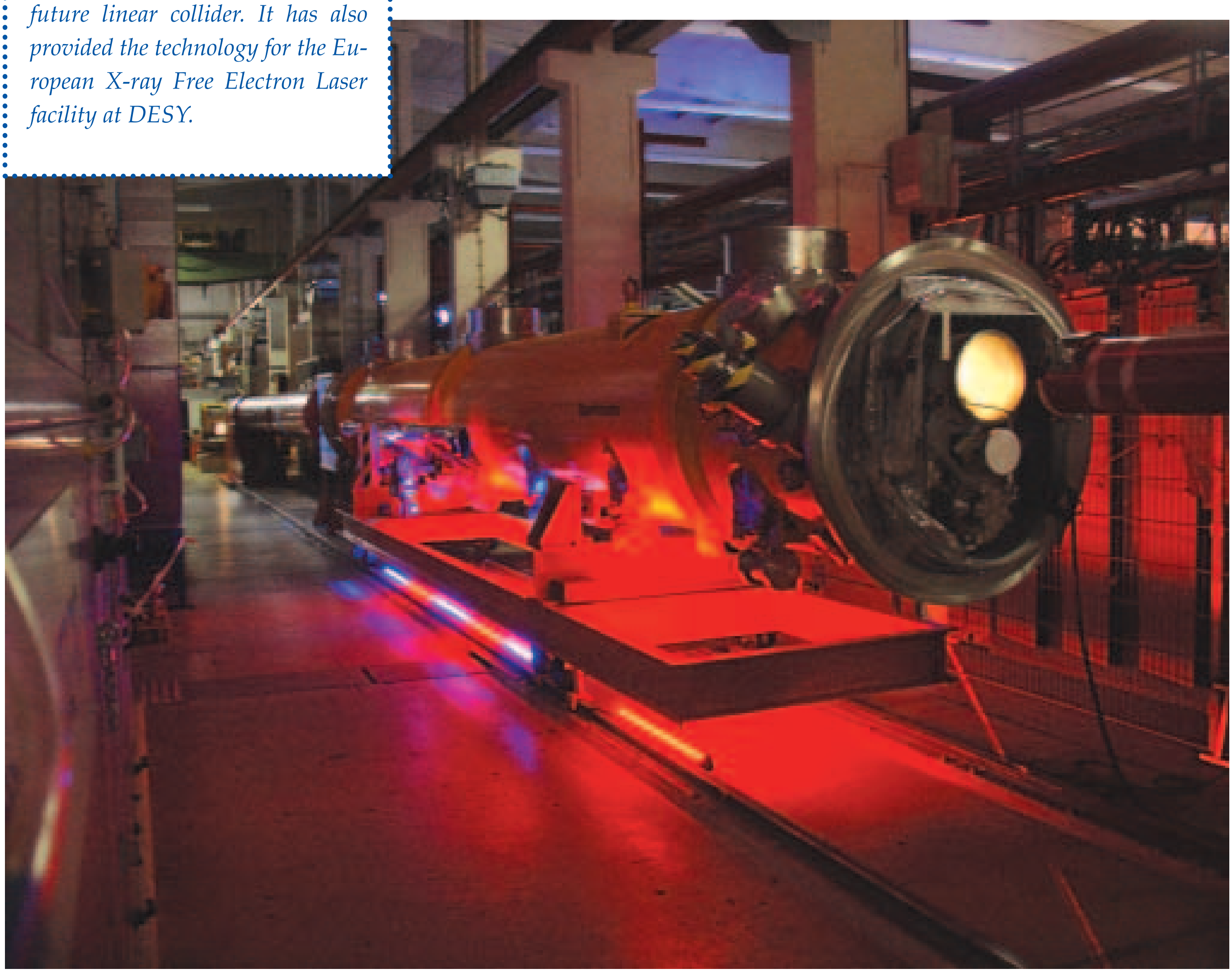
Could all of Nature's seemingly different forces be manifestations of the same thing? One of the ultimate goals of particle physics is to find out, and a big step on the way would be to see a proton decay. Protons are the most stable of all composite particles, with an average lifetime of at least 10^{33} years: a million billion billion times longer than the Universe has so far existed. But theories that enable Nature's forces to be unified also predict that protons must decay. The only way to find out is to observe very large quantities of protons, since if they do decay, each year a few will do so long before their average life expectancy. European physicists are part of the global effort to design large underground detectors for this task.

Light sources powered by particle physics

Certain kinds of particle accelerators have energy to spare. That was a problem, once. But the radiation that spills from curved beams now lights up the invisible intricacies of manufacture and medicine. No wonder Europe's scientists took a shine to the synchrotron.

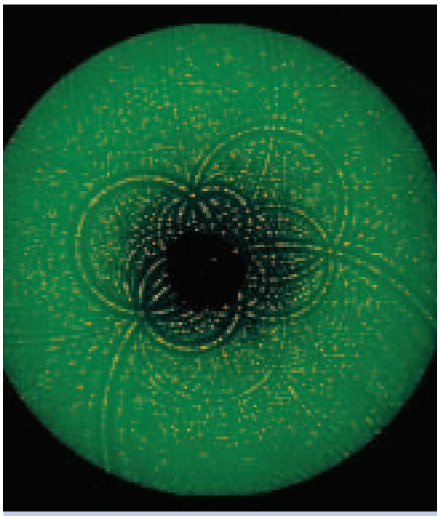
Their brilliance, their intensity, their coherence... scientists swoon over the virtues of accelerator-based light sources. These are now among the most important tools of research, from material science to molecular biology, and they began in particle physics. Accelerators are the basic tools of particle physics, but they are versatile instruments that can be used in many ways. Today, more than 60 of them serve as light sources in over 20 countries all around the world. Light sources are a prime example of how today's fundamental research provides tomorrow's applications

The TESLA test facility at the DESY laboratory in Hamburg is a valuable proving ground for a future linear collider. It has also provided the technology for the European X-ray Free Electron Laser facility at DESY.



Undulators like this one at the European Synchrotron Radiation Facility shake photons from electron beams.

Installing a sample on a protein crystallography beamline at the Swiss Light Source.



Diffraction images like this one from HASYLAB at DESY in Hamburg are produced when a protein crystal is irradiated with X-rays from a particle accelerator. Using X-ray diffraction, scientists can decode the internal structure of complex protein molecules.

Wide-ranging applications

Charged particles that travel on curved paths at almost the speed of light emit a wide spectrum of electromagnetic radiation. Accelerator-based light sources make use of this radiation, and the most useful wavelength they deliver is that of invisible X-rays, around 10 millionths of a millimetre. That is roughly the size of an atom and the study of atoms is what light sources do best: they serve as super-microscopes that can peer into atomic structures in materials and biological cells.

The results are new and fundamental insights with a remarkable range of applications in industry and medicine. Light source results contribute to the development of computer chips, catalysts and LED-screens. They bring about advances in welding seams, bone replacements and anti-viral medication, to name but a few examples.

Rooted in physics

Light sources were first developed in the 1960s at particle accelerator laboratories. The researchers exploited a phenomenon that is a nuisance for particle physics itself, but which has become an invaluable tool for applied science: synchrotron radiation. Synchrotron radiation means that particles lose energy when they follow curved paths: this is exasperating for particle physicists, who want ever-higher energies from their accelerated particles. But one man's poison is another man's meat, and it soon became clear that this nuisance radiation could be put to good use. The first generation of light sources consequently piggybacked on research programmes at particle physics laboratories.

Since the 1960s, new generations of light sources have been developed. Many circular accelerators called synchrotrons have been developed specifically to make this once-undesirable radiation, and specialised devices called wigglers and undulators have been devised to shake light out of the beams in ways that can serve drug designers or materials technologists. Today, many third generation light sources are in operation around the world, but particle physics has not simply taken a back seat.

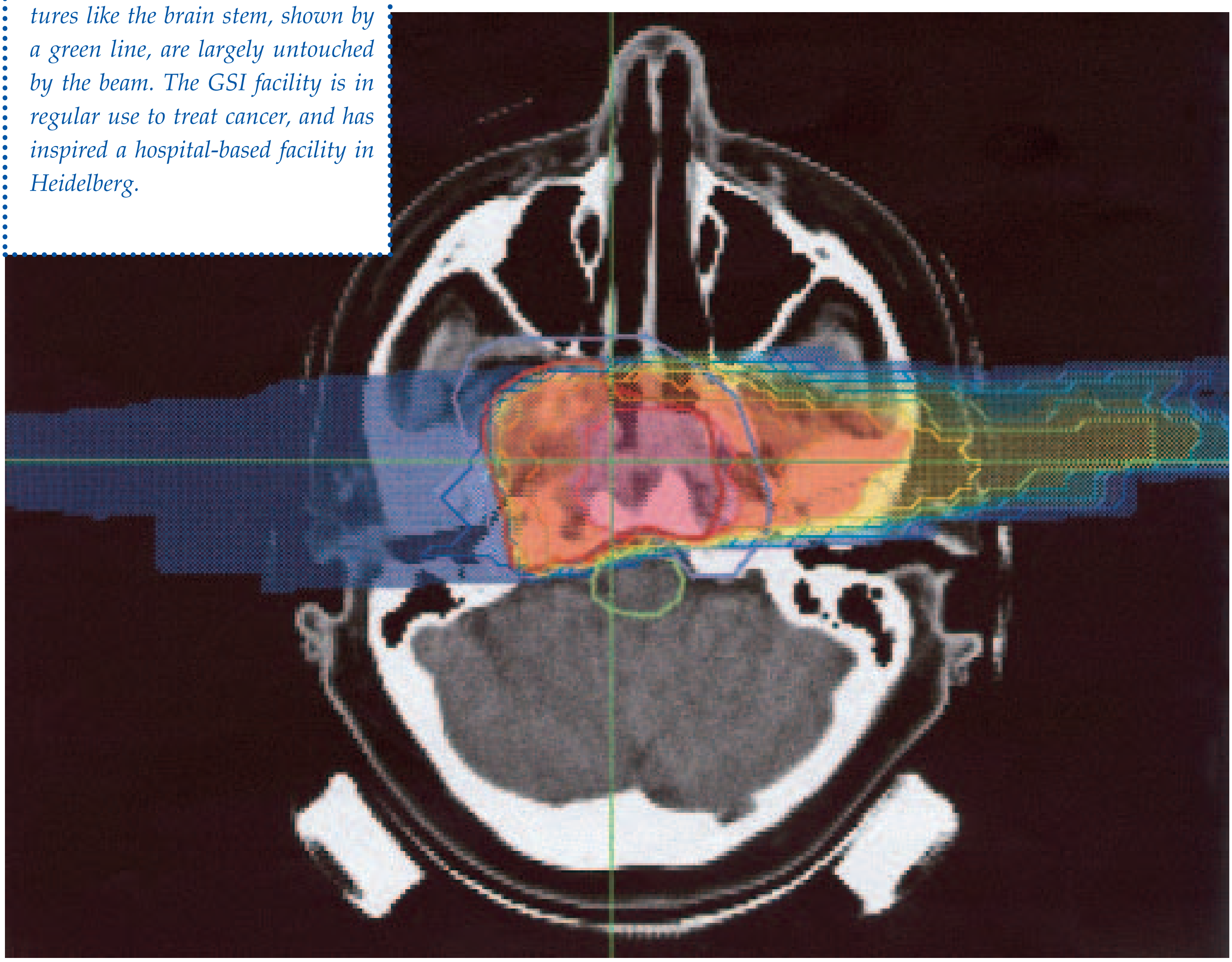
The fourth generation

A fourth generation of light sources is just around the corner. These will be a radical departure from the first three generations' sources, and once again they have emerged directly from contemporary particle accelerator technology. Fourth generation light sources go by the name of free-electron lasers, or FELs, and they are based on linear electron accelerators currently under development for the next frontier in particle physics. FELs are poised to open a whole new window onto the nano-world. Their pulsed laser-like beams even make it possible to film dynamic processes on an atomic level. Research on the world's first X-ray free-electron laser, XFEL, started at the DESY laboratory in 2005. This 300-metre device is a prototype for a 3-kilometre European XFEL facility due to start up in 2013.

Applications in medicine

Particle and nuclear physics have begun to power medical treatment as well as basic research. Beams developed to explore the Universe could also reach intractable tumours. And detectors fashioned to witness subatomic mayhem have begun to help doctors map the human metabolism.

A section through the head of the first patient to undergo hadron therapy at the GSI laboratory in Darmstadt. It is overlaid with the physical dose distribution for a proton beam that comes from the right. Critical structures like the brain stem, shown by a green line, are largely untouched by the beam. The GSI facility is in regular use to treat cancer, and has inspired a hospital-based facility in Heidelberg.



Crystals like these, developed by the Crystal Clear Collaboration, are being used in experiments at the LHC. Similar crystals from a previous generation of experiments have found application in medical diagnostic techniques such as PET.

High-quality detector, accelerator, and beam technologies – the tools of particle physics - are being deployed to create better diagnostic techniques in medicine and to provide new forms of radiation treatment of disease.

Diagnosis

The detectors developed for particle physics must spot subatomic particles that survive for tiny fractions of a second: so they provide precision, sensitivity and high-speed response. These attributes are valuable in medicine, where there is a demand for accurate, fast diagnostic imaging that uses as little radiation as possible. There are now semiconductor detectors under development that will detect single X-rays or photons and provide enhanced contrast. This could mean better X-ray images for the doctor as well as a lower X-ray dose for the patient.

Emission tomography is an increasingly important method for imaging in both diagnosis and treatment. The patient takes a dose of a radioactive tracer, and the radiographer tracks its distribution through the body. The main techniques are PET (positron emission tomography) and SPECT (single photon emission computed tomography). In each, an array of detectors senses the radiation emitted as the tracer arrives at its target within the patient. SPECT uses tracers that emit gamma-rays, while in PET the tracer emits positrons, which annihilate with electrons in the surrounding atoms to produce back-to-back pairs of gamma rays.

Detectors developed for particle physics are now being applied to improve the performance of both techniques. In traditional SPECT, for example, few of the emitted gamma rays are really observed, as they must first pass through tiny holes in lead collimators to define their direction before detection. Silicon detectors could be designed to recognise the direction of the gamma rays without the need for collimation: the pay-off would be more precise information and surer diagnosis from a smaller dose of tracer.

Therapy

Every day, in radiation treatment centres around the globe, thousands of patients are treated with X-rays produced at linear electron accelerators. Now in many countries another kind of treatment, known as hadron therapy, is on the way. Hadron therapy makes use of strongly interacting particles – hadrons – that deposit most of their energy close to the end of their range in matter. This means that most of the radiation gets all the way to a tumour inside the body, while causing much less damage to the healthy tissue around it than, for example, with X-rays.

The particles that could kill off cancer cells are protons and carbon ions – nuclei of carbon atoms. Proton therapy is well suited to cases in which a tumour is close to organs at risk. Carbon ion beams, being much more ionizing, can control tumours that are resistant both to X-rays and to protons. By the beginning of 2006, around 45 000 patients had been treated with proton beams and some 2500 with carbon ions at centres around the world.

Hadron therapy requires a circular accelerator to provide the beams and large 'gantries' to deliver the radiation to patients. These complex high-tech systems run effectively and continuously because of the experience developed for understanding the subatomic world through research in nuclear and particle physics.
Proton-therapy facilities exist in France, Germany, Italy, Russia, Sweden, Switzerland and the UK. Recent initiatives in accelerator laboratories in Europe have led to important steps in the development and construction of dual centres for protons and carbon ions in hospitals. The Heidelberg Ion Therapy (HIT) Centre designed by the GSI laboratory in Darmstadt was approved in 2001 and the first treatment will take place in 2007. Construction of the Italian national centre CNAO started in 2002 and will be finished in 2007. At PSI in Switzerland there is a new superconducting cyclotron for proton therapy and related research. Further centres are under construction or planned in Wiener Neustadt in Austria, Lyon in France and Uppsala in Sweden.

From the Web to the Grid

New dimensions of space exist – in theory. New dimensions in cyberspace are now a reality. Particle physics invented the World Wide Web. Now the field is in the vanguard of something even bigger that may change the way research is done around the world. Who can predict the power and the social impact of the Grid?

Blue skies research has down-to-earth benefits. The pursuit of fundamental science can change our daily lives in unexpected ways. It may be difficult for many teenagers today to imagine a world without the World Wide Web. But when they were born, this technology was just in its infancy. It was developed at CERN for use by high energy physicists. Now, in the era of the Large Hadron Collider, the needs of particle physicists are driving the development of an even more powerful concept. It is called the Grid. Will this be just as revolutionary as the Web?

First came the Internet

It is important to understand the past before we speculate about the future. The Internet, which was developed in the 1970s, connects together millions of computers worldwide. The World Wide Web is a service that uses the Internet, and allows computers to share information. If the Web is compared with a parcel delivery service, then the Internet is the transport infrastructure (roads, rail, air). The Internet supports services such as the Web and e-mail.

Why was the Web invented at CERN?

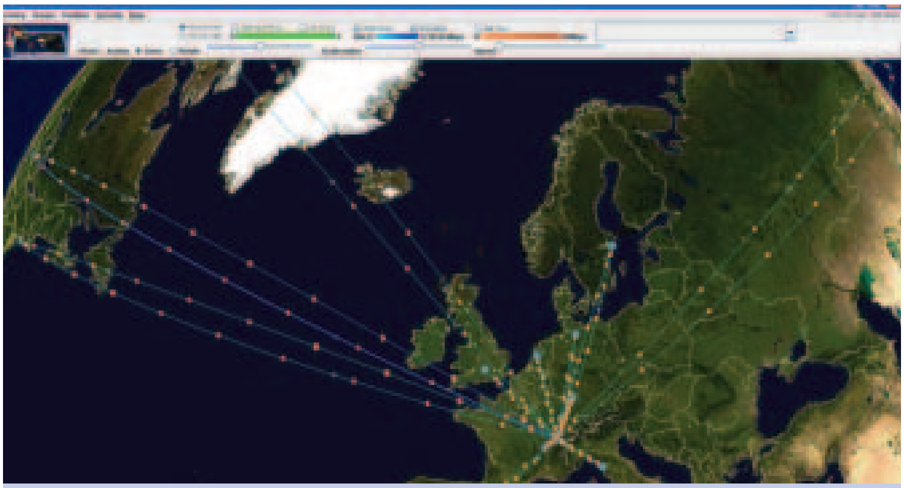
Science is a community effort, which depends on free access to information. Research at CERN involves more than 6700 scientists from 85 countries, who must share information on a global scale. In 1989, CERN researcher Tim Berners-Lee proposed a new approach to the management of general information about accelerators and experiments at CERN. This proposal launched the World Wide Web.

Revolution or evolution?

In some ways, the Web was an evolution of computer networking, integrating several existing technologies, such as hypertext. But it rapidly gained popularity, first amongst scientists in other domains, and then – when browsers such as Netscape became available – with the general public. As a result, today global commerce and finance are dependent on the Web, and new Web-based technologies such as blogs and podcasts are fundamentally changing the media industry. The Web has spawned a revolution.

A simple plaque in a corridor at CERN marks the birthplace of the World Wide Web.

The Grid links computing and data storage resources from around the world into a seamless whole.



Testing the Grid. This map shows the path of real data flowing out from CERN to a few selected grid nodes during an LHC computing grid data challenge.

What is the Grid?

The Grid is a service for sharing computer power and data storage capacity in a geographically distributed way. Like the Web, the Grid is a service that runs on the Internet. Unlike the Web, there is no uniform standard or protocol for the Grid today; rather there are many different Grids for different applications. Some Grids link resources on a local or national scale. Scientific Grids, such as the LHC Computing Grid (LCG) led by CERN, link together major computing centres.

How does the Grid work?

The essential ingredient is the 'middleware', which is software that allows the user to access remote data and processing power in a simple, reliable and efficient way. The middleware also manages security, monitoring, accounting and other features of the Grid. The underlying physical infrastructure of the Grid consists of clusters of PCs, supercomputers, tape and disk storage systems, as well as the networks that link them together.

What does the Grid do for particle physics?

When fully operational, the LHC experiments will each produce roughly 1 million Gigabytes (some 100 thousand DVDs) of data annually. Thousands of scientists can only access and analyse so much data if they unite the computing resources of hundreds of research institutes around the globe into a single computing Grid.

Will the Grid replace supercomputers?

Grids like LCG are good at solving problems that can be divided into relatively small independent tasks, and can thus rely on clusters of PCs, where each processor works alone. But some scientific problems require frequent high-speed communication between processors, and therefore need a supercomputer where hundreds or thousands of processors are able to work together efficiently.

An example is the notoriously intractable problem of quantum chromodynamics (QCD), the fundamental theory of the strong force that binds protons and neutrons. Supercomputers involving thousands of processors are beginning to reveal what the theory predicts. It is even possible to join geographically dispersed supercomputers into a Grid. So supercomputers and Grids are really complementary approaches.

How will the Grid affect you?

Around 2,000 computers in 11 British laboratories linked up in a Grid project recently to simulate 300,000 compounds and electronically sample them for properties that might help combat the avian flu virus H5N1. It was an exercise that might have tied up one computer for 100 years. The Grid is already changing the way science is done and is starting to have an impact in the commercial and financial worlds.

CERN also leads the world's largest multiscience Grid project, Enabling Grids for E-sciencE, which is supported by the European Union. Its impact on a number of computer and data-intensive fields includes:

- speeding up the search for new drugs and facilitating computer-based medical diagnostics
- simplifying disaster relief by sharing data globally and accelerating forecasting simulations of floods and volcanic activity
- helping geophysical analysis for oil exploration, as well as enabling the design of future fusion reactors
- supporting distributed search and cataloguing for electronic libraries
- running complex financial simulation programs.

Particle physics in Europe

CERN, the European Organization for Nuclear Research, has its headquarters in Geneva. At present, its Member States are Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom. India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO have Observer status.

DAPNIA
The DAPNIA laboratory is dedicated to research into the fundamental laws of the Universe. Its research portfolio includes astrophysics, particle physics and nuclear physics.

DESY
The German Electron Synchrotron (DESY) is one of the world's leading accelerator centres. It is a national research centre with locations in Hamburg and Zeuthen, near Berlin. It is host to the HERA collider, and is an important centre for light source research.

LAL
The Linear Accelerator Laboratory (LAL) near Paris has a 50 year tradition at the frontier of research. Its main area of research is particle physics, complemented by a strong engagement with cosmology and astrophysics.

LNF
The Frascati laboratory (LNF) near Rome is home to DAFNE, a high-intensity electron-positron collider allowing precision studies to be made.

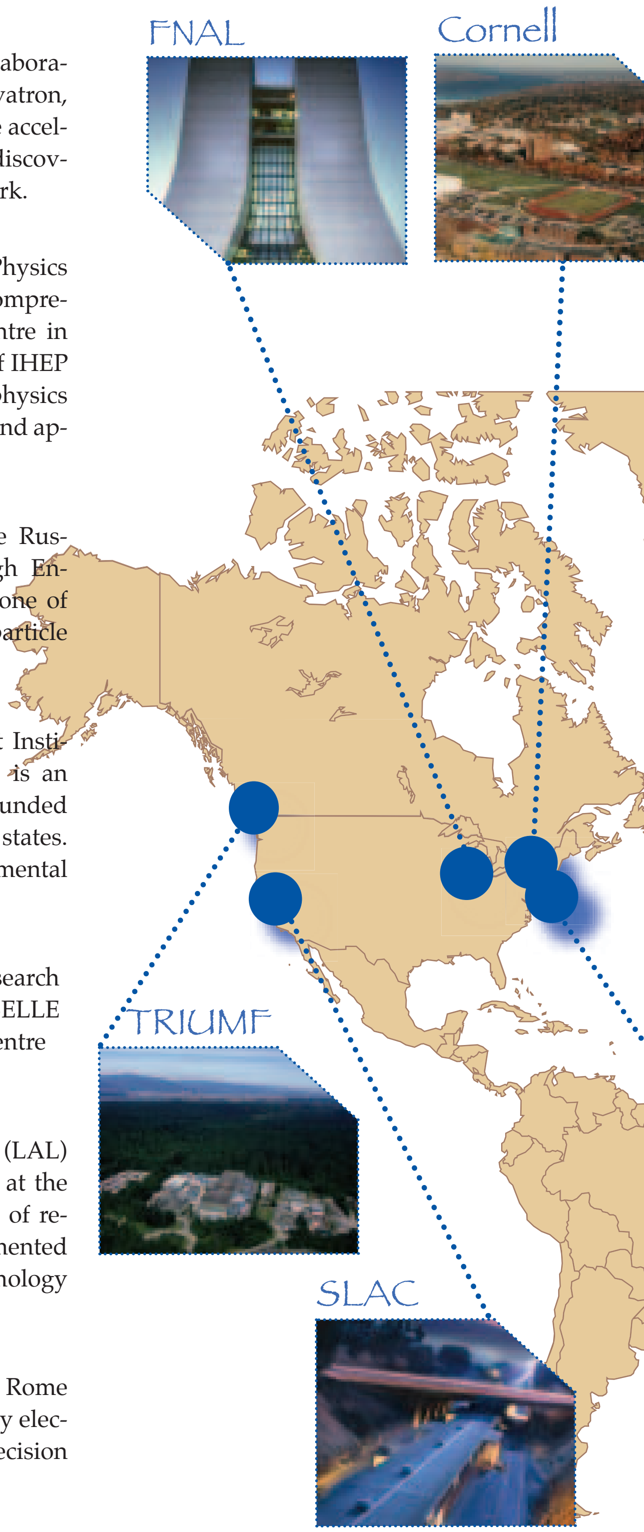
LNGS
The Gran Sasso laboratory (LNGS) is the world's largest deep underground laboratory for experimental particle physics and nuclear astrophysics.

PSI
The Paul Scherrer Institute, home to the Swiss Light Source, is also a base for particle physics.

RAL
The Rutherford Appleton Laboratory, operated by the Council for the Central Laboratory for the Research Councils (CCLRC), is a focus for particle physics.

Particle physics in the World

Laboratories represented at the Joint ICFA-Laboratory Directors' meeting.



BINP, Russia
The Budker Institute of Nuclear Physics is a major centre for nuclear physics research in Russia. It is also host to the Siberian Synchrotron Radiation Centre.

BNL, USA
The Brookhaven National Laboratory (BNL) is a large, multi-disciplinary research centre. It is host to the RHIC heavy-ion collider.

CCLRC, UK
The Council for the Central Laboratory for the Reseach Councils (CCLRC) operates the Rutherford Appleton and Daresbury laboratories, which provide a UK focus for particle physics, accelerator science and light sources.

CERN
The European Organization for Nuclear Research (CERN) operates the world's largest particle physics research centre. W and Z particles were discovered at CERN, and the centre is also the birthplace of the World Wide Web. In 2007, it will start bringing the Large Hadron Collider into operation. The LHC will be the world's highest energy particle collider.

Cornell, USA
Cornell University is host to the CESR electron-positron collider, and is an important centre for accelerator R&D.

DAPNIA, France
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The German Electron Synchrotron (DESY) is one of the world's leading accelerator centres. It is a national research centre with locations in Hamburg and Zeuthen, near Berlin. It is host to the HERA collider, and is an important centre for light source research.

FNAL, USA
The Fermi National Accelerator Laboratory (FNAL) is the home of the Tevatron, the world's most powerful particle accelerator. It is the scene of important discoveries, including that of the top quark.

IHEP, China
The Institute of High Energy Physics (IHEP) is the largest and most comprehensive fundamental research centre in China. The major research fields of IHEP are particle physics, accelerator physics and their associated technologies and applications.

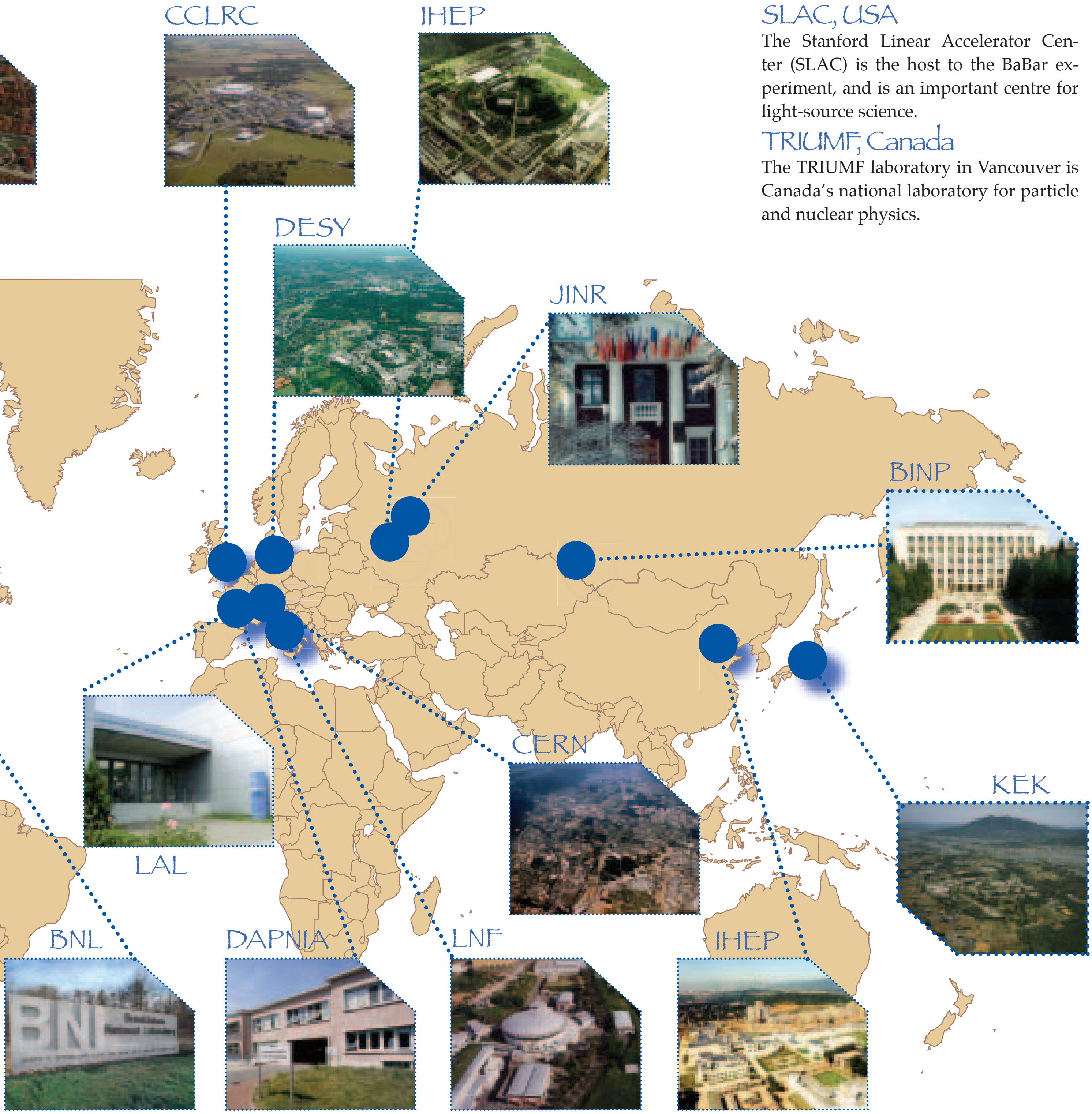
IHEP, Russia
The State Research Centre of the Russian Federation Institute for High Energy Physics (IHEP), Moscow, is one of the leading Russian centres for particle physics.

JINR
Based in Dubna, Russia, the Joint Institute for Nuclear Research (JINR) is an intergovernmental organization founded in 1956, with currently 18 member states. Its mission is to study the fundamental properties of matter.

KEK, Japan
Japan's high energy accelerator research organization (KEK) is host to the BELLE experiment, and is an important centre for accelerator R&D.

LAL, France
The Linear Accelerator Laboratory (LAL) near Paris has a 50 year tradition at the frontier of research. Its main area of research is particle physics, complemented by a strong engagement with cosmology and astrophysics.

LNF, Italy
The Frascati laboratory (LNF) near Rome is home to DAFNE, a high-intensity electron-positron collider allowing precision studies to be made.



SLAC, USA

The Stanford Linear Accelerator Center (SLAC) is the host to the BaBar experiment, and is an important centre for light-source science.

TRIUMF, Canada

The TRIUMF laboratory in Vancouver is Canada's national laboratory for particle and nuclear physics.

The European strategy *for particle physics*

Particle physics stands on the threshold of a new and exciting era of discovery. The next generation of experiments will explore new domains and probe the deep structure of space-time. They will measure the properties of the elementary constituents of matter and their interactions with unprecedented accuracy, and they will uncover new phenomena such as the Higgs boson or new forms of matter. Long-standing puzzles such as the origin of mass, the matter-antimatter asymmetry of the Universe and the mysterious dark matter and energy that permeate the cosmos will soon benefit from the insights that new measurements will bring. Together, the results will have a profound impact on the way we see our Universe; *European particle physics should thoroughly exploit its current exciting and diverse research programme. It should position itself to stand ready to address the challenges that will emerge from exploration of the new frontier, and it should participate fully in an increasingly global adventure.*

General issues

1. European particle physics is founded on strong national institutes, universities and laboratories and the CERN Organization; *Europe should maintain and strengthen its central position in particle physics.*

2. Increased globalization, concentration and scale of particle physics make a well coordinated strategy in Europe paramount; *this strategy will be defined and updated by CERN Council as outlined below.*

Scientific activities

3. The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; *the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance.* A subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; *to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.*

4. In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; *a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play a significant role in the study and development of a high-intensity neutrino facility.*

5. It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier; *there should be a strong well-coordinated European activity, including CERN, through the Global Design Effort, for its design and technical preparation towards the construction decision, to be ready for a new assessment by Council around 2010.*

6. Studies of the scientific case for future neutrino facilities and the R&D into associated technologies are required to be in a position to define the optimal neutrino programme based on the information available in around 2012; *Council will play an active role in promoting a coordinated European participation in a global neutrino programme.*

7. A range of very important non-accelerator experiments take place at the overlap between particle and astroparticle physics exploring otherwise inaccessible phenomena; *Council will seek to work with ApPEC to develop a coordinated strategy in these areas of mutual interest.*

8. Flavour physics and precision measurements at the high-luminosity frontier at lower energies complement our understanding of particle physics and allow for a more accurate interpretation of the results at the high-energy frontier; *these should be led by national or regional collaborations, and the participation of European laboratories and institutes should be promoted.*

9. A variety of important research lines are at the interface between particle and nuclear physics requiring dedicated experiments; *Council will seek to work with NuPECC in areas of mutual interest, and maintain the capability to perform fixed target experiments at CERN.*

10. European theoretical physics has played a crucial role in shaping and consolidating the Standard Model and in formulating possible scenarios for future discoveries. Strong theoretical research and close collaboration with experimentalists are essential to the advancement of particle physics and to take full advantage of experimental progress; *the forthcoming LHC results will open new opportunities for theoretical developments, and create new needs for theoretical calculations, which should be widely supported.*

Organizational issues

11. There is a fundamental need for an ongoing process to define and update the European strategy for particle physics; *Council, under Article II-2(b) of the CERN Convention, shall assume this responsibility, acting as a council for European particle physics, holding a special session at least once each year for this purpose. Council will define and update the strategy based on proposals and observations from a dedicated scientific body that it shall establish for this purpose.*

12. Future major facilities in Europe and elsewhere require collaborations on a global scale; *Council, drawing on the European experience in the successful construction and operation of large-scale facilities, will prepare a framework for Europe to engage with the other regions of the world with the goal of optimizing the particle physics output through the best shared use of resources while maintaining European capabilities.*

13. Through its programmes, the European Union establishes in a broad sense the European Research Area with European particle physics having its own established structures and organizations; *there is a need to strengthen this relationship for communicating issues related to the strategy.*

14. Particle physicists in the non-Member States benefit from, and add to, the research programme funded by the CERN Member States; *Council will establish how the non-Member States should be involved in defining the strategy.*

Complementary issues

15. Fundamental physics impacts both scientific and philosophical thinking, influencing the way we perceive the universe and our role in it. It is an integral part of particle physics research to share the wonders of our discoveries with the public and the youth in particular. Outreach should be implemented with adequate resources from the start of any major project; *Council will establish a network of closely cooperating professional communication officers from each Member state, which would incorporate existing activities, propose, implement and monitor a European particle physics communication and education strategy, and report on a regular basis to Council.*

16. Technology developed for nuclear and particle physics research has made and is making a lasting impact on society in areas such as material sciences and biology (e.g. synchrotron radiation facilities), communication and information technology (e.g. the web and grid computing), health (e.g. the PET scanner and hadron therapy facilities); *to further promote the impact of the spin-offs of particle physics research, the relevant technology transfer representatives at CERN and in Member states should create a technology transfer forum to analyse the keys to the success in technology transfer projects in general, make proposals for improving its effectiveness, promoting knowledge transfer through mobility of scientists and engineers between industry and research.*

17. The technical advances necessary for particle physics both benefit from, and stimulate, the technological competences available in European industry; *Council will consolidate and reinforce this connection, by ensuring that future engagement with industry takes account of current best practices, and continuously profits from the accumulated experience.*

Unanimously approved by the CERN Council at the special Session held in Lisbon on 14 July 2006

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