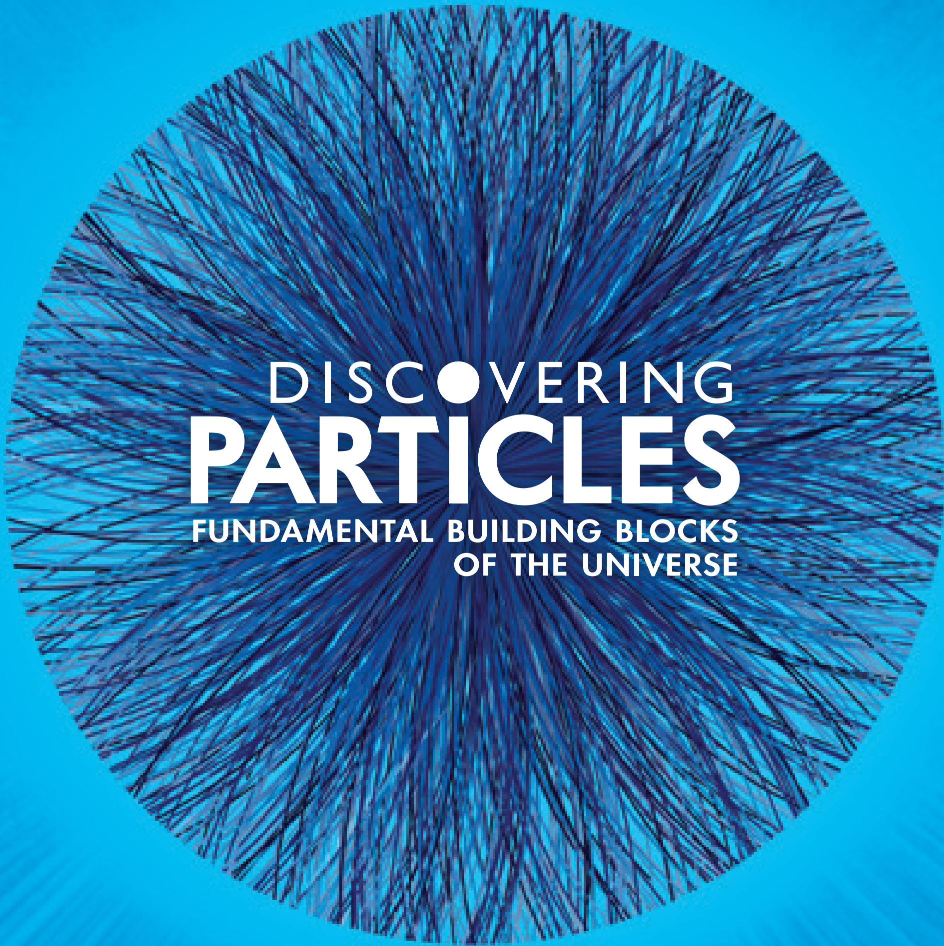
DISCOVERING PARTICLES

FUNDAMENTAL BUILDING BLOCKS OF THE UNIVERSE



www.hep.ph.bham.ac.uk/discovering-particles

UNIVERSITY OF BIRMINGHAM

british science festival
BIRMINGHAM
6-11 SEPT 2014

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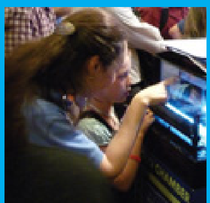
Exhibit Background

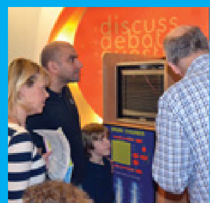
Discovering Particles: Fundamental Building Blocks of the Universe was developed for the Royal Society Summer Science Exhibition 2011, in a joint venture between the Particle-Physics Group at the University of Birmingham and the High-Energy Physics Group at the University of Cambridge. It has been staged, in full or in part, at the following events:

Royal Society Summer Science Exhibition, London, 5th-10th July 2011
Physics at Work, Cambridge, 20th-22nd September 2011
Physics Fun at the *Manchester Science Festival*, 29th October 2011
PhysicsFest 2011: Light Fantastic, Ipswich, 4th December 2011
Particle Physics Ideas, Birmingham, 7th December 2011
Thinktank: Meet the Scientist, Birmingham, 14th-16th February 2012
Quabinet of Quantum Quriosities at the *Brighton Science Festival*, 19th February 2012
Visualising the Invisible at *The Big Bang Fair*, Birmingham, 15th-17th March 2012
Bang Goes the Theory Live, Sheffield, 5th-7th May 2012
Bang Goes the Theory Live, Poole, 2nd-4th June 2012
Cosmic 100 at *Royal Society Summer Science Exhibition*, London, 3rd-8th July 2012
Science and Technology at *National Eisteddfod of Wales*, Llandaw, 4th-11th August 2012
British Science Festival, Birmingham, 6th-11th September 2014

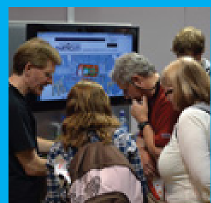


Royal Society Summer Science Exhibition

Manchester Science Festival



Thinktank: Meet the Scientist



The Big Bang Fair

The University of Birmingham and the University of Cambridge both have proud traditions in Particle Physics. The electron, proton and neutron were all discovered at the Cavendish Laboratory, University of Cambridge. Europe's first proton accelerator of synchrotron design, the design used for the Large Hadron Collider (LHC), was built and operated at the Nuffield Laboratory, University of Birmingham. In recent decades, Birmingham and Cambridge physicists have made key contributions to a number of large-scale international experiments that have produced landmark results. Highlights have included the discovery of the W and Z bosons, the determination of the number of light neutrino types, the unravelling of the structure of the proton, and high-precision measurements of matter-antimatter differences. Today, researchers from the two institutes are involved in three of the four main LHC experiments: ATLAS, LHCb and ALICE. They're also engaged in a wide spectrum of complementary activities. These include studies in non-LHC experiments, design of future accelerators, detector construction and testing, exploitation of distributed computing, and development of high-speed electronics.

Civilisations throughout history have tried to answer the question of how the world is made. Science's best answer is represented by a set of theories known as the Standard Model of Particle Physics. In this model, the behaviour of the Universe at the smallest distance scales is understood in terms of just a few types of particle, and the interactions between them.

The Standard Model successfully describes a wealth of experimental data, but leaves a number of puzzling questions. Current research in Particle Physics is trying to address these. Some of the most exciting research is being carried out at the Large Hadron Collider (LHC), the world's highest-energy particle accelerator, at the European Laboratory for Particle Physics (CERN), near Geneva, Switzerland.

The LHC has gained a firm foothold in popular culture. It has featured in newspaper stories, radio dramas, television comedy shows, video games, and a best-selling novel, later made into a film. However, the way in which the LHC is presented isn't always helpful to an accurate understanding of its purpose. In a sketch by David Mitchell and Robert Webb, the former's character, a television presenter interviewing a CERN researcher, announces to his audience: "Roland, and the other boffins here at the Large Hadron Collider, are up to something rather exciting, because they're trying to blow up the Universe – which, I have to say Roland, to a layman like me sounds like a terrible idea!" As Robert Mitchell's researcher explains: "That's not what we're trying to do."

Discovering Particles: Fundamental Building Blocks of the Universe is an invitation to explore the ideas, methods and history of Particle Physics, and to learn about the experiments being performed at the Large Hadron Collider.

Building Blocks

A particle is a microscopic object that may be characterised in terms of its position, its velocity, and its physical properties, for example mass and electric charge. A particle is said to be fundamental if it cannot be broken down into smaller pieces, or otherwise is composite. The fundamental particles can be divided into quarks, leptons, force carriers, and a particle linked to the origin of mass.

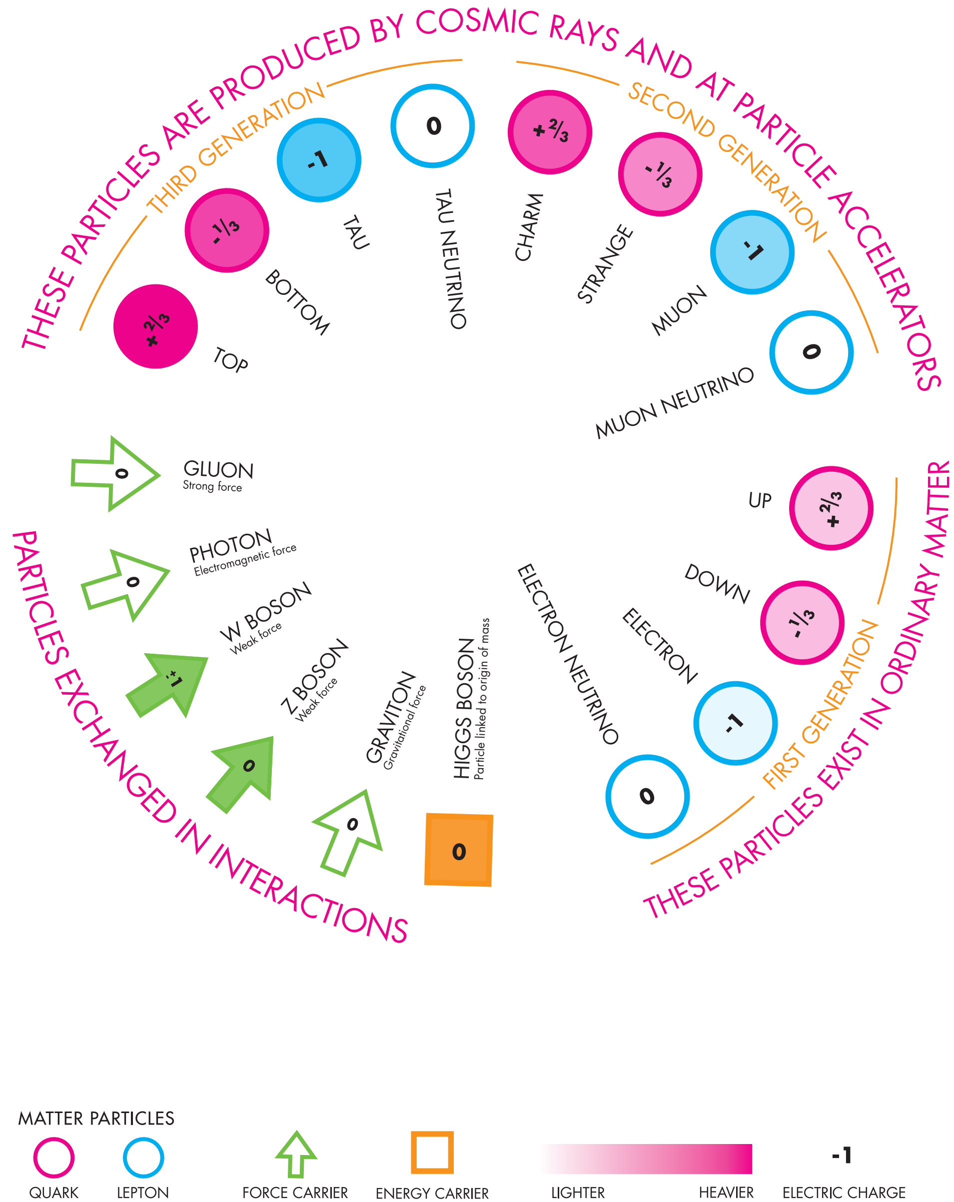
Force carriers transmit four types of force. These are the strong force, experienced by quarks but not by leptons; the weak force, experienced by leptons as well as quarks; the electromagnetic force, experienced by particles with non-zero electric charge; and the gravitational force, experienced by particles with non-zero mass.

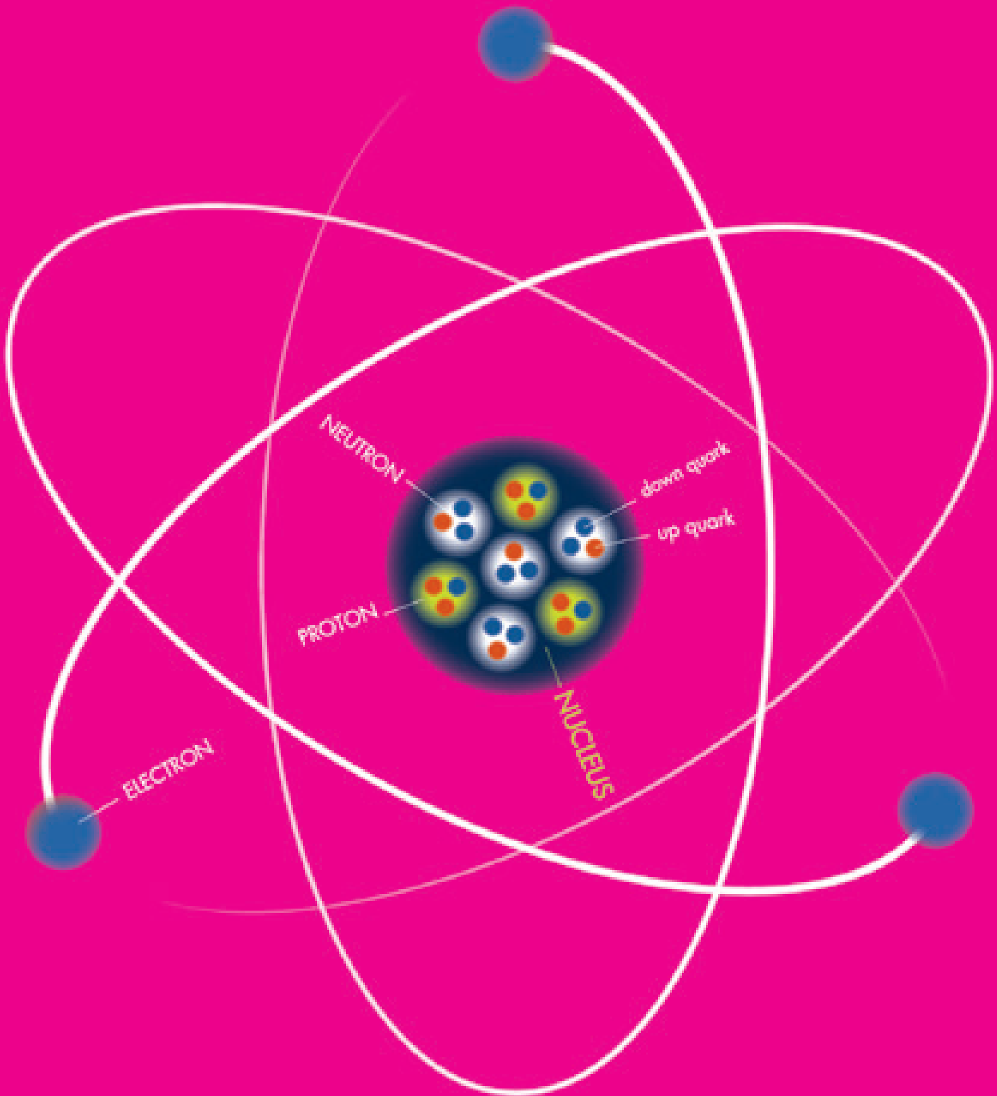
The substance that makes up any gas, liquid or solid found on Earth is referred to as matter. All known matter is built from just three types of fundamental particle: the down quark, the up quark and the electron. Together with the electron-type neutrino, which plays an important role in radioactive decay, these form the first generation of matter particles. Two other generations of matter particle are known. Each consists of two quarks and two leptons, and is essentially a replica of the first generation, but with higher mass. The higher-mass matter particles would have been present in the early Universe, and today are produced in the interactions of cosmic-ray particles and at particle accelerators. They survive for only a fraction of a second.

For each matter particle there is a corresponding antimatter antiparticle, having the same mass but oppositely signed electric charge. Quarks and antiquarks have never been detected in isolation, but are confined in composite particles known as hadrons. These may consist of three quarks (baryon), three antiquarks (antibaryon) or a quark-antiquark pair (meson).

Particles behave as if they're spinning about an axis. Quantum mechanics only allows spin values equal to a base unit, written $\hbar$, times $n/2$, where n is a non-negative integer. Particles for which n is odd obey statistical laws developed by Enrico Fermi and Paul Dirac, and are known as fermions. Particles for which n is even obey statistical laws developed by Satyendra Bose and Albert Einstein, and are known as bosons. Quarks, leptons, baryons and antibaryons are all fermions. Force carriers and mesons are all bosons. The differences in behaviour between fermions and bosons are crucial to the way in which the Universe has developed.

Fundamental particles are thought to acquire mass through interactions with an energy field, present throughout space. This energy field has an associated particle, of zero spin, known as the Higgs boson. The situation is different for a composite particle, where most of the mass is usually due to the energy that holds the pieces together.





RUTHERFORD'S MODEL
OF THE ATOM
100 Years

1911 - 2011

INTO THE *atom*

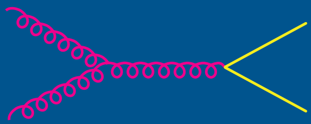
The idea that matter is made of particles was given strong scientific foundations in the nineteenth century, through the work of John Dalton, Amedeo Avogadro, Robert Brown and others. The basic unit of matter from a chemical perspective was given the name atom, from the Greek **ἄτομος** (átomos), meaning indivisible. The name was inaccurate, and the first atomic constituent, the electron, was discovered by J.J. Thomson in 1896. A year earlier, Henri Becquerel had found that certain materials spontaneously emitted radiation. Work by Ernest Rutherford and Paul Villard divided this radiation into three types: alpha particles (now known to consist of two protons and two neutrons), beta particles (electrons) and gamma rays (photons).

In an experiment performed in 1909, Hans Geiger and Ernest Marsden found that alpha particles fired at gold foil could be scattered through large angles. Rutherford, who supervised the work, thought the result astonishing: "almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." An analysis of the measurements led, in 1911, to his model of the atom as a small, dense, positively charged nucleus, orbitted by negatively charged electrons. Subsequent studies showed that the atomic nucleus is built from protons and neutrons, collectively known as nucleons. Rutherford's demonstration, in 1919, that the hydrogen nucleus is contained in other nuclei can be regarded as the discovery of the proton. The neutron was discovered by James Chadwick, in 1932.

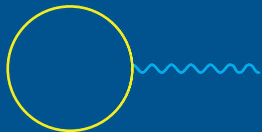
The number of protons in the nucleus of an atom is exactly equal to the number of orbitting electrons, and defines the atom's chemical identity. Materials consisting of atoms that all have the same number of protons are termed elements. Atoms of an element that contain different numbers of neutrons are said to be isotopes of the element, and are labelled by the total number of protons and neutrons. For example, carbon-12 contains 6 protons and 6 neutrons; carbon-14 contains 6 protons and 8 neutrons. An atom that gains or loses electrons, so becoming electrically charged, is known as an ion. The physical process that causes ions to form is ionisation.

Experiments in the late 1960s and early 1970s to study the scattering of high-energy leptons by nucleons provided first evidence that nucleons are themselves composite particles. The model today is that a proton is made from two up quarks and one down quark, and a neutron is made from two down quarks and one up quark. The quarks in each nucleon are strongly bound by gluons.

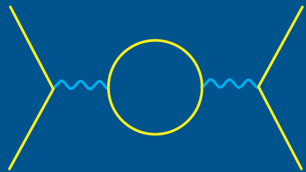
Lives in Pictures



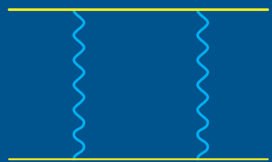
tree diagram



tadpole diagram



loop diagram



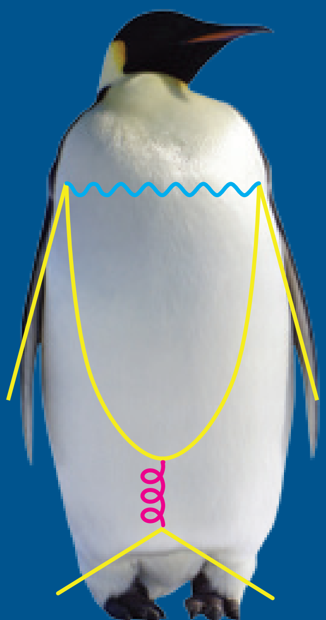
box diagram

matter particle

Higgs boson

electroweak interaction

strong interaction



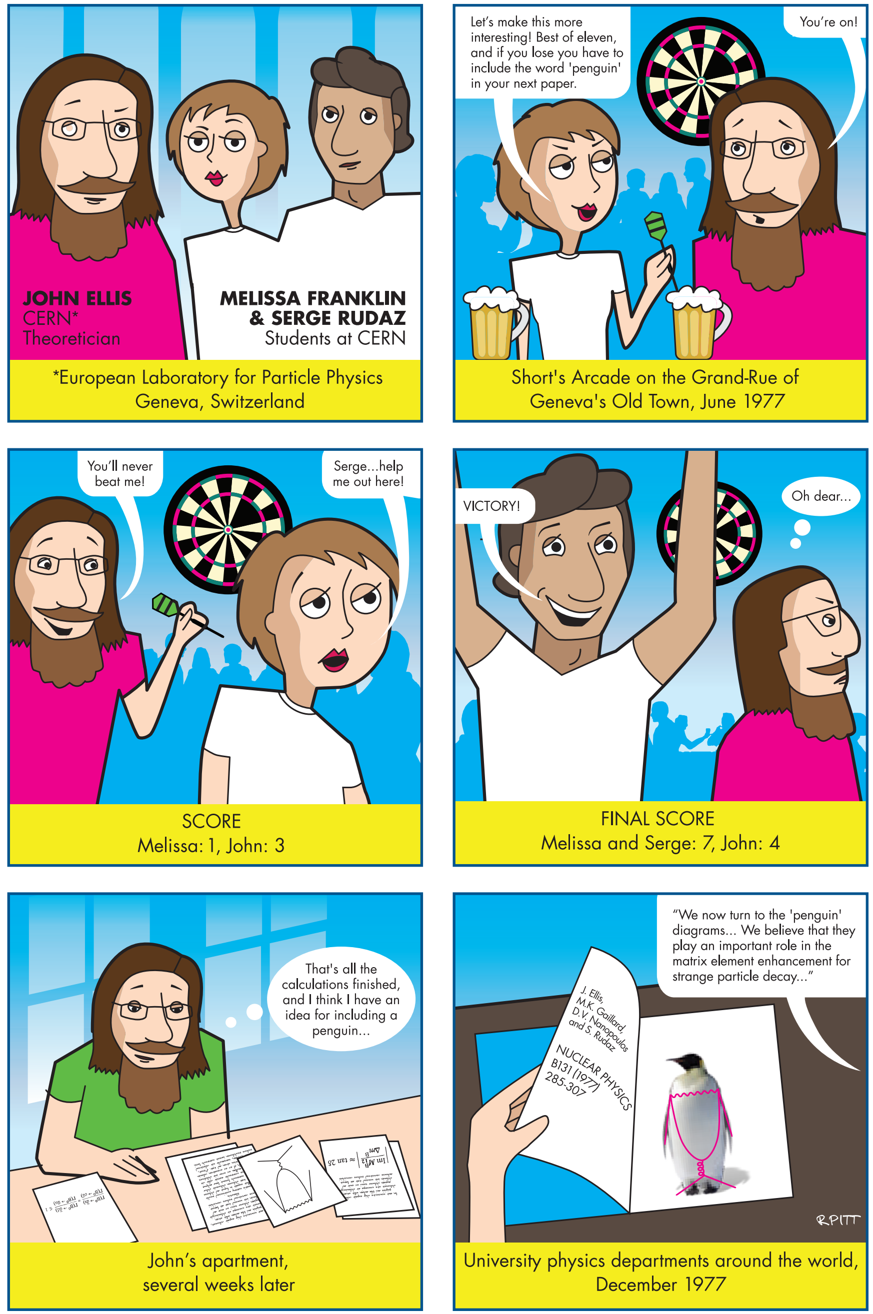
Matter particles interact with one another by emitting and absorbing force carriers. When two particles are smashed together at high speeds, their interaction can result in energy being released for the creation of new particles. The muon and tau leptons, the W and Z bosons, the Higgs boson, and all hadrons except the proton and neutron, survive for only a fraction of a second before they decay. This is a process through which the initial particle is replaced by two or more particles of lower mass.

Particle interactions and decays are represented pictorially in Feynman diagrams, named after their inventor, Richard Feynman. These diagrams show development in time from left to right, and show positions in space vertically. Different types of line are used to identify different types of particle. Points where lines meet are called vertices.

Feynman diagrams are powerful calculational tools. Individual lines and vertices are shorthand for lengthy mathematical expressions. Multiplying together the expressions for all lines and vertices of a diagram for a given interaction or decay gives a measure of how often the process occurs.

Some classes of Feynman diagram have been given names based on their appearance, making it easier for physicists to refer to them when discussing calculations. Examples include tree diagrams, tadpole diagrams, loop diagrams, box diagrams and penguin diagrams.

John, Melissa, Serge & The Penguin



Particles in the wild

Subatomic particles are locked together in everyday objects, but unbound particles are produced in radioactive emission, and in cosmic-ray showers. These naturally occurring particles were used in the earliest studies of subatomic physics.

DISCOVERY OF COSMIC RAYS

100 Years

1912 - 2012

Cosmic rays are charged subatomic particles of extraterrestrial origin, with sources including the sun and other stars.

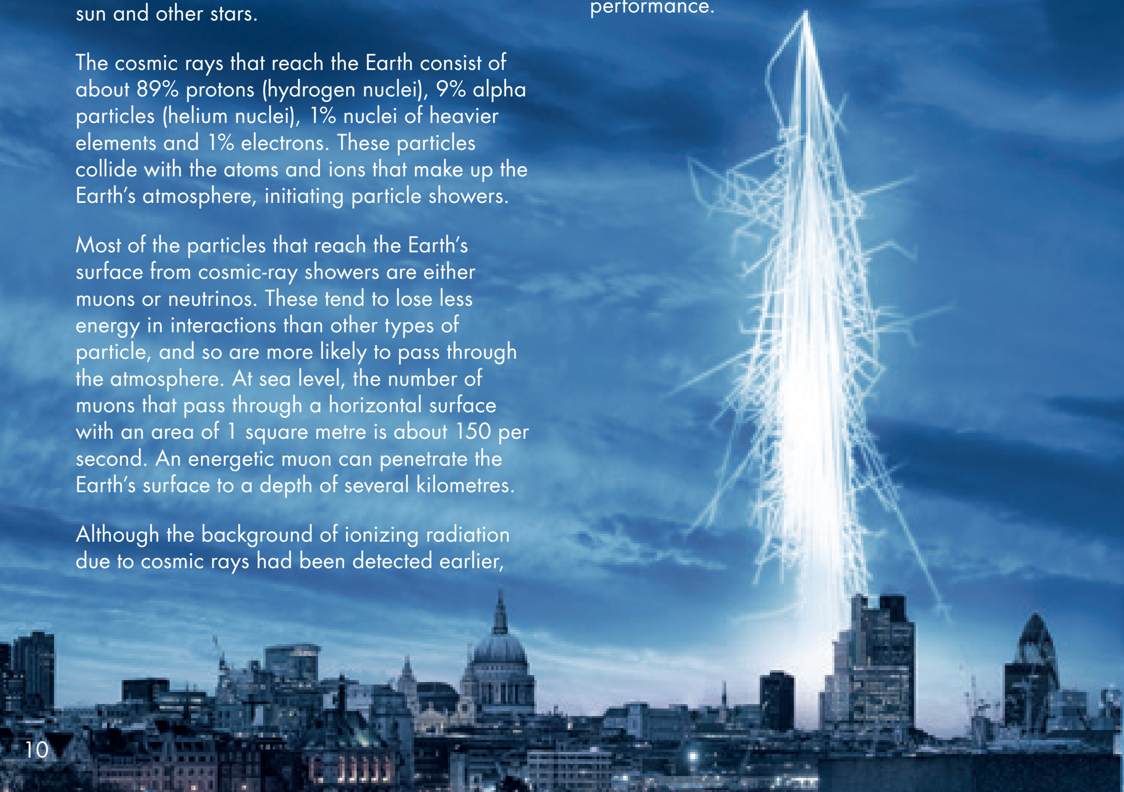
The cosmic rays that reach the Earth consist of about 89% protons (hydrogen nuclei), 9% alpha particles (helium nuclei), 1% nuclei of heavier elements and 1% electrons. These particles collide with the atoms and ions that make up the Earth's atmosphere, initiating particle showers.

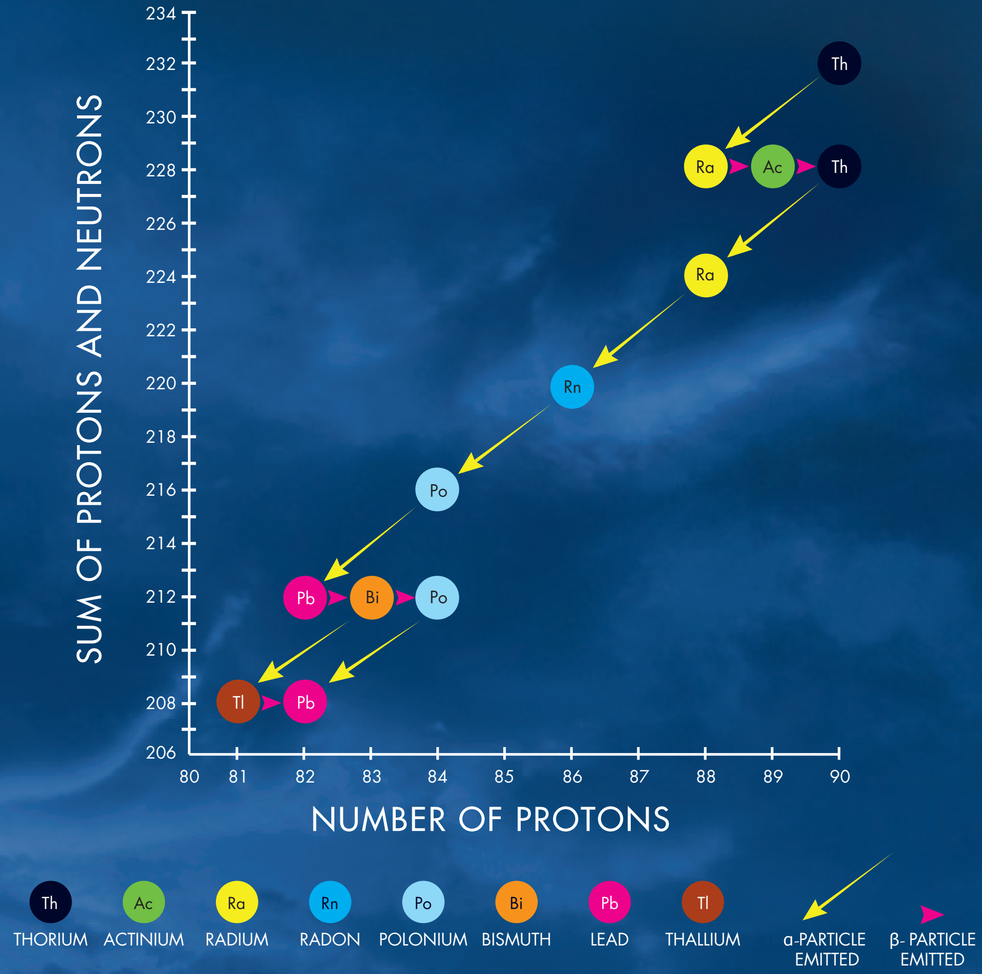
Most of the particles that reach the Earth's surface from cosmic-ray showers are either muons or neutrinos. These tend to lose less energy in interactions than other types of particle, and so are more likely to pass through the atmosphere. At sea level, the number of muons that pass through a horizontal surface with an area of 1 square metre is about 150 per second. An energetic muon can penetrate the Earth's surface to a depth of several kilometres.

Although the background of ionizing radiation due to cosmic rays had been detected earlier, its nature wasn't understood until ionisation levels at altitudes up to 5.3 kilometres were measured by Victor Hess, in a series of balloon flights, during 1911 and 1912. His results led him to the conclusion that: "a radiation of very great penetrating power enters our atmosphere from above."

Studies using cosmic rays in the 1930s and 1940s saw the discovery of particles such as the anti-electron or positron (first antiparticle); the muon (first second-generation matter particle); the pion (first meson); and both the kaon and the lambda (first particles containing the strange quark). Experiments were often performed at high altitudes, in aeroplanes or on top of mountains, so as to catch the cosmic-ray showers earlier in their development.

At the Large Hadron Collider, cosmic-ray muons were used in the first tests of detector performance.



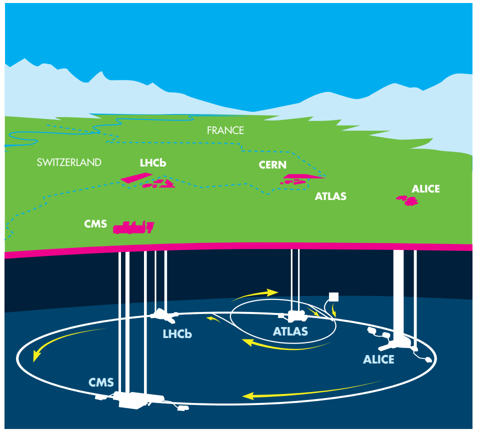


RADIOACTIVE EMISSION

An atom of a radioactive material can emit alpha particles (helium nuclei) or can undergo beta decay, where a neutron is replaced by a proton, with accompanying emission of a beta particle (electron) and an electron-type antineutrino. Both processes change the atom's chemical identity. The new atom may also be radioactive, leading to decay chains that end when a stable isotope is reached, for example lead-208.

Historically, studies using alpha particles were crucial to establishing the nuclear model of the atom. In the early 1930s, analysis of the energy spectrum of beta particles led Wolfgang Pauli and Enrico Fermi to a theory requiring the existence of neutrinos. These were first detected experimentally in 1956.

At the Large Hadron Collider, particles from radioactive sources are used to calibrate the response of detector components.



Particles in Captivity

PARTICLE ACCELERATORS

The studies that can be performed using particles as they occur naturally are limited by two factors: particle energy and collision frequencies. Higher energies are needed to be able to produce and study particles with larger masses, and more-frequent collisions are needed to investigate interactions and decays that occur rarely, but can have important consequences. The solution is to use particle accelerators.

These take advantage of the fact that charged particles can be accelerated to higher energies using electric fields, and are deflected by magnetic fields. With an appropriate arrangement of magnets, beams of charged particles can be focused in much the same way as light can be focused using optical lenses.

Particle energies are usually measured in multiples of the electronvolt (eV), the energy gained by an electron when accelerated through an electric potential of 1 volt. For comparison, commonly used household batteries, when new, produce electric potentials of between 1.5 volts and 9 volts. Useful multiples include the megaelectronvolt (1 MeV = 1,000,000 eV), the gigaelectronvolt (1 GeV = 1,000,000,000 eV) and the terraelectronvolt (1 TeV = 1,000,000,000,000 eV). Although the electric potential through which an electron must pass to gain an energy of 1 TeV is enormous, the actual amount of energy is tiny – about enough to operate a 10-watt low-energy light bulb for 0.00000001602 seconds (16.02 nanoseconds).

There are two mains types of particle accelerator in use today: the linear accelerator, where particles pass once along a straight-line track, and the synchrotron. The latter uses synchronised electric and magnetic fields to accelerate particles around circular paths, and to keep them orbitting, at a fixed energy, until they're made to interact. The design was suggested by Marcus Oliphant, Professor of Physics at the University of Birmingham, in 1943.

The world's first two proton synchrotrons both began operation in 1953: a 3.3 GeV machine at the Brookhaven National Laboratory, USA; and a 0.97 GeV machine at the University of Birmingham. They continued in use until 1968 and 1967 respectively.

THE LARGE HADRON COLLIDER

The European Laboratory for Particle Physics (CERN), hosts a unique arrangement of interlocking particle accelerators. Each of the lower-energy machines delivers particles that are either used directly in experimental studies, or are accelerated further by a more-powerful machine. The highest-energy accelerator at CERN is the Large Hadron Collider (LHC).

The LHC is a synchrotron that accelerates beams of protons or ions in both directions around a near-circular tunnel, with a circumference of 26,659 metres (16.6 miles) – a little over half the length of the channel tunnel (31.4 miles). The LHC tunnel, which is at a depth below ground of between 45 metres (towards Lake Geneva) and 170 metres (at the foot of the Jura mountains), was excavated in the 1980s, and originally housed a different machine, the Large Electron-Positron (LEP) collider.

Particles reach the LHC after having their energy boosted by a linear accelerator and a series of three synchrotrons. The LHC is designed to be able to accelerate protons from 0.45 GeV, their energy on arrival, to 7.0 TeV. Beams of protons travelling in opposite directions are made to collide in four caverns, each of which hosts one of the main LHC experiments: ALICE, ATLAS, CMS, LHCb. The collision energy has a design value of 14.0 TeV, the sum of the energies of the two protons involved.

Keeping protons with energies of up to 7.0 TeV circulating at the LHC requires powerful magnetic fields. The main contribution to these comes from 1232 electromagnets, each 14.3 metres in length. The magnets are operated in liquid helium, at a temperature of –271.3°C – colder than outer space (–270.4°C). At this temperature, the niobium-titanium alloy of the magnet coils acts as a superconductor, allowing the large electric currents needed to produce magnetic fields of the required strength.

Overheating magnets caused damage shortly after protons were first circulated in the LHC, in September 2008. The incident resulted in an extended shutdown for remedial work, to repair the damage and to introduce additional safeguards. It also led to proton collision energies during the first period of operation (November 2009 to February 2013) being limited to 8.0 TeV.

The LHC has been the world's highest-energy particle accelerator since November 2009, and has held the world record for collision frequency since April 2011. It's expected to achieve design values for collision energy and frequency during its second period of operation (2015 to 2017), and the collision rate may be futher increased by future upgrades.

LHC timeline

21-27 Mar 1984
Workshop in Lausanne and Geneva to assess feasibility of the LHC

Feb 1985 - Feb 1988
Excavation of tunnel used first for the Large Electron-Positron (LEP) collider and subsequently for the LHC

13 Aug 1989
First interactions at the LEP collider

20 Dec 1994
CERN council approves the LHC project

2 Nov 2000
End of operation of the LEP collider

10 Sep 2008
First protons circulated in the LHC

19 Sep 2008
Overheating magnets damage a section of the LHC tunnel, requiring shutdown for remedial work

20 Nov 2009
Circulating protons reestablished

23 Nov 2009
First proton-proton collisions at 0.9 TeV

30 Nov 2009
First proton-proton collisions at 2.36 TeV

30 Mar 2010
First proton-proton collisions at 7.0 TeV

7 Nov 2010
First lead-lead collisions at 2.76 TeV per nucleon pair

5 Apr 2012
First proton-proton collisions at 8.0 TeV

4 Jul 2012
ATLAS and CMS announce discovery of new particle, subsequently confirmed as Higgs boson

13 Sep 2012
First proton-lead collisions, involving protons of 4.0 TeV and lead ions of 1.58 TeV per nucleon

14 Feb 2013
Start of two-year shutdown for upgrades to accelerator and detectors

2015-2017
Proton-proton collisions at 13.0 TeV, and then at 14.0 TeV (design energy)

2018-2030
Upgrades, and operation at higher collision frequencies

Collision-Scene Investigation

Physicists investigate particle interactions by placing devices known as particle detectors in a region where collisions are expected.

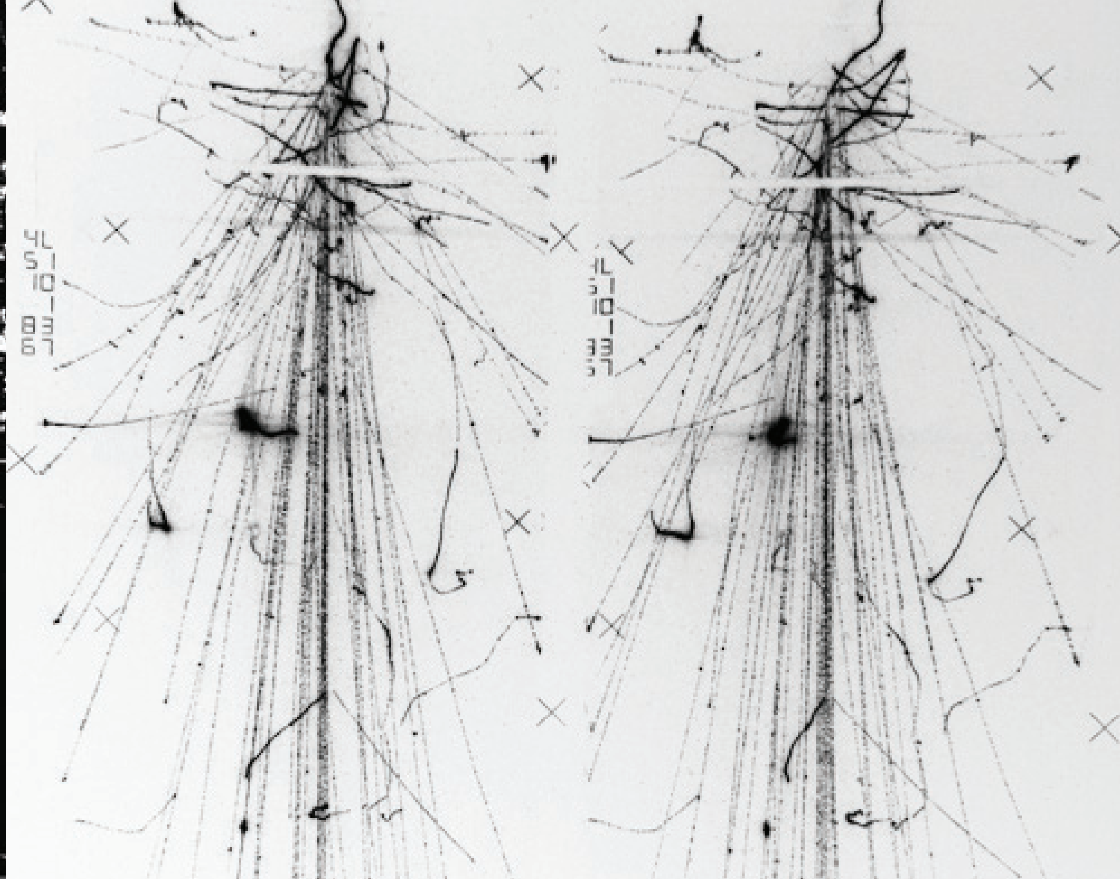
Particles that emerge from the collision leave evidence of their passage through the detectors. Physicists analyse this evidence to reconstruct what happened in the collision, and in any subsequent particle decays. The approach is similar to that of a detective who, to reconstruct a sequence of events, analyses evidence left at a crime scene.

When a high-energy charged particle crosses a material, it may transfer energy to electrons in the material's atoms. This results in ionisation if an electron gains enough energy to escape from its orbit, leaving behind a positively charge ion, or otherwise is referred to as excitation.

Effects relating to ionisation and excitation are exploited in devices known as tracking detectors, which are used to trace out particle trajectories.

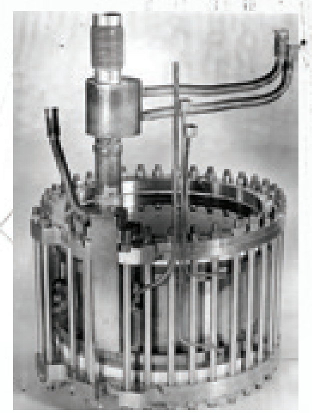
Ionisation may be seen, for example, from the blackening of photographic plates (nuclear emulsions); from the formation of liquid droplets in a vapour on the point of condensing (cloud chamber); from the formation of gas bubbles in a liquid close to boiling point (bubble chamber); from electric discharge (spark chamber); from electron-ion recombination to produce light (streamer chamber); from the accumulation of electric charge on sensor wires in a gas (multiwire proportional chamber, drift chamber); or from charge movement in a semiconductor (silicon-microstrip detector, charge-coupled device).

In materials classed as scintillators, energy that an electron gains through excitation may be dissipated as light (scintillation counters, scintillating-fibre detectors).



Tracking detectors are often placed in a magnetic field, so that charged particles follow hellical paths, and the amount of curvature gives a measurement of particle momentum (product of mass and velocity). Signals recorded by early tracking detectors were recorded as photographic images, and were examined individually by teams of scanners. Signals from more-modern detectors are stored digitally, and are analysed using computers

Tracking detectors contain only small amounts of material, so that the particles they measure pass through essentially undisturbed. A different approach is used in devices known as calorimeters. These are formed of dense material, designed to absorb all of the energy of an incident particle. The particle's original energy is measured from the total amount of ionisation or excitation recorded. Thinner calorimeters are used to measure the energies of photons and electrons. Thicker calorimeters are used to measure the energies of hadrons.



Bubble chamber, late 1950s

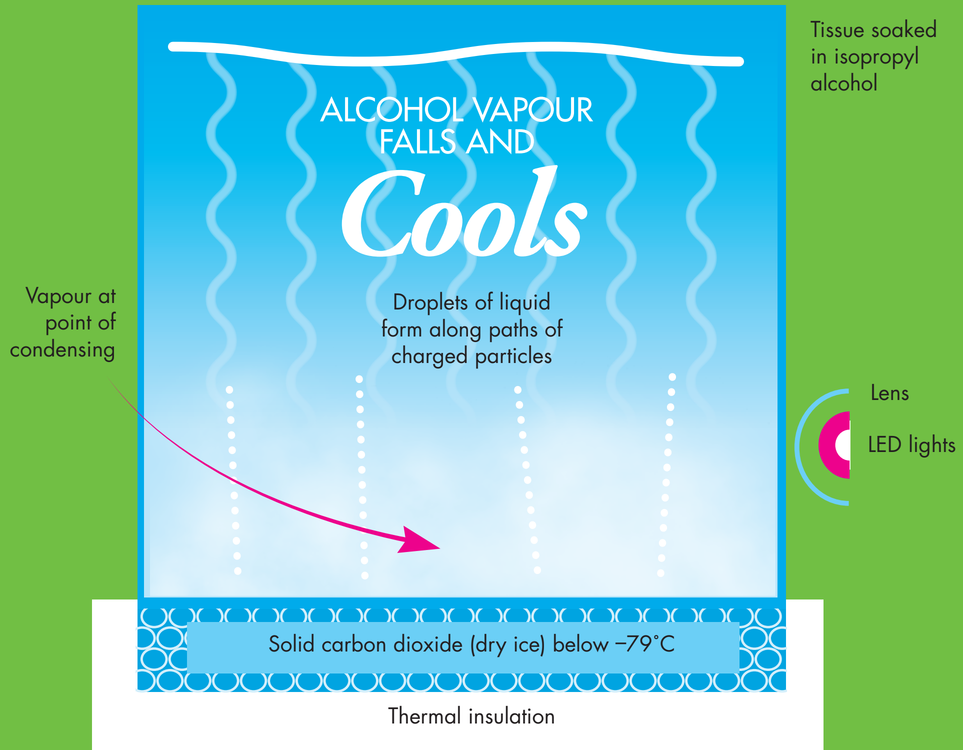
BUBBLE CHAMBER

The bubble chamber was developed by Donald Glaser, at the University of Michigan, in 1952. An early, unsuccessful, prototype was filled with beer, but the usual choice is liquid hydrogen.

CLOUD CHAMBER

100 Years

1911 - 2011



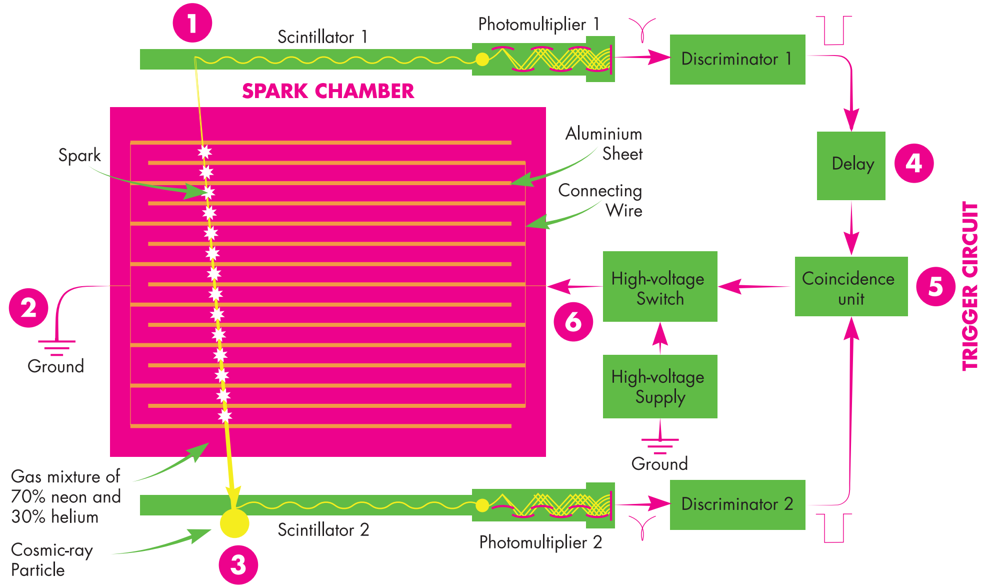
The cloud chamber, first demonstrated in 1911, was developed at the Cavendish Laboratory, University of Cambridge, by Charles T. R. Wilson. It is essentially a transparent-walled, sealed container, filled with air and some vapour at the point of condensing – a supersaturated environment. A charged particle that crosses the chamber causes ionisation along its path. The vapour condenses about the ions, and the particle's path is traced out by what Wilson referred to as "little wisps and threads of cloud".

The mechanism at work here is the same as the one that sometimes gives rise to condensation trails (contrails) in the wake of an aeroplane.

In the original design, the chamber was filled with air and water vapour, and the supersaturated environment was achieved by first compressing and then expanding the mixture. In a later development, the diffusion cloud chamber, alcohol is used instead of water, and the base of the chamber is cooled to –79°C or lower, for example using dry ice. Alcohol vapour in the warmer upper part of the chamber cools and falls, so that a supersaturated region is formed just above the base.

A cloud chamber was used in the discovery of the first antiparticle, the positron, in 1932.

SPARK CHAMBER



1 & **3** The cosmic-ray particle crossing the scintillator causes light to be emitted. A part of this light travels to the photomultiplier, where it is converted into an electronic signal. The discriminator gives a binary (yes/no) response, producing a square-wave signal if the output from the photomultiplier is above a noise threshold, or no signal otherwise

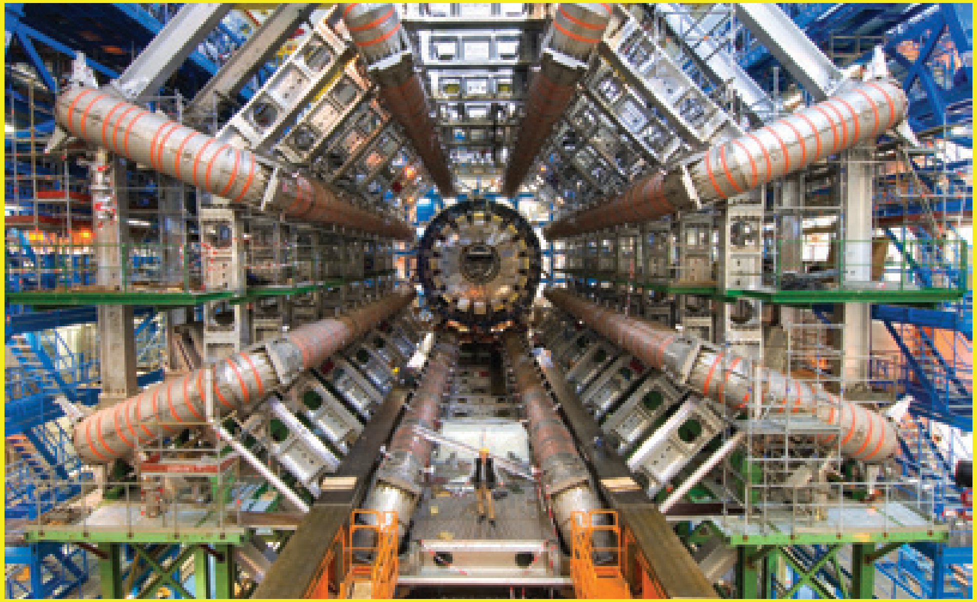
2 As the cosmic-ray particle crosses the neon-helium gas mixture inside the chamber, it causes ionisation along its path, locally decreasing the electrical resistance.

4 A length of cable is used to delay the signal from discriminator 1 by the time taken for the cosmic-ray particle to travel between scintillator 1 and scintillator 2.

5 When the coincidence unit records signals arriving simultaneously from the two discriminators, it triggers the switching on of the high-voltage supply for a short time interval. This creates large electric fields between neighbouring aluminium sheets in the spark chamber.

6 The large electric fields create current flows along the paths of lowest electrical resistance, meaning where the cosmic-ray particle caused ionisation. These current flows are seen as sparks.

The spark chamber was developed between the late nineteen fourties and the early nineteen sixties, with contributions from many people. It is a variation on a particle detector first demonstrated by Hans Geiger and Walther Müller, at the University of Kiel, in 1928. Spark chambers were the first widely used track-visualisation devices that allowed triggering. This meant that they could be used with an independent logic circuit that triggered activation of the detector when specific conditions were satisfied. In most studies, only a tiny fraction of particle interactions are of interest, and having detectors that can be triggered so as to select these is essential. Large-volume spark chambers were used in the discovery of the muon-type neutrino, in 1962.



ATLAS detector

Experiments

AT THE LARGE HADRON COLLIDER

Four main experiments are installed at the Large Hadron Collider (LHC). Two are general-purpose experiments, studying many aspects of particle production and decay. These are ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid), each of which involves more than 3000 scientists and engineers, almost 200 research institutes, and around 40 countries, drawn from all continents except Antarctica.

The other experiments, each involving around 1000 scientists and engineers, are more specialised: ALICE (A Large Ion-Collider Experiment) focuses on heavy-ion collisions, and LHCb (LHC b-hadron experiment) is mainly concerned with the decays of hadrons containing the bottom quark. The LHC experiments use the largest-volume particle detectors built to date. These detectors have been constructed as a series of layers, or subdetectors, and all follow roughly the same scheme. Starting from the inner layers, which are positioned closest to the interaction region, each detector consists of: subdetectors to measure charged-particle trajectories; subdetectors to stop photons, electrons and hadrons, and measure their energies; subdetectors to record muons, the only charged particles that reach the detector's outermost layers. The ALICE, ATLAS and CMS detectors are approximately cylindrical in shape, so as to be sensitive to particles emerging in all directions from an interaction. The majority of the particles of interest in LHCb are emitted at small angles, and so the experiment's detector covers only a narrow cone around the direction of the incoming protons.

ALICE, ATLAS, CMS and LHCb have organisational structures comparable in complexity to those of a large multinational company. Experiment members work in cross-institute groups that take on specific responsibilites. For example, a group might have responsibility for a subdetector, for a piece of electronics, for some computer software, or for a physics measurement.

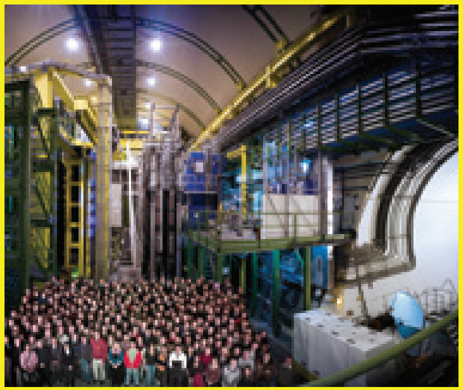
During operation of the LHC, the experimental areas are sealed off, and the detectors are controlled remotely using computers. Teams of physicists work in shifts to keep the detectors running, and to monitor their performance, twenty-four hours a day.

The four main LHC experiments are complemented by three smaller experiments, each involving fewer than 100 scientists: LHCf (LHC forward experiment), MoEDAL (Monopole and Exotics Detector At the LHC) and TOTEM (TOTal Elastic and diffractive cross-section Measurement).

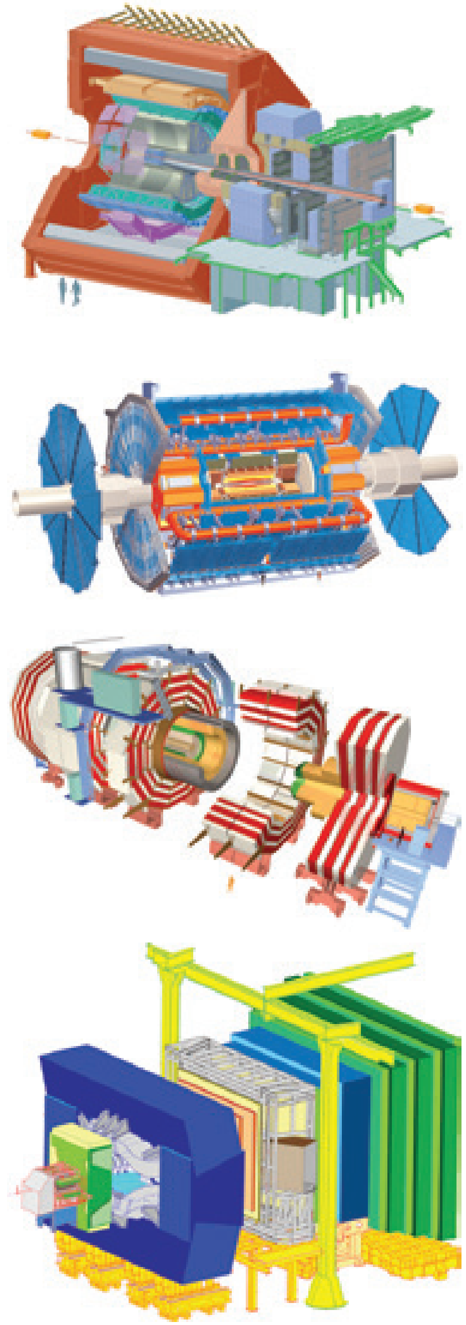
DETECTOR SIZES AND WEIGHTS

	Length	Cross section	Weight
ALICE	26 m	Circular: 16 m diameter	10,000,000 kg*
ATLAS	46 m	Circular: 25 m diameter	7,000,000 kg
CMS	21 m	Circular: 15 m diameter	12,500,000 kg
LHCb	21 m	Rectangular: 13 m × 10 m	5,600,000 kg

*about the same as the Eiffel Tower



LHCb collaboration and detector



Top to bottom: ALICE detector; ATLAS detector; CMS detector; LHCb detector

QUESTIONS BEING ASKED AT THE *Large Hadron Collider (LHC)*

WHAT MAKES THINGS *Heavy?*

Any theory of particle interactions must combine the physics of the very small (quantum mechanics) and the physics of the very fast (special relativity). In the simplest theory that satisfies the various constraints, all fundamental particles have zero mass.

Experimentally, this isn't true. The theory can be improved by introducing a new energy field, in some ways analogous to an electric or magnetic field, but present everywhere. This is the Higgs field, named after Peter Higgs, who played an important part in the theoretical developments. The mass of a particle is then proportional to the energy gained in moving through the Higgs field. The field has an associated particle, known as the Higgs boson, undetected before the start of collisions at the LHC.

In July 2012, the ATLAS and CMS experiments announced discovery of a particle consistent with a Higgs boson. Subsequent measurements have confirmed this identification, showing that the new particle's spin (zero) and decays are in agreement with predictions for a Higgs boson. As they collect and analyse more data, the LHC experiments are aiming to perform detailed studies of the observed Higgs boson; to establish whether this is the only Higgs particle, or the first of a new family; and so to improve understanding of how mass is generated

WHY ARE THERE NO *Anti-worlds?*

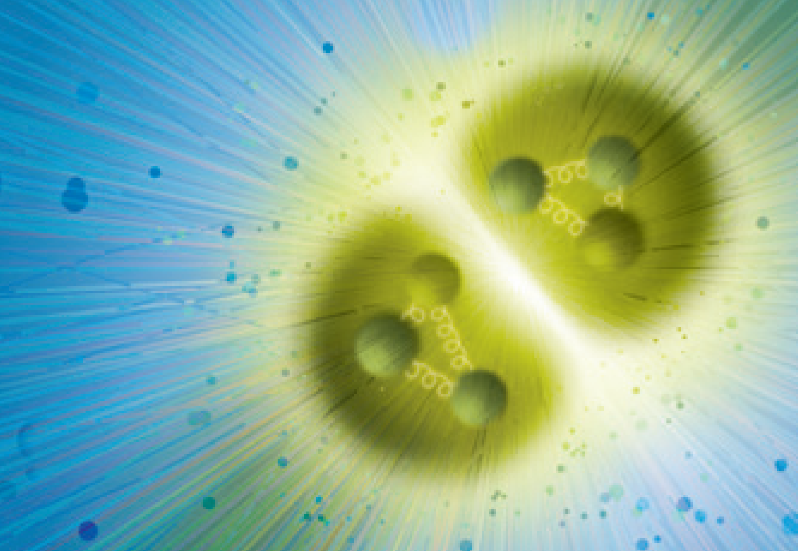
All known processes for particle creation produce matter and antimatter in exactly equal amounts. This suggests that the Universe itself would have been created as equal amounts of matter and antimatter, which might have been expected to annihilate one another, leaving only energy in the form of heat and light.

This clearly didn't happen, and the visible Universe today consists almost entirely of matter. Earlier experiments have measured subtle differences in the way that matter and antimatter behave. Differences of this type might explain how the Universe has evolved to its current state, but the observed differences are too small to account for the near-total absence of antimatter. Experiments at the LHC are looking for further matter-antimatter differences, to help solve the puzzle.

WHAT FLAVOUR IS QUARK-GLUON SOUP?

Head-on collisions between lead ions at the LHC can produce, in a tiny volume, matter and energy densities similar to those thought to have existed a few millionths of a second after the Universe was created.

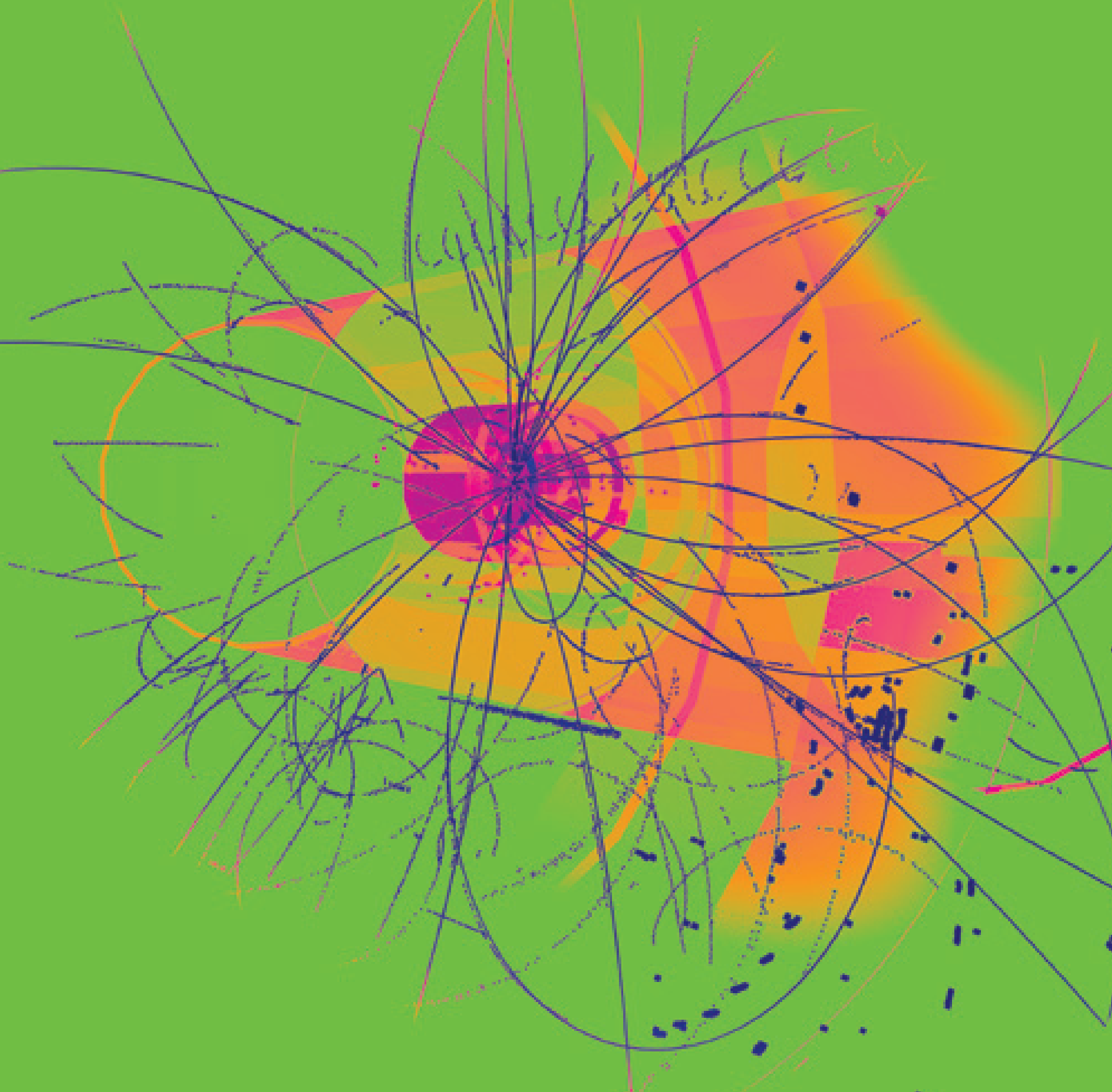
Under these extreme conditions, the lead nucleons dissociate into their component parts. The unbound quarks and gluons then form a primordial state of matter known as quark-gluon plasma or, more informally, as quark-gluon soup. This state of matter, and its transition to hadrons, is being studied by the LHC experiments to learn more about the workings of the strong force. Primary aims include understanding how quarks become confined in hadrons, and understanding if the confinement mechanism generates contributions to hadron masses.



What Keeps Galaxies Spinning?

Stars in a galaxy move in orbits about the galactic centre. Based on the distribution of visible matter, stars nearer the centre would be expected to move faster than stars further out.

Measurements over many galaxies suggest that this isn't the case, and orbital speeds are almost independent of star-to-centre distance. The most widely accepted interpretation is that the gravitational effect of the visible matter is supplemented by the effect of additional matter, given the name dark matter, which doesn't emit or reflect light. This dark matter is estimated to account for about 83% of the total mass of the Universe. There are hints from astronomical observations that dark matter is composed of unknown particles that, like neutrinos, interact only through the weak force. These particles could be found by the LHC experiments.



WHERE'S *SUSY?*

Supersymmetry, often abbreviated as SUSY, is a theory that relates fermions and bosons. It requires the existence of currently undetected particles, known variously as SUSY particles, superpartners, and sparticles.

Each of the fundamental fermions (quarks and leptons) should have a boson superpartner, and each of the fundamental bosons (force carriers) should have a fermion superpartner. Supersymmetry has been widely studied as part of possible extensions to the Standard Model of Particle Physics, and has some appealing features. For example, it allows the weak, electromagnetic and strong forces to be understood as having a common origin. The LHC experiments are searching for evidence of SUSY particles, which may have high masses. The lightest SUSY particle could be a candidate for dark matter.

Can black holes be made at home?

A black hole is a region in space where the escape of anything that enters, including light, is prevented by the region's gravitational field. Astronomers have found black-hole candidates that could have formed from collapsed stars, but microscopic black holes are theoretically possible also.

With three spatial dimensions, the energy needed to create a microscopic black hole is far beyond the reach of any particle accelerator that could be built with today's technology. However, the existence of extra dimensions would be likely to reduce the energy requirement, so that microscopic black holes might be produced and detected in LHC interactions. Any such black holes would be expected to evaporate almost instantly, radiating particles and antiparticles through a mechanism first proposed by Stephen Hawking. If microscopic black holes are produced at the LHC, then they're also regularly produced around the Earth in cosmic-ray interactions.

WHY DO APPLES FALL SO *Slowly?*

Isaac Newton recounted how his idea of gravity "was occasion'd by the fall of an apple". A puzzle that remains is why apples fall so slowly, or, equivalently, why gravity is so feeble compared with other forces.

Some theories suggest that gravity's apparent weakness comes from its strength being spread across more dimensions than the three space dimensions and one time dimension experienced in everyday life. In collisions at the LHC, energy could potentially be carried to the extra dimensions by gravitons. The effect of extra dimensions may then be visible to the experiments as interactions with large energy deficits.

WHAT DOES *Nobody Know?*

Although the LHC experiments have been designed to help answer many intriguing questions, one of the most exciting prospects of all is that they will discover something completely unexpected.

Seeing the Penguins Among the Trees

LHC DATA PROCESSING IN NUMBERS

The number of proton-proton collisions produced by the Large Hadron Collider (LHC) in each of ATLAS and CMS, the two general-purpose experiments, is up to 60,000,000 per second. Proposed upgrades could increase this value by a factor of 5.

Lower, but still large, collision frequencies are generated in the more-specialised experiments, ALICE and LHCb. In all experiments, the great majority of particle interactions and decays can be understood in terms of Feynman diagrams of the tree type, and are of limited interest. The processes sought by the experiments tend to be rare. For example, a decay described by a penguin diagram occurs in fewer than one collision in every 1,000,000,000, as does production of a Higgs boson; and the frequency for producing SUSY particles may be lower again, by a factor of 100 or more. These signal processes need to be identified against the enormous background.

As collisions take place, the experiments perform a rapid first selection, using both high-speed electronics and software running on local computer clusters. Data from the detectors are recorded only for interactions that satisfy the selection criteria, but the total number of such interactions for a year's operation of the LHC is huge. Away from the experiments, the recorded data are processed so as to reconstruct the interactions, extracting maximum information on the types of particle produced in each, and on the particles' characteristics. Reconstructed interactions are divided into categories, and are then subject to detailed analysis by groups of physicists. Different groups are interested in different categories of interaction, and perform different studies.

The processing power needed to be able to reconstruct and analyse all of the interactions recorded at the LHC is provided by a computing grid. This links together computing resources distributed across the globe, at research institutes (grid sites) participating in the LHC experiments, and is known as the Worldwide LHC Computing Grid (WLCG). It is described in a news feature in the journal *Nature* as "the most sophisticated data-taking and analysis system ever built".

8,000,000,000

Proton-proton collisions recorded each year

200,000,000

Heavy-ion collisions recorded each year

TOTAL COLLISION DATA RECORDED EACH YEAR

15,000,000 *gigabytes*

SPEED OF DATA TRANSFER BETWEEN CERN AND MAJOR GRID SITES

10,000 *megabits per second*

500,000

Processor cores worldwide

40,000

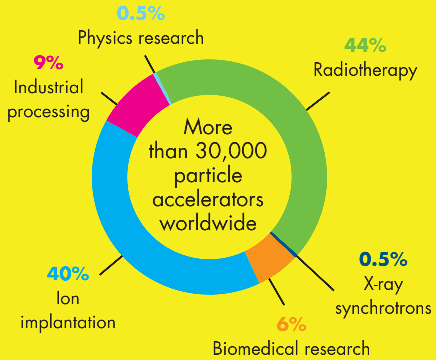
Processor cores in the UK

6	**40**	**160**	**20**
Continents involved	Countries involved	Grid sites worldwide	Grid sites in the UK

NUMBER OF PHYSICISTS WITH ACCESS TO LHC DATA

8,000

Particles at work



PARTICLE ACCELERATORS

Accelerators come in many shapes and sizes, with some small enough to fit on a table. Some are used to accelerate charged particles for direct use. Electron synchrotrons are also used as sources of X-rays (high-energy photons), emitted by the electrons as they circulate.

In medicine, particle accelerators are used in the treatment of cancer. This has traditionally been through radiotherapy, meaning doses of X-rays. More recently, use has also been made of hadron therapy, which allows tumours to be targetted more accurately.

In industry, accelerated ions are fired into materials in a technique known as ion implantation. This is used, for example, to modify the electrical properties of semiconductors, and to toughen steel.

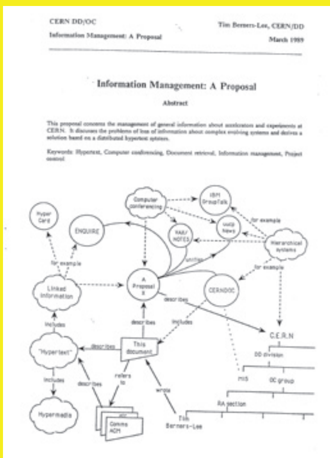
X-rays produced using synchrotrons are used for non-destructive examinations of structure. Such studies have improved understanding of items as diverse as engines, paintings, spider silk, and ancient artefacts. For example, an X-ray examination of timbers from the Mary Rose revealed the presence of sulphur compounds, and helped guide the preservation treatment.

PARTICLE PHYSICS AND COMPUTING

In March 1989, while working at the European Laboratory for Particle Physics (CERN), Oxford physics graduate Tim Berners-Lee set out to answer a question that he'd noted ended many discussions about the proposed Large Hadron Collider: "Yes, but how will we ever keep track of such a large project?"

He outlined ideas for "a universal linked information system" in a short document, summed up by his supervisor as: "Vague, but exciting." This was the starting point of the World Wide Web, one of the most revolutionary innovations of the late twentieth century.

Just as the World Wide Web provides access to information, grid technology provides access to computing power. Developments for the Worldwide LHC Computing Grid (WLCG) have significantly increased the scale, reliablity and ease-of-use of grid computing. The WLCG has been used for a wide range of applications outside of Particle Physics, including drug searches, image indexing, landslide modelling and climate studies.


CERN DD/OC
Information Management: A Proposal

Tim Berners-Lee, CERN/DD
March 1989

Information Management: A Proposal

Abstract

This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext system.

Keywords: Hypertext, Computer conferencing, Document retrieval, Information management, Project control.

The first page of Tim Berners-Lee's proposal for the World Wide Web, in March 1989

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