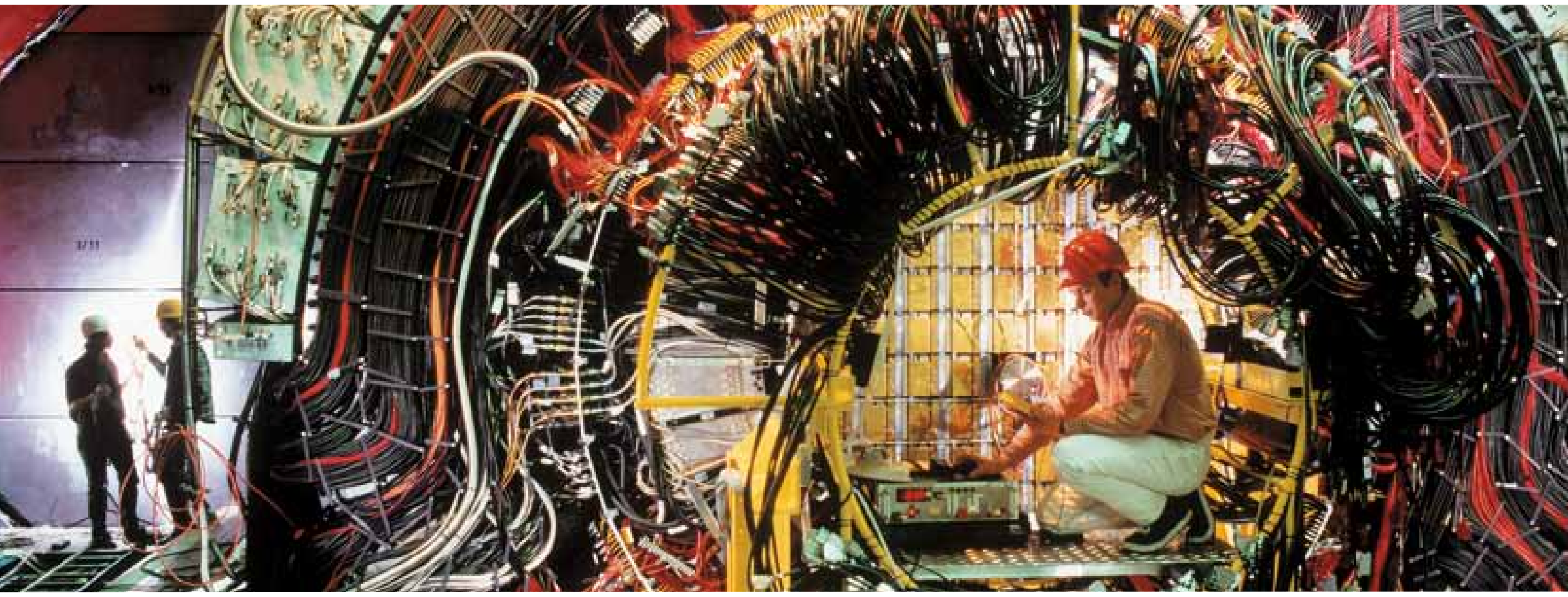
MICRO COSM.

DESY explores what binds the universe together at its core

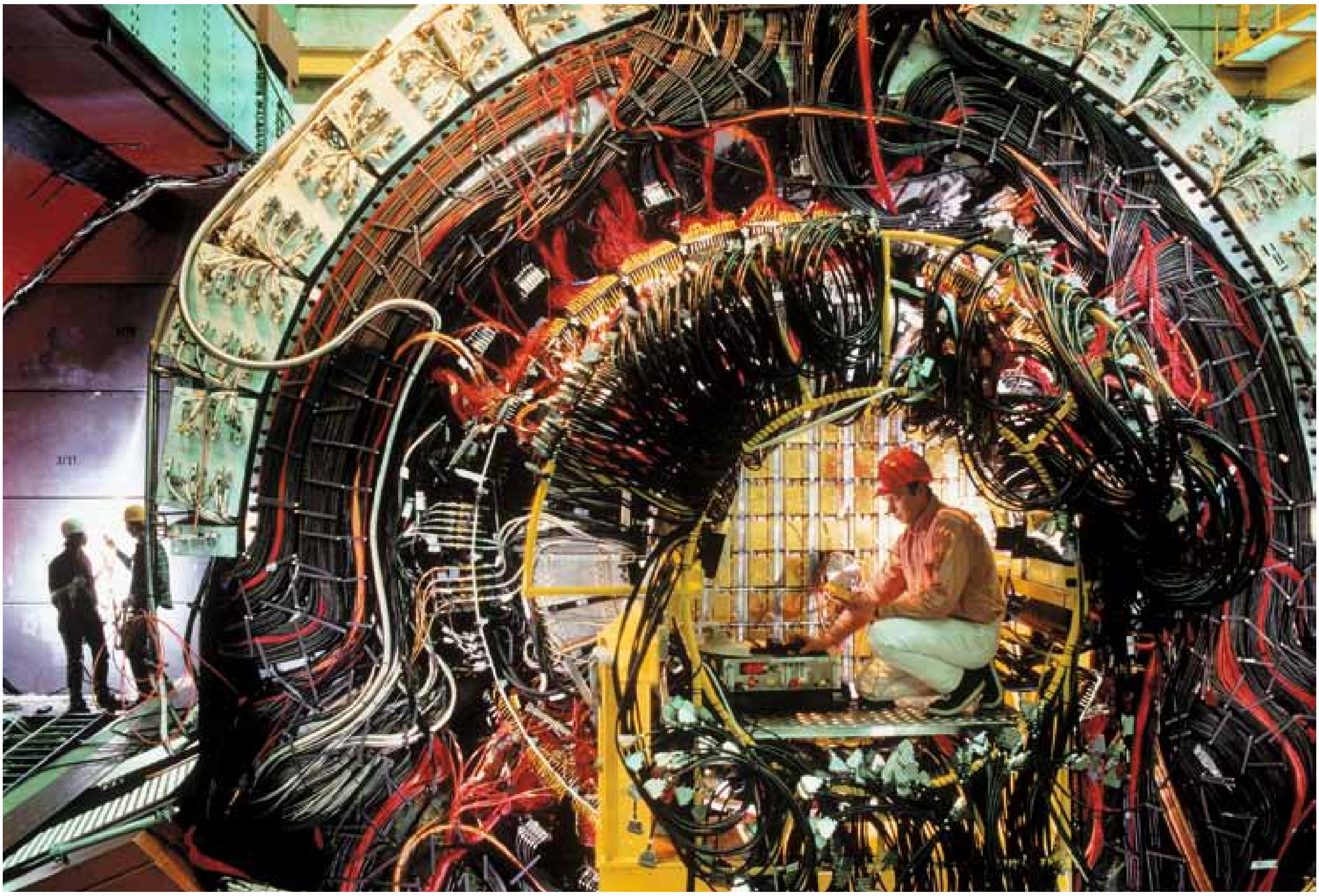


On the trail of quarks, supersymmetry and extra dimensions – particle physicists at DESY inquire into the very structure of our world. Using large accelerator facilities, supercomputers and leading-edge technology at the limits of the possible, they shed light on the secrets of the universe's fundamental forces and building blocks. In pursuit of these goals, they work in national and international networks with colleagues from all over the world.

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

In the heart of the H1 detector at the HERA accelerator



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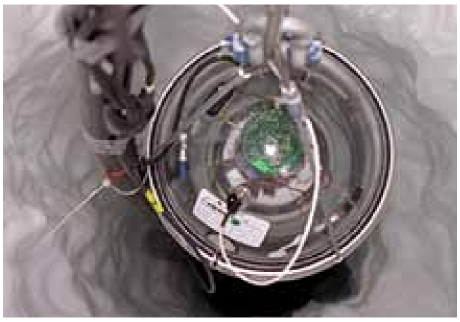


DESY.

Insight starts here

DESY is one of the world's leading accelerator centres for investigating the structure of matter. DESY develops, builds and uses particle accelerators and detectors for photon science and particle physics.

DESY carries out fundamental research in a range of scientific fields and focuses on three principal areas:

> **Accelerators:**
> DESY develops, builds and operates large facilities that accelerate particles to extremely high energies.

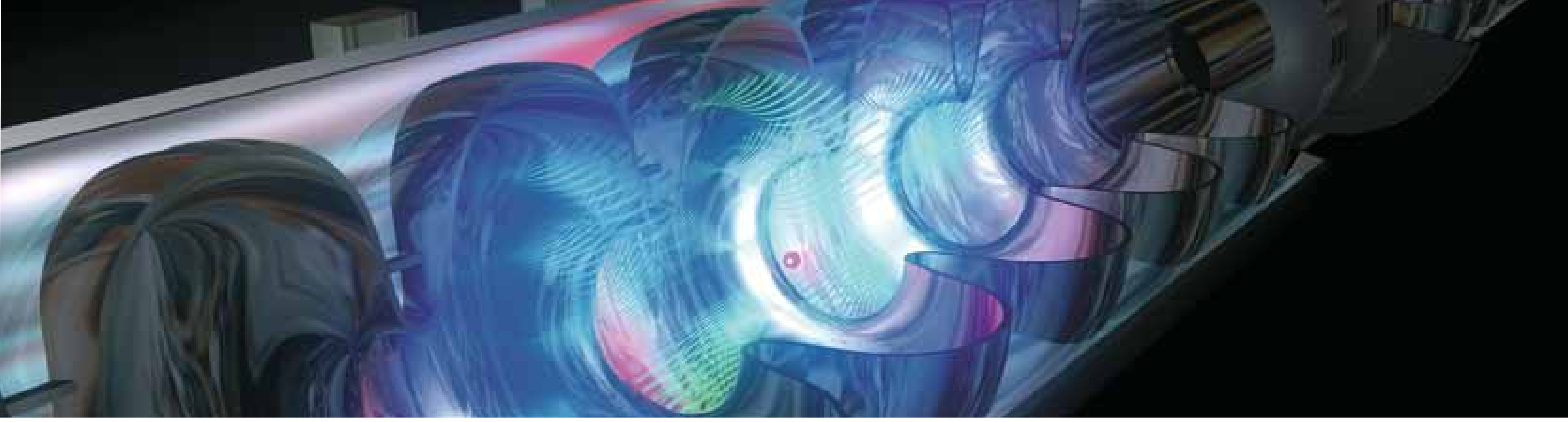
> **Photon science:**
> Physicists, chemists, geologists, biologists, medical researchers and material scientists use the special light from DESY's accelerators to study structures and processes in the microcosm.

> **Particle physics:**
> Scientists from around the world use accelerators to investigate the fundamental building blocks and forces of the universe.

The spectrum of research at DESY is correspondingly diverse – as is the cooperation with partners both national and international. All in all, more than 3000 scientists from 45 countries come to Hamburg each year to work at DESY. The research programme is not restricted to the facilities in Hamburg and Zeuthen. Indeed, DESY is closely involved in a number of major international projects, including the European XFEL X-ray laser in Hamburg, the Large Hadron Collider LHC in Geneva, the international neutrino telescope IceCube at the South Pole and the International Linear Collider ILC.

DESY facts and figures

- Deutsches Elektronen-Synchrotron DESY
- A Research Centre of the Helmholtz Association
- A public funded national research centre
- Locations: Hamburg and Zeuthen (Brandenburg)
- Employees: 1900, including 200 in Zeuthen
- Budget: 170 million euros (Hamburg: 154 million; Zeuthen: 16 million)



Computer simulation of particle acceleration

Accelerators

The development of particle accelerators involves special challenges for both humans and machines. Time and again it is necessary to push back the frontiers of science and technology. Over 50 years DESY has accumulated vast experience of accelerator development and is now one of the world's leading authorities in this field. DESY focuses on two principal areas of research:

- The development of light sources for science with photons in order to enable structures and processes to be observed on extremely small space and time scales. To this end, particles are first accelerated and then deflected by means of large magnetic structures in such a way that they emit a special form of radiation.
- The development of increasingly powerful accelerators for particle physics research in order to accelerate particles to ever greater energies and thereby obtain deeper insights into the very heart of matter and the origin of the universe.

Photon science

The intense radiation generated by particle accelerators can illuminate even smallest details of the microcosm. At DESY scientists from around the world use this light to investigate the atomic structures and reactions of promising new materials and biomolecules that might one day be used to make new drugs. DESY's unique spectrum of light sources makes it one of the world's leading centres for photon science:

- The DORIS III particle accelerator provides radiation suitable for a whole range of experimental purposes. This includes the analysis of catalysts and semiconductor crystals.
- Unique experimental opportunities are provided by the new free-electron laser FLASH, which generates extremely intense short-wavelength laser pulses.
- From 2009, researchers at DESY will have access to the world's best storage ring-based X-ray radiation source, PETRA III.
- The forthcoming X-ray laser European XFEL will complement the unique range of light sources in the Hamburg region.

Particle physics

On the trail of quarks, supersymmetry and extra dimensions – particle physicists at DESY inquire into the very structure of our world.

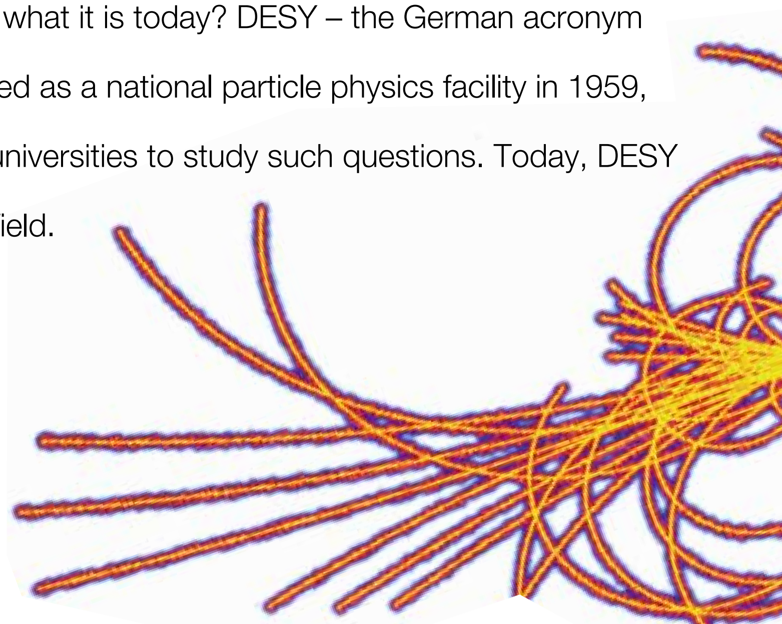
- Using data recorded with the “super electron microscope” HERA, an underground accelerator six kilometres in circumference, scientists investigate the structure of the proton and the fundamental forces of nature.
- Researchers will have unique opportunities to decipher the mysteries of matter, energy, time and space with the next major projects in the field of particle physics, in which scientists from DESY are also participating: the Large Hadron Collider LHC in Geneva, which is the world's most powerful accelerator, and the forthcoming International Linear Collider ILC.
- Using the neutrino telescope IceCube at the South Pole, DESY researchers and their colleagues gaze into the vast expanses of the cosmos in search of ghost particles from space.

Meanwhile scientists in the field of theoretical particle physics are working at DESY to try and piece together the big picture that corroborates the host of experimental findings.

TIME TRAVEL.

Insight into the world of elementary particles

Particle physics explores questions that are central to our understanding of the universe: What are we made of? What are the building blocks of our world and what holds them together? How did the universe come into existence and how did it become what it is today? DESY – the German acronym stands for German electron synchrotron – was founded as a national particle physics facility in 1959, in order to make it possible for scientists at German universities to study such questions. Today, DESY is one of the world's leading research centres in this field.



"We study, 'what binds the universe together at its core'. That's what makes basic research so fascinating."

50 years of particle research at DESY

Over the last 50 years, the results of particle physics research have revolutionized our understanding of the world. DESY has made major contributions to this progress. The research centre's first outing on the international stage came in 1966, with precision measurements carried out using the first particle accelerator in Hamburg: the "Deutsches Elektronen-Synchrotron", or DESY for short, the facility after which the research centre is named. These results made it possible to resolve an important controversy about the validity of quantum electrodynamics – the theory of the electromagnetic force – in favour of the theory.

In 1978, PETRA – at that time the largest storage ring of its type – was commissioned at DESY. Just one year later, the PETRA experiments made a groundbreaking discovery: for the first time ever, they were able to directly observe the gluon – the exchange particle of the strong force, which holds together the quarks, the fundamental building blocks of all matter.

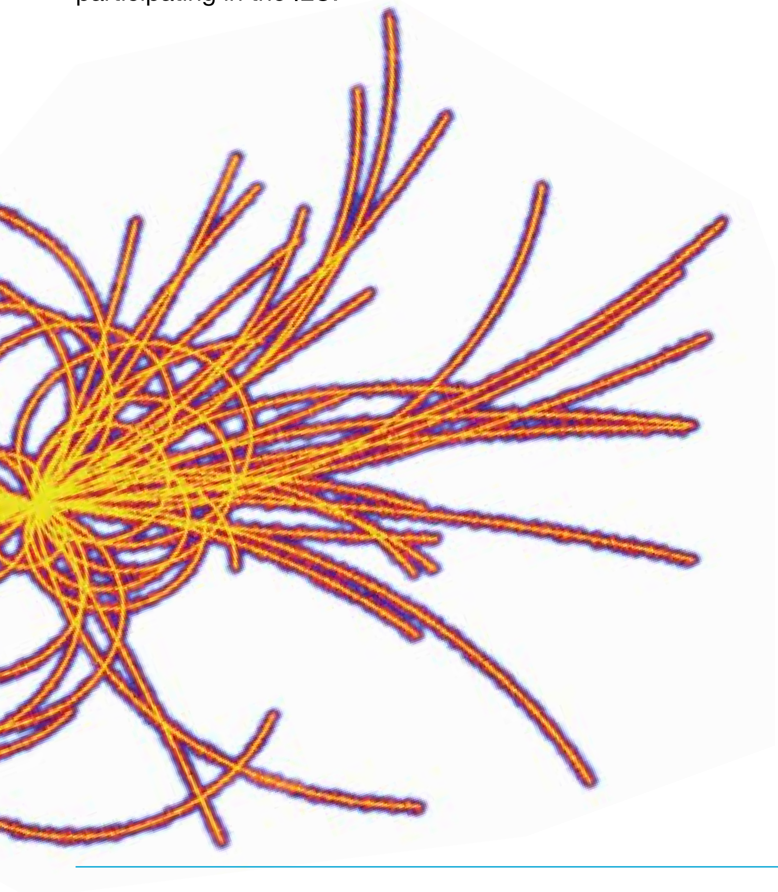
Germany's largest research instrument, the electron-proton accelerator HERA, was in operation at DESY from 1992 to 2007. The 6.3-kilometre-long super electron microscope provided physicists with the world's sharpest view of the proton's interior. Today many of the insights gained with HERA belong to our fundamental knowledge of how the world is put together. For many years to come, the evaluation of the HERA data will continue to provide unique insights into the inner structure of the proton and the fundamental forces of nature.

"We are building on the successes of the past, in order to realize the research visions of the future."

Particle physics with a future

International cooperation across cultural and political boundaries enjoys a long tradition at DESY. DESY participates in a number of international facilities which are no longer supported by one country alone, but are instead realized as wide-ranging international projects. In particular, DESY is involved in the experiments at the world's most powerful accelerator, the Large Hadron Collider LHC in Geneva, Switzerland. In addition, computing centres for monitoring LHC data acquisition and data analysis are being established at DESY.

DESY is playing a leading role in particle physics' large future project, the planned International Linear Collider ILC. The ILC is based on the superconducting accelerator technology developed and tested by DESY and its international partners. This technology is also used in two facilities for photon science – the free-electron laser FLASH at DESY and the X-ray laser European XFEL, which is currently under construction. All these activities create important synergy effects that distinguish DESY as one of key research centres participating in the ILC.



The DESY researchers at the Zeuthen location are primarily active in the field of astroparticle physics. As part of their work in large international projects, they use various messengers from the cosmos – neutrinos and high-energy gamma rays – to uncover the secrets of stellar explosions, cosmic particle accelerators and dark matter. Projects in which the Zeuthen scientists are participating include the IceCube neutrino telescope at the South Pole and development work associated with the planned CTA gamma-ray telescope.

"Particle physics forges the link between the very small and the very large."

Even the best experiments don't count for much without a solid theoretical foundation. DESY is a cornerstone of theoretical particle physics in Europe and worldwide. The DESY theory groups in Hamburg and Zeuthen study the underlying principles that explain the world of elementary particles and its physical laws. They explore the many facets of the Standard Model and aim to acquire new insights that embed the model into a unified theory of matter and forces – ideas which are of the highest interest in relation to the experiments at the LHC and the ILC.

In its role as the leading centre for particle physics in the Helmholtz Association, DESY initiated the Helmholtz Alliance "Physics at the Terascale" in 2007. The alliance brings together all of the German universities and institutes participating in the LHC and ILC. The objective is to focus and, in the long term, to enhance all of the expert knowledge of particle physics available in Germany. Within a short time, the alliance significantly improved the networking and international profile of particle physics in Germany – achievements that also helped to consolidate DESY's position in the front ranks of particle physics. ●

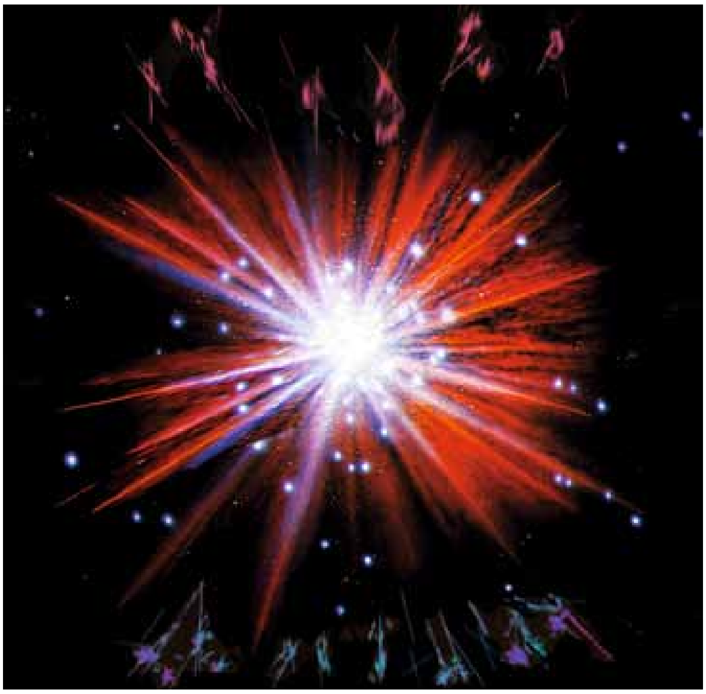
"With its 50-year success story in particle research and its unique facilities, DESY has played a decisive role in particle and astroparticle physics. DESY's many-facetted activities will contribute to securing and enhancing the facility's future as one of the world's leading research centres in this field."

●
Prof. Dr. Joachim Mnich
DESY Director in charge of
High Energy Physics and Astroparticle Physics

WORLD VIEW.

The big mysteries of the universe

In the course of the last century, physicists ventured into ever smaller dimensions. Today, the Standard Model of particle physics very successfully describes the fundamental building blocks of our world and the forces acting between them. Nevertheless, central questions remain unanswered. What is the origin of mass? What is dark matter made of? What happened right after the big bang? Are there any extra dimensions? Physicists hope to find the answers to these questions with the help of experiments at the large particle accelerators LHC and ILC. These answers would represent a decisive step on the way to an all-encompassing Theory of Everything.



Our universe came into existence almost 14 billion years ago in a gigantic explosion – the big bang.

What is the origin of mass?

Explaining how particles acquire their mass is one of the fundamental challenges physicists face. In the Standard Model, particles gain mass by interacting with a so-called Higgs field. That, at least, is the theory. If this field exists, then so must the Higgs particles connected with it. The search is on for these elusive particles. The experiments at the proton accelerator LHC in Geneva have especially good prospects of making this sensational discovery. In order to really explain the mechanism by which mass is created, however, it is necessary to precisely determine the properties of the Higgs particle. This is one of the great strengths of an electron-positron linear accelerator such as the planned International Linear Collider ILC.

What is dark matter made of?

Astronomical observations present us with yet another mystery. Just like the world we perceive, we are made up of conventional matter. However, this type of matter accounts for just four per cent of the universe. The remaining 96 per cent is probably made up of the unknown dark matter and dark energy. Dark matter is extremely difficult to observe and to investigate, as it only interacts weakly with normal matter. Dark energy appears like a previously completely unknown

property of space – it causes the cosmos to expand at an increasing rate. To explain the nature of dark matter and dark energy is one of the biggest challenges facing modern particle physics and cosmology.

What happened right after the big bang?

We live in a world of matter. In the big bang, matter and antimatter should have been formed in equal amounts. Since both annihilate each other in a burst of energy whenever they meet, however, there must have initially been more matter than antimatter – otherwise neither we, nor our material world, would actually exist. Obviously, nature preferred matter to antimatter – but why?

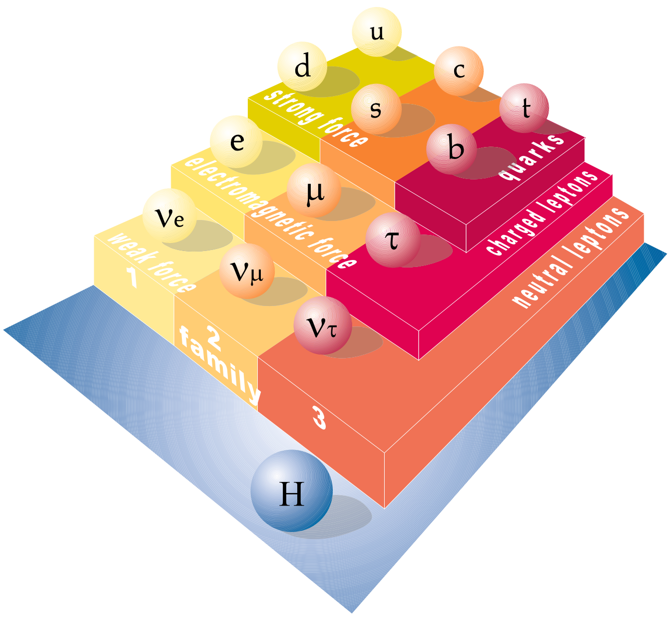
Today, conventional matter consists of atoms whose nuclei are made up of protons and neutrons. These in turn are made up of quarks, which are held together by gluons. Right after the big bang, however, the universe was so hot and laden with energy that the gluons could not bind the quarks together. During the first microseconds after the big bang, the universe was probably filled with a kind of primordial cosmic soup, an inconceivably hot and dense mixture of quarks, gluons and other elementary particles. To generate such a quark-gluon plasma and measure its properties would not only shed new light on the strong force that acts between the quarks; it would also enable physicists to explain how stars and galaxies were able to form at all in the early days of the cosmos.

Are there any extra dimensions?

Does our universe exist in more than three dimensions of space? This idea is more than unfounded speculation by science fiction authors. Some theories that go beyond the Standard Model, such as string theory for example, postulate that our universe possesses additional dimensions of space in addition to the three we are familiar with – dimensions that have so far remained hidden from us. At very high energies, it might be possible to experimentally demonstrate the existence of such extra dimensions.

The building blocks of our world

The Standard Model of particle physics describes the structure of our world in terms of 12 matter particles: six quarks and six leptons. These occur in three families, each consisting of two quarks and two leptons. The "normal" matter that we are familiar with consists exclusively of particles from the first family – the up and down quarks, from which all atomic nuclei are composed – and the electrons, which belong to the leptons of the first family. The particles of the other families only existed in the early stages of the universe. Today, these varieties of particle can be produced in particle accelerators. They are, however, unstable and exist only for a very short time before decaying.



For each of the 12 particles there is a corresponding antiparticle. For example, the antiparticle of the electron is the positron. The Higgs particle (H) is responsible for the mass of elementary particles. The matter particles are bound together by three forces: the electromagnetic, the strong and the weak interactions. The fourth known force, gravity, cannot yet be described within the framework of the Standard Model.

WORLD RESEARCH.

DESY
An international centre for particle physics

All over the world, scientists strive to answer the key questions of the origin and nature of our universe. However, it will only be possible to make headway here if everyone involved joins together in national and international research networks. This networking – across political and cultural borders – enjoys a long tradition at the particle physics research centre DESY.

Particle physics goes global

The construction of the HERA accelerator at DESY in the 1980s was a prime example of successful international cooperation. In what was a first in the history of particle physics, 11 countries collaborated to realize the project. Prior to then, it had been common practice to build the detectors in international cooperation, but the accelerators remained the preserve of the host institute. The international interest in HERA was so great, however, that more than 20 per cent of the accelerator was financed from outside Germany; the corresponding figure for the four HERA experiments, which were operated by large international teams of physicists from all over the world, was around 60 per cent. This "HERA model" of international cooperation functioned so well that it became a role model for carrying out large international research projects.

This long-term international networking continues to benefit DESY now that HERA has been switched off. As in astronomy, where researchers from all over the world work with a few telescopes constructed and operated in international collaboration, the focus of particle physics is shifting to a few large-scale facilities that can no longer be sustained by one country alone, but can only be realized in wide-ranging international cooperation. Nowadays, the particle physicists at DESY contribute their knowledge at various such large-scale, international facilities, including the particle accelerators LHC and ILC, the neutrino telescope IceCube and the gamma-ray telescope CTA. This leads to new forms of cooperation both on the national and international level.

The Helmholtz Alliance "Physics at the Terascale"

At the initiative of DESY, all the German universities and institutes working on the LHC and ILC joined forces in a so-called Helmholtz Alliance. The common goal of the partners in the Alliance "Physics at the Terascale" is to bring together and, in the long term, to enhance the expert knowledge of particle physics at German research institutions. The term "terascale" refers to the energy realm of trillions of electronvolts, which the LHC and later the ILC are to reach. Particle physicists are expecting decisive new discoveries to occur at these teraelectronvolt energies.

One main goal of the Helmholtz Alliance is to network the particle physics research infrastructure distributed throughout Germany – for example, high-technology laboratories and high-performance computing infrastructure – so that it can be jointly utilized by all Alliance members. In addition, the Alliance promotes and supports young scientists and creates a range of new job opportunities. DESY plays a major role in this new network, contributing its extensive know-how and infrastructure to promote the development of accelerators and detectors, its comprehensive expertise regarding the analysis of physics data plus its large computing resources. For example, a major centre for the analysis of LHC data will be established at DESY.

The five main subjects of particle physics at DESY:

> HERA

Using data recorded with the "super electron microscope" HERA, particle physicists investigate the structure of the proton and the fundamental forces of nature. For 15 years, electrons and protons collided inside the HERA particle accelerator, which lies deep in the earth beneath Hamburg. Data taking at Germany's largest research instrument, which has written physics history, ended in the summer of 2007. The evaluation of the recorded measurement data, however, will extend well into the next decade. The knowledge gained will give us a comprehensive overall picture of the proton and the forces at work inside it.

> LHC

DESY is also playing a part in work at today's most powerful accelerator worldwide: the new Large Hadron Collider LHC at CERN in Geneva, Switzerland. In the LHC, protons collide at energies of 14 teraelectronvolts, i.e. 14 trillion electronvolts – the highest energies ever attained in a particle accelerator. The LHC will enable physicists to venture far into the uncharted territories of the terascale. With the help of its particle collisions, the physicists hope to find answers to a wide range of unresolved questions in current particle theory. The insights into the proton provided by HERA are an indispensable basis for their work.

> ILC

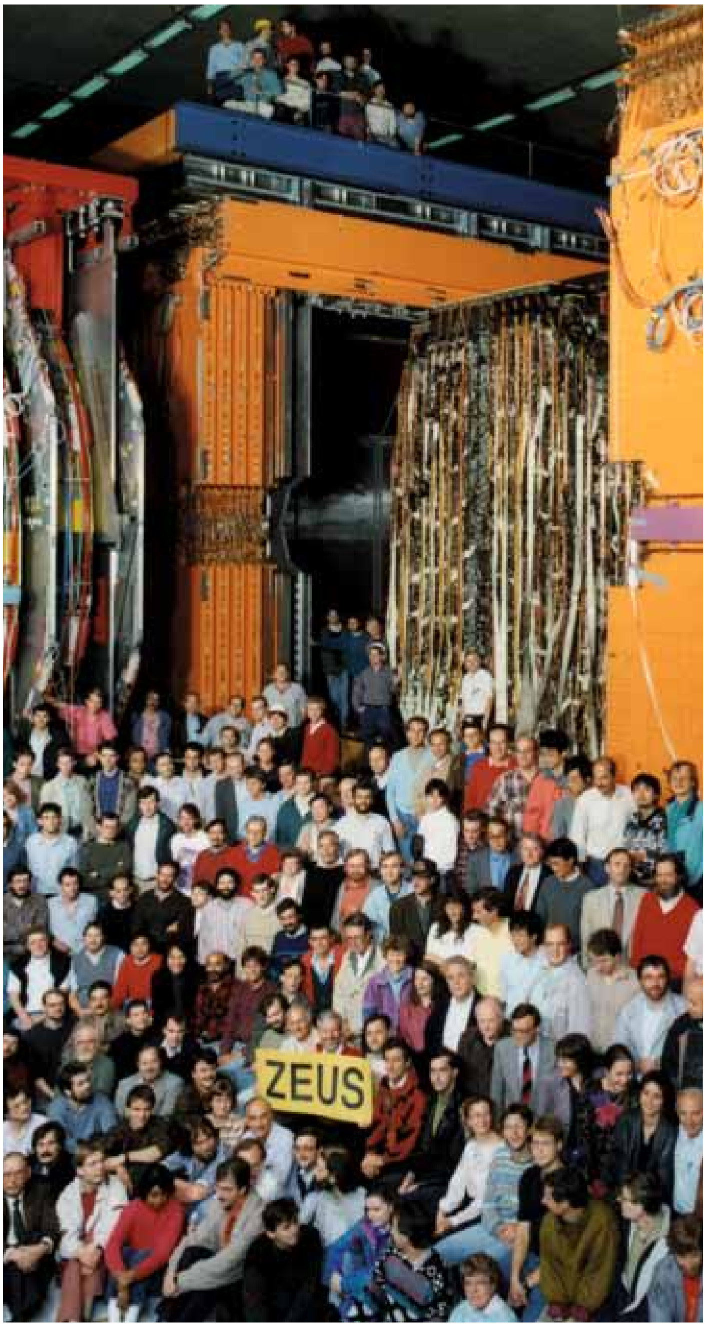
The discoveries at the LHC can only be fully comprehended in conjunction with an electron-positron accelerator whose unique precision will enable physicists to reveal the secrets of the terascale in all their facets. One such big project planned for the future is the International Linear Collider ILC – a linear accelerator in which electrons and their antiparticles, the positrons, will collide at energies of 500 to around 1000 billion electronvolts. DESY is a major participant in this accelerator of the future, whose concept is based on the superconducting accelerator technology developed at DESY.

> IceCube and CTA

DESY is active in astroparticle physics at its location in Zeuthen, Germany. The DESY researchers use various particles – messengers from the cosmos – to uncover the secrets of stellar explosions, cosmic particle accelerators and dark matter. DESY is a major participant in the international neutrino telescope IceCube – the world's largest particle detector – which has been frozen deep into the ice of the South Pole. In the future, the scientists will also be hunting for high-energy electromagnetic radiation from outer space with the planned gamma-ray telescope CTA.

> Theory

Theoretical particle physics strives to piece together the big picture that underlies all the various experimental results. In order to explain the world of elementary particles and the laws of physics that rule it, the theorists at DESY use numerous mathematical tools and high-performance computers developed especially for this purpose. Only by working closely together will theorists and experimentalists be able to penetrate the mysteries of nature and – so the scientists hope – to ultimately work out a comprehensive theory of all particles and forces.



Ventures such as today's experiments in particle physics are so complex and expensive that they can only be undertaken in wide-ranging international cooperation.

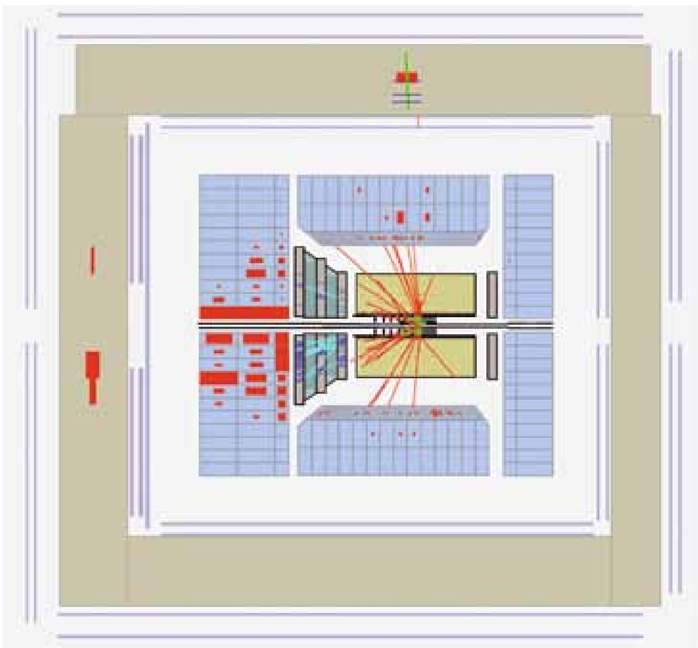
POINTING THE WAY.

HERA
The super electron microscope

The Hadron-Electron Ring Accelerator HERA was the largest particle accelerator at DESY and Germany's largest research instrument. For 15 years, this gigantic super electron microscope provided physicists with the world's sharpest view of the proton's interior. During this time, electrons and protons collided at extremely high energies inside the particle accelerator ring, which lies deep in the earth beneath Hamburg. Research operation was concluded in summer 2007 and HERA was switched off. The evaluation of the recorded data, however, will continue far into the next decade. The prospects are exciting. The HERA physicists are now perfecting a comprehensive overall picture of the proton and the forces acting within it, whose precision won't be matched by any other particle accelerator in the world for years to come.

A precision machine

The HERA storage ring facility at DESY was the only accelerator in the world in which two different types of particle were accelerated separately and then collided head-on. Here, in a 6.3-kilometre-long tunnel located deep below Hamburg, lightweight electrons – or their antiparticles, positrons – collided with hydrogen nuclei, which are nearly 2000 times heavier. These nuclei are protons – particles of the hadron family. In such collisions, the point-like electron acts like a tiny probe that scans the inside of the proton and reveals its inner structure. The higher the energy of the particle collision, the deeper physicists are able to gaze into the proton, and the more details are revealed. That's why HERA was dubbed a "super electron microscope": thanks to HERA's highly precise "electron probes", particle physicists are able to investigate the inner structure of the proton and the fundamental forces of nature in great detail.



Picture of a particle collision: This event was recorded by the ZEUS detector during the collision of a proton and a positron (antiparticle of the electron). Key information can be obtained from the measured track directions and particle energies.

The sharp eyes of HERA

There are four immense underground halls at the HERA storage ring, one for each point of the compass. The detectors used by international research teams to investigate

the most minute building blocks of matter stood here, seven stories beneath the earth. In 1992, the first two HERA experiments – H1 in the North Hall and ZEUS in the South Hall – went into operation. Both experiments observed the high-energy collisions of electrons and protons in order to unravel the internal structure of the proton and the mysteries of nature's fundamental forces. The HERMES experiment started taking data in the East Hall in 1995. It used the HERA electron beam to investigate the intrinsic angular momentum – the spin – of protons and neutrons. From 1999 to 2003, the HERA-B experiment in HERA's West Hall used the proton beam from the storage ring to shed light on the properties of heavy quarks.

Unique insights

The huge detectors were in operation until mid-2007, and between them they have recorded a gigantic amount of data. During that time, many of HERA's insights into the microcosm found their way into the physics textbooks. They are now part of our basic knowledge of the workings of our world. The journey of discovery is far from over, however. Active data taking has been completed, but the HERA experiments are continuing: the evaluation of the recorded measurement data will provide unique insights into the inner structure of the proton and the fundamental forces of nature well beyond 2010.

The HERA physicists will thus ultimately reveal an all-encompassing, global picture of the proton – a comprehensive experimental description unprecedented in its precision and multifaceted quality – which, given HERA's unique nature, will remain valid and unchallenged for years and possibly decades to come.

HERA: Hadron-Electron Ring Accelerator

Electron-proton storage ring facility at DESY in Hamburg
Research operation: 1992-2007
Evaluation of the recorded data: until well beyond 2010
Length: 6336 m
Energy of the electrons: 27.5 gigaelectronvolts (GeV)
Energy of the protons: 920 gigaelectronvolts (GeV)
Longitudinally polarized electron beam
Experiments: H1, ZEUS, HERMES, HERA-B

> H1 and ZEUS electron-proton collision experiments
Decoding the internal structure of the proton
Extending our understanding of the fundamental forces
Looking for new forms of matter
Looking for unexpected phenomena in particle physics

> H1 experiment
Data taking: 1992-2007; HERA North Hall
Universal detector: 12 m x 10 m x 15 m; 2800 tonnes

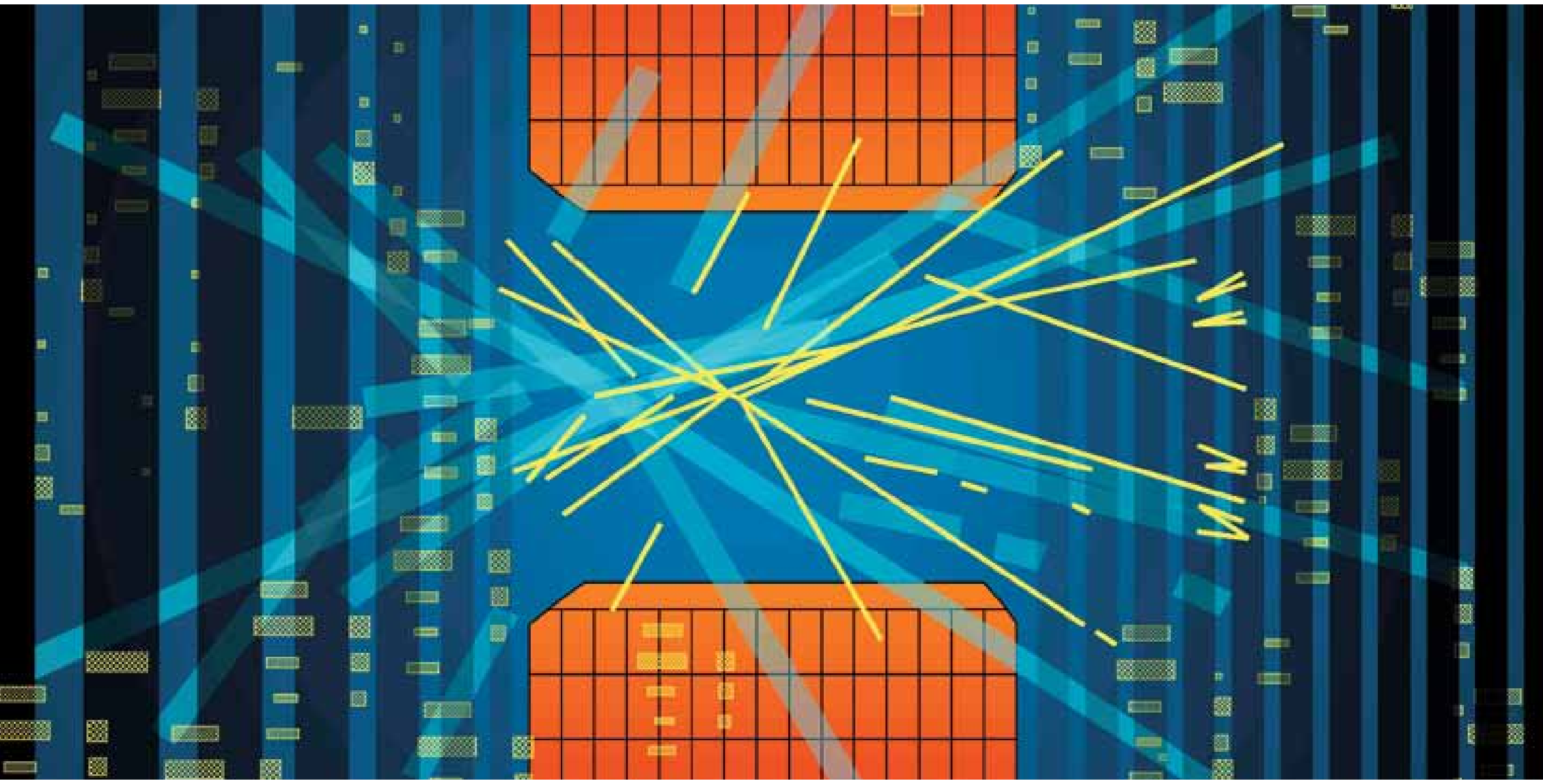
> ZEUS experiment
Data taking: 1992-2007; HERA South Hall
Universal detector: 12 m x 11 m x 20 m; 3600 tonnes

> HERMES beam-target experiments
Investigation of the origin of nucleon spin
Use of the longitudinally polarized electron beam
Data taking: 1995-2007; HERA East Hall
Detector: 3.50 m x 8 m x 5 m; 400 tonnes

> HERA-B beam-target experiment
Investigation of the properties of heavy quarks
Use of the proton beam
Data taking: 1999-2003; HERA West Hall
Detector: 8 m x 20 m x 9 m; 1000 tonnes

H1 AND ZEUS.

Particles on a collision course



Tiny probes

The colliding-beam experiments H1 and ZEUS took data from 1992 to 2007. Right in the centre of these detectors, the electrons that circled around the HERA ring in one direction smashed head-on into the protons coming from the other direction. In such collisions, the point-like electron acts as a tiny probe that scans the inside of the proton. It penetrates into the proton, where it comes up against one of the quarks from which the proton is made and communicates with it through the exchange of a force particle. The quark is expelled from the proton in the process, forming a bunch of new particles that fly off in all directions along with the electron.

The tracks that the particles leave behind in the detectors enable the physicists to draw conclusions about what's going on inside the proton. This involves more than just learning about the different components that make up the proton; it also concerns the fundamental forces of nature acting between the particles. The energy available for these experiments at HERA was about ten times greater than that of similar experiments in the past. The super electron microscope HERA thus provided the physicists with the world's sharpest view of the proton's interior.

Quark-gluon soup

HERA did a terrific job in performing its main task of creating high-resolution "images" of the proton's interior. The HERA experiments H1 and ZEUS already provided totally new insights into the workings of the proton during HERA's first phase of operation. Physicists discovered that the proton consists of three quarks more than 30 years ago. The quarks are bound together by the strong force. The exchange particles of this force are the gluons, which were first observed at DESY in 1979. In 1992, as HERA commenced operation, it was known that the quarks in the proton emit gluons, and these, in turn, give rise to further gluons or pairs of quarks and antiquarks. Beyond that, however, there were only vague expectations of what would be found in the proton's interior. It was generally assumed that apart from the three valence quarks that are responsible for the charge of the proton, there are only very few quark-antiquark pairs and gluons in the proton.

As the HERA experiments H1 and ZEUS discovered, the inner life of the proton is in fact a lot more turbulent than was previously supposed. Thanks to HERA's extremely high energy, the H1 and ZEUS experiments were able to measure the structure function F_2 of the proton – a function that describes the distribution of the quarks and antiquarks in the proton – over a range that was up to a thousand times greater than what was accessible to earlier experiments. What the physicists discovered during these tests came as a great surprise: the HERA measurements show that the interior of the proton is much like a thick, bubbling soup in which gluons and quark-antiquark pairs are continuously emitted and annihilated again. The closer you look, the more particles appear to exist within the proton. This high density of gluons and quarks in the proton, which increases more and more the smaller the momentum fractions of the quarks and gluons, represented a completely new and until then uninvestigated state of the strong force. Theorists and experimental physicists are working together to discover how this arises.

The "sea" of short-lived quark-antiquark pairs in the proton contains more than the light up, down and strange quarks. Thanks to HERA's high resolution during its second operating phase, the physicists at the facility were able to detect the heavy charm and bottom quarks inside the proton for the first time and separately measure their structure functions. An exact understanding of the mechanisms that generate heavy quarks is particularly important for the physics programme at CERN's LHC accelerator.

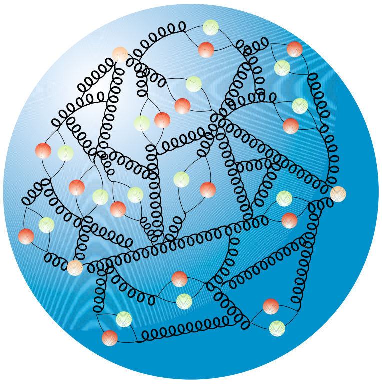
The puzzling case of diffraction

The HERA physicists were greeted by another surprise soon after the facility went into operation. In collisions with the highest momentum transfers, a quark is thrown out of the proton with great force. Instead of "bursting apart" into many new particles, however, the proton remains completely intact in approximately 10 to 15 per cent of such cases, despite the intensity of the collision. This would be like discovering that no marks or scratching occur in 15 per cent of all head-on vehicle collisions! Such phenomena were familiar at low energies, and were generally described using the ideas of diffractive physics. The phenomenon was explained by means of a pomeron – a hypothetical neutral particle that has the quantum numbers of the vacuum and possesses very little structure or significance of its own. However, early measurements at HERA showed that this concept of the pomeron simply did not hold up, failing completely in the case of large momentum transfers – the so-called hard diffraction range. So what mechanism leads to this surprising observation?

To conform with QCD, the theory of the strong force, at least two gluons must be involved in a diffractive interaction. Otherwise it couldn't be colour-neutral, as is observed in experiments. Could this phenomenon therefore possibly have something to do with the high proportion of gluons in the proton at small momentum fractions? The H1 and ZEUS results were clear: the colour-neutral exchange is dominated by gluons. These observations led to the development of an entire industry devoted to describing hard diffraction, and the analyses and interpretation attempts continue unabated. Although some successes have already been achieved, the results are still not yet completely understood. It is therefore important that the HERA data should be analysed and evaluated from all conceivable points of view so that the theoretical interpretations can be appropriately assessed.

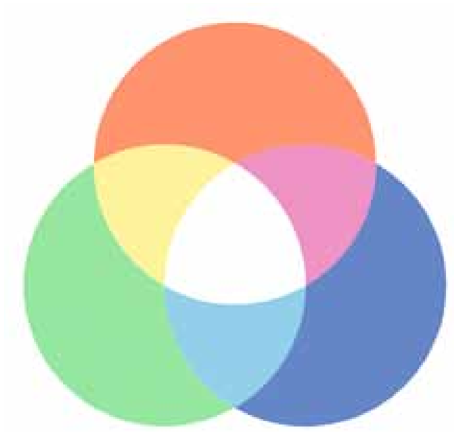
Valence quarks, sea quarks and gluons

The super electron microscope HERA made the proton's detailed structure visible. There are three valence quarks inside the proton, which are bound together by the exchange of gluons. Quantum theory allows the gluons to transform into quark-antiquark pairs for an extremely short time. Alongside the valence quarks, the proton therefore also contains a whole "sea" of gluons and short-lived quark-antiquark pairs.



Momentum fraction and momentum transfer

- Momentum fraction (x): the fraction of the proton's momentum carried by the quark with which the electron collides
- The momentum transfer (Q^2), also called the resolution parameter, is the square of the momentum transferred in the collision between the collison partners. It is a measure of the resolution of the HERA microscope (Q^2 = 1 GeV^2 corresponds to a resolution equal to one-fifth of the proton radius).



Coloured quarks

In the Standard Model, the strong force is caused by an abstract particle property called colour charge. Quarks for instance exist in the colours red, green and blue, antiquarks in antired, antigreen and antiblue. However, only colour-neutral combinations are observed in experiments: particles made up of three quarks – red, green and blue quarks – such as the proton, or quark-antiquark combinations with one colur and the corresponding anticolour. Only colourless combinations like these exist as free particles – no single-colour particle has ever been observed.

The fundamental forces of nature

Four basic forces rule the world: gravity, electromagnetism, and the weak and strong interactions. It is the force of gravity that causes apples to fall from trees and the planets to orbit the sun. The electromagnetic force binds electrons and protons into atoms and provides the electric current flowing from the wall socket. The weak force is at the origin of nuclear fusion in the sun and the radioactive decay of atomic nuclei. And the strong force holds the quarks and gluons together inside the proton, and the protons and neutrons inside the atomic nucleus.

Each of the forces (or interactions) is mediated by specific exchange particles: the electromagnetic force by the photons, which are also known as light quanta; the weak force by the electrically neutral Z particle and the negatively and positively charged W particles; the strong force acting between the quarks by the gluons; and gravity by the massless, as yet undiscovered graviton.

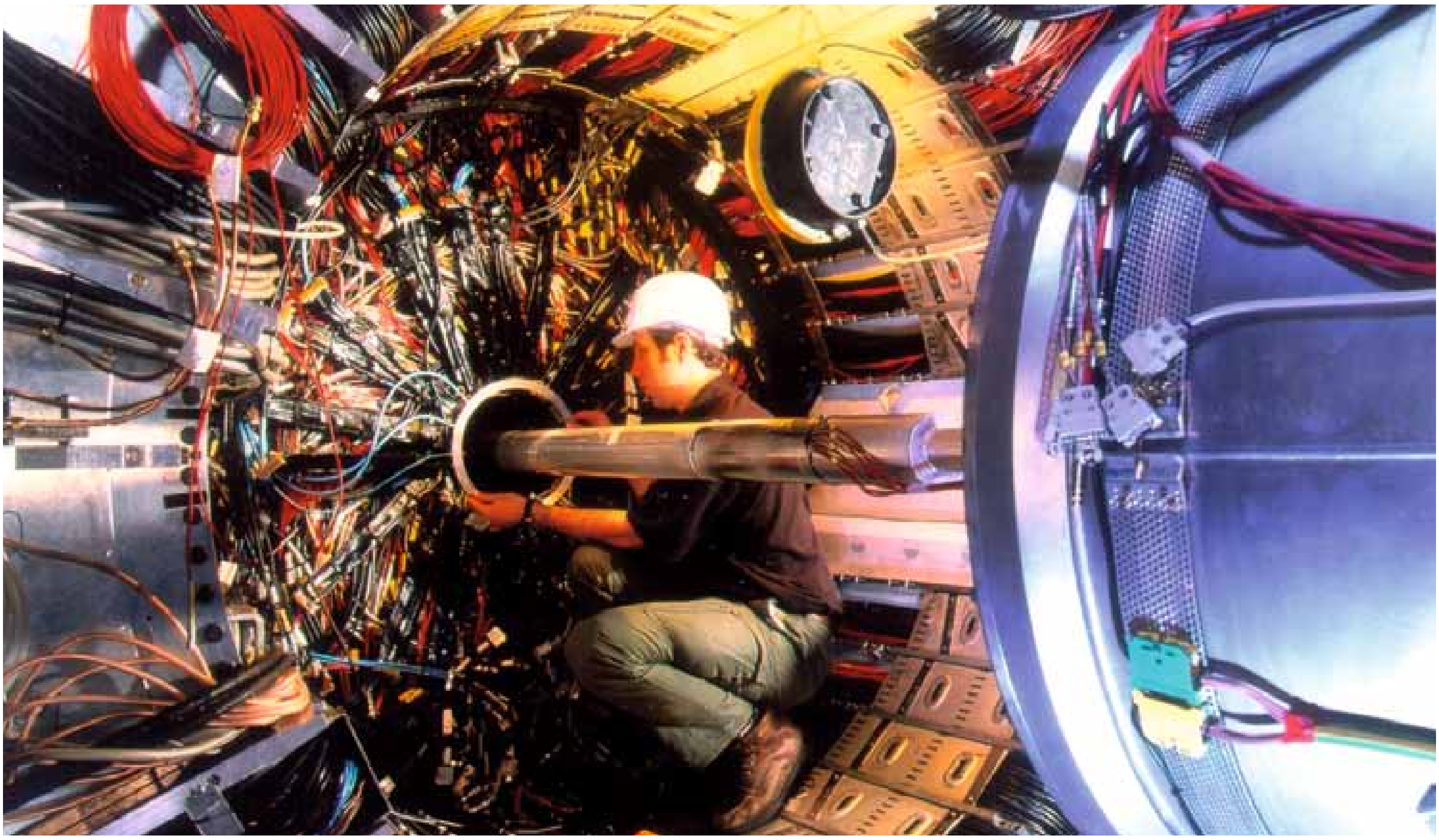
Today, physicists assume that shortly after the big bang, when the whole universe was still a minuscule fireball of incredibly high energy, a single primal force controlled all interactions. Experiments at particle accelerators such as HERA allow us to study forces and particles with the utmost precision. That permits physicists to draw conclusions about the conditions at extremely high energies, where the fundamental forces unify into a single, original force – and thus to reconstruct the evolution of the universe shortly after the big bang.

HERA and the Nobel Prize

The experiments H1 and ZEUS have also been able to take a close look at the properties of the forces of nature. For instance, H1 and ZEUS have enabled the physicists to precisely measure the strength of the strong force acting between the quarks. A special attribute of the strong force is its unusual behavior with respect to the distance between particles: while the electromagnetic interaction gets weaker as the distance gets larger, the exact opposite is the case with the strong force. Quarks are able to move more freely the closer they get to one another; the farther they are apart, the stronger is the pull of the strong force that draws them together. In many ways, the strong force acts like a rubber band. The quarks are thus more or less trapped in the proton; no one has ever observed a free quark.

While it is true that the strong coupling constant – a measure of the strength of the force – has been determined as a function of distance also in other experiments, H1 and ZEUS were able to demonstrate for the first time the special behaviour of the coupling constant over a broad range of energies in a single experiment. The HERA results thus impressively confirmed the behaviour of the strong force, which was predicted 20 years ago by David Gross, David Politzer and Frank Wilczek. For their work, the three physicists were awarded the Nobel Prize in Physics in 2004.

In the heart of the H1 detector



Back to the primordial force

Although HERA was used mostly for studies of the strong interaction, its high-energy electron-proton collisions also enabled scientists to take a close look at other forces of nature. The H1 and ZEUS experiments impressively confirmed one of the central predictions of the currently accepted particle theory, the Standard Model: they were able to show that two of the fundamental forces of nature are just different aspects of one single force. The electromagnetic force and the weak force are normally dissimilar in strength. As its name gives away, at low energies the weak force is much weaker than the electromagnetic force. However, the two forces become equally strong at the highest collision energies HERA could provide. This behaviour is an important property of the electroweak force, which the two forces unite to at very high energies. H1 and ZEUS therefore directly observed the effects of electroweak unification – the first step toward the grand unification of the fundamental forces of nature.

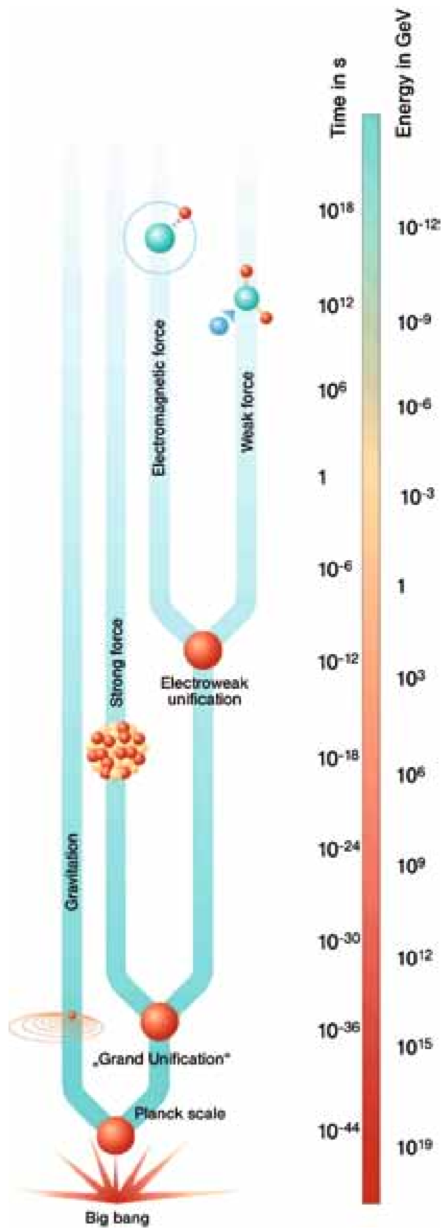
Testing the limits of the Standard Model

After the luminosity upgrade in 2000 and 2001, the HERA experiments were able to fully exploit the extremely high resolution of the super electron microscope in its second phase of operations. Particle collisions in the realm of the highest momentum transfers, i.e. at the highest resolution, are comparatively rare. Yet it is precisely here, at the known limits of the Standard Model, that any new effects beyond current particle theory should appear. Thanks to the increased collision rate, there were also more collision events here. As a result, the HERA physicists were able to investigate this realm extremely precisely with high statistical corroboration. To date, no significant deviations from the Standard Model have been observed. The HERA experiments can thus substantially broaden the Standard Model's scope of validity and thereby progressively restrict the possible phase space for new phenomena, new particles or new interactions. In so doing, they increasingly refine the insights of the Standard Model all the way up to the highest momentum transfers.

An essential foundation for the LHC

HERA's results are vital if physicists are to correctly interpret the measurements from the Large Hadron Collider LHC in Geneva. In the LHC, protons collide at an energy around 50 times the one reached in HERA. Because protons are extended, composite particles rather than point-like ones, the collisions that take place in the LHC are extremely complex, and therefore difficult to describe in theoretical terms. That is why it is crucial to have the most precise knowledge possible of the collisions' input state – which is supplied by the HERA experiments with their detailed image of the proton.

Precision measurements of the different densities of the quarks and gluons in the proton are extremely important, particularly when it comes to explaining the Higgs mechanism. Many of these measurements, which are fundamental to the LHC, could only have been taken at HERA. Thanks to the intensive cooperation of DESY and CERN during the last years of HERA operation, an active, long-term relationship has been established between the researchers at HERA and the LHC. This connection has made it possible to optimally prepare the experiments at the LHC in the light of the knowledge gained at HERA.



A journey through time to the beginning of the universe: the scale shows the age of the universe from the big bang to the present day along with the corresponding average energy of radiation and matter particles.

HERMES.

The right spin

The last setup work on the recoil detector of the HERA experiment HERMES. The target – a gas-filled cell – is located at the heart of this detector. The polarized electron beam from the HERA storage ring passes through this cell (from front to rear in this picture) and collides with the atoms of the gas. These particle reactions provide information on the origin of nucleon spin. The remainder of the HERMES detector with the large spectrometer magnet is in the back behind the recoil detector.

HERMES and the spin puzzle

Much like the Earth, the nucleons – i.e. the protons and neutrons – inside the atomic nucleus revolve around their axes. In other words, they possess spin. Physicists are still puzzled by this phenomenon. Back in the mid-1980s, experiments at the research centres CERN and SLAC discovered that the three main constituents of a nucleon – the valence quarks – account for only around a third of the nucleon's total spin. So where do the remaining two-thirds come from? The HERA experiment HERMES, which took data from 1995 to 2007, was built to find out. The scientists working on HERMES observed what happened when electrons from the HERA storage ring passed through a gas-filled cell and collided with the atoms of that gas. The key feature was that both the electrons from HERA and the gas atoms were polarized, i.e. their spins were aligned in a specific direction. Given that the frequency and type of collision depends on this alignment, the particle reactions observed provide researchers with insights into where the spin of the proton actually comes from.

The spin of the quarks

Today, it is clear that the three valence quarks cannot alone account for the nucleon spin. After all, protons and neutrons also comprise a whole sea of quarks, antiquarks and gluons. All of these subatomic particles possess spin; all of them are in constant motion and thus also possess orbital angular momentum. Consequently, to properly understand nucleon spin, you must determine the contribution made by each individual member of this seething mass. And this is exactly what HERMES is good at: the experiment's special concept enabled physicists to separately measure the contribution made by each different type of quark to the total spin.

During HERA's first operational phase, HERMES impressively completed this first assignment. Using measurements on longitudinally polarized gases, the HERMES physicists provided the world's first determination of the separate contributions made to the nucleon spin by the up, down and strange quarks. The results reveal that the largest contribution to the nucleon spin comes from the valence quarks. The up quarks make a positive contribution as their spin is preferably aligned with the spin of the nucleon, while the down quarks provide a contribution with opposite sign. The polarizations of the sea quarks are all consistent with zero – an especially important result, as previous experiments had led to the conclusion that the strange quarks play a significant, cancelling, role in the nucleon spin. The HERMES results now show that the polarizations of the sea quarks are all small: there is thus little evidence for such a cancellation between the contributions of valence and sea quarks. The HERMES measurements prove that the spin of the quarks generates less than half of the spin of the nucleon, and that the quark spins that do contribute come almost exclusively from the valence quarks. HERMES thus succeeded in taking an initial and decisive step toward the solution of the spin puzzle.

Gluon spin and orbital angular momentum

Following their studies of the quark spins, the HERMES physicists turned their attention to the gluon spin and the orbital angular momentum of the quarks and gluons, which could also be contributing to the nucleon spin. Here, they succeeded in making one of the first measurements providing a direct indication that the gluons make a small but positive contribution to the overall spin. More detailed information will be obtained through the analysis of the latest data.

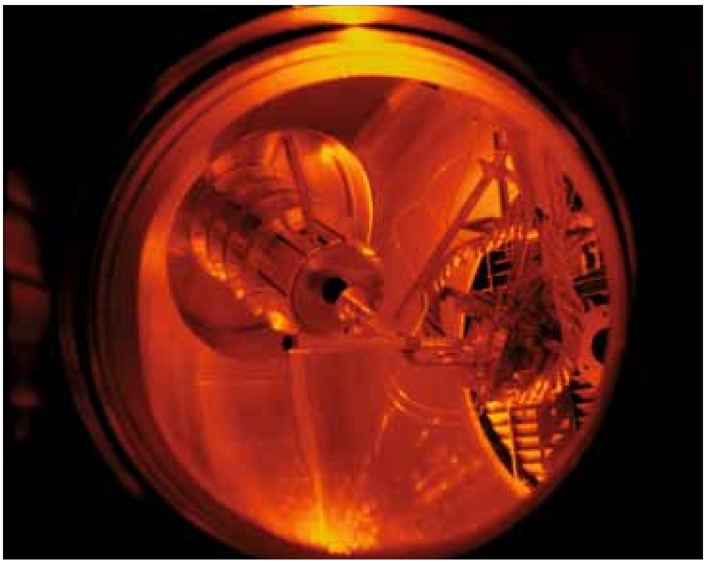
Up until recently, it had been impossible to experimentally investigate the orbital angular momentum of the quarks in the nucleon. The latest theoretical work has, however, pointed in new directions for determining the contribution made by the orbital angular momentum. During the second phase of HERA operations, the HERMES physicists therefore made measurements on transversely polarized hydrogen gases, i.e. with their spins aligned perpendicularly to the direction of travel of the electrons. The data thus obtained enabled them to study these remaining aspects of the spin puzzle.

The HERMES physicists were thus able to realize a first, albeit model-dependent extraction of the total orbital angular momentum of the up quarks. The team will refine these results even further through the utilization of measurements taken with a new recoil detector from 2006–2007, in the hope of being able to identify the total orbital angular momentum of the up quarks in the near future.

The HERMES physicists also succeeded in determining the so-called transversity distribution for the first time. This distribution describes the difference in the probabilities of finding quarks in a transversely polarized nucleon with their spin aligned to the spin of the nucleon and quarks with their spin anti-aligned. In addition, they also gained access to a function that describes the distribution of unpolarized quarks in a transversely polarized nucleon. This function should vanish in the absence of quark orbital angular momentum. Analysis of the initial data shows that it seems to be significantly positive, which indicates that the quarks in the nucleon do in fact possess a non-vanishing orbital angular momentum.

Beyond the spin puzzle

Although HERMES focuses on nucleon spin, the overall physics programme of the experiment extends far beyond that particular aspect. For example, the HERMES physicists utilize measurements on unpolarized gases to study exactly how hadrons, i.e. particles comprised of quarks, form, and how quarks propagate in nuclear matter. They also use such measurements to determine whether exotic states consisting of five quarks, so-called pentaquarks, actually exist. Analysis of the data collected up until the summer of 2007 will provide new and unique insights into the proton and the properties of the strong force in these areas as well.



View of the HERMES target chamber: innovations such as the gas target enable the HERMES team to separately determine the various contributions to the nucleon spin.

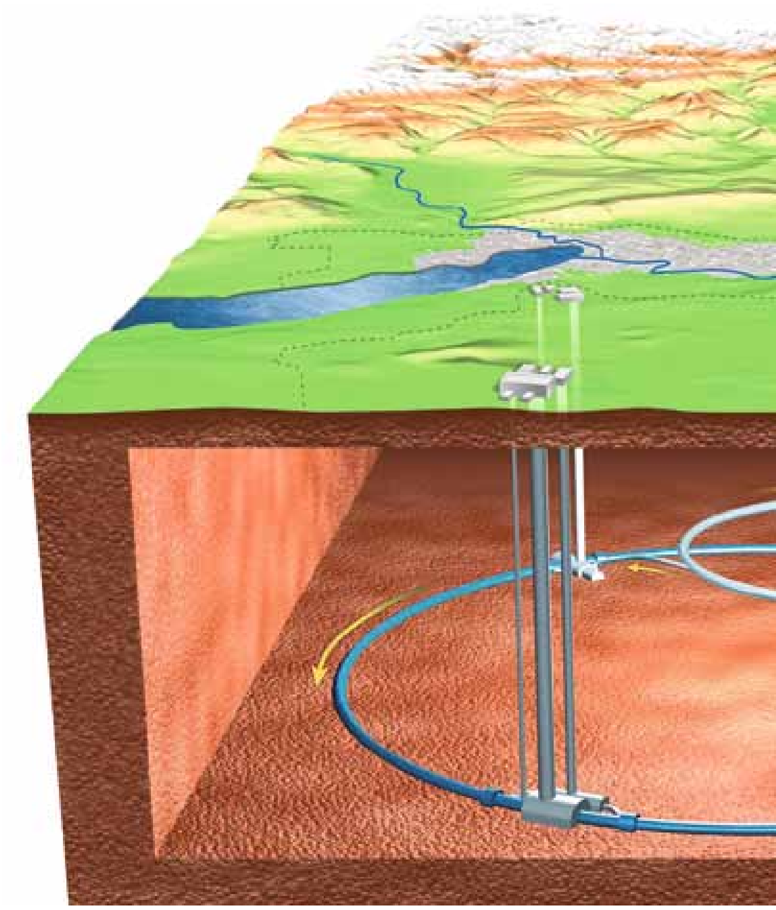
WORLD MACHINE.

LHC
The most powerful accelerator in the world

In 2008, the world's largest machine went into operation at the European research centre CERN near Geneva: the Large Hadron Collider LHC, a gigantic particle accelerator ring with a circumference of 26.7 kilometres. At a depth of up to 175 metres below Geneva's outskirts and the French Jura mountains, protons or heavy ions collide with one another head-on – at the highest energies ever attained in a particle accelerator. The LHC acts in effect like a time machine that enables physicists to look back billions of years into the past. Indeed, using the high-energy particle collisions in the LHC, they recreate the conditions that prevailed in the universe tiny fractions of a second after the big bang. The DESY physicists also participate in this exciting journey back to the origin of our cosmos.

From the Higgs particle to extra dimensions

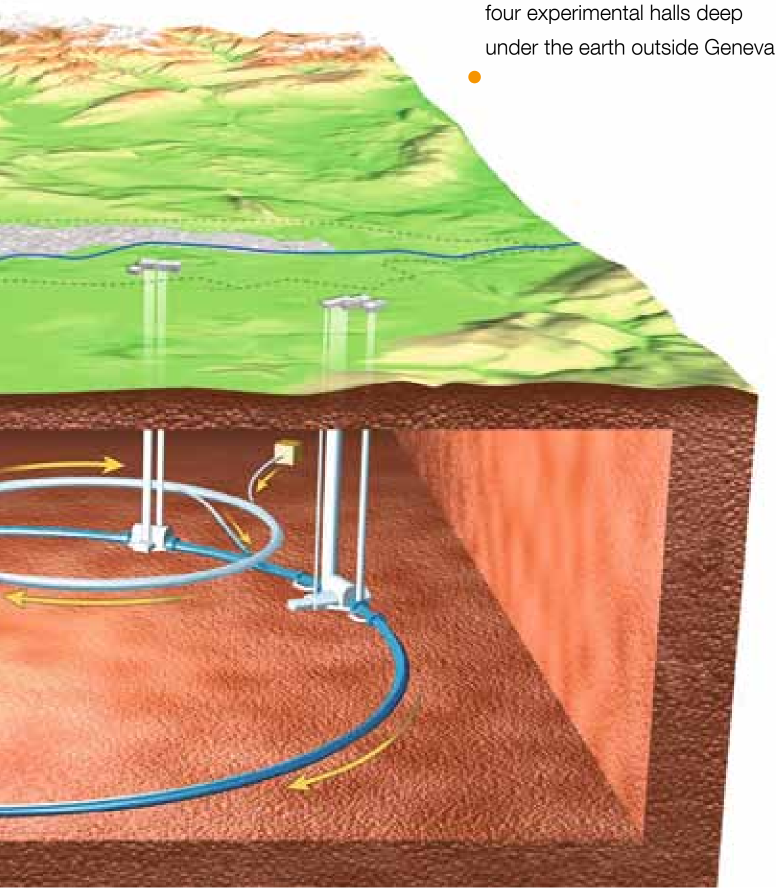
As the flagship of particle physics worldwide for the next 15 to 20 years, the LHC promises to revolutionize our view of the world – from the realm of the smallest particles to the far reaches of the universe. For decades, the Standard Model has rendered excellent service, enabling the physicists to describe the laws of nature with increasing detail. The Model contains many gaps, however; it raises questions that a comprehensive theory of the building blocks and forces in the universe should actually answer. How do the particles acquire their mass? Is there a Higgs boson? What exactly are the unknown dark matter and dark energy that make up 96 per cent of the universe? Why is there more matter than antimatter in the cosmos? What did the universe look like in the first second after the big bang? Are there more than three dimensions of space, as some theories postulate? To be able to answer these questions and pave the way towards a comprehensive Theory of Everything, physicists require new experimental data in the teraelectronvolt energy range – at substantially higher energies than could be achieved by particle accelerators to date. With the LHC, they will venture far into this uncharted territory in the hope of finally being able to answer a whole range of these questions.



A joint project of superlatives

The LHC is the most complicated piece of technology humanity ever built. The accelerator alone is a technological and logistic masterpiece. For a start, its superconducting magnets are cooled down to minus 271 degrees Celsius – about two degrees above absolute zero – by the world's largest refrigeration system. The billion proton-proton collisions that take place inside the LHC every second are recorded and analysed by four large detectors – ATLAS, CMS, ALICE and LHCb – installed in huge underground caverns located around the ring of the LHC. The detectors, too, are breathtaking in their complexity and size. More than 2000 scientists, technicians and engineers from over 37 countries are participating in each of the ATLAS and CMS experiments. ATLAS is the largest detector ever realized at a particle accelerator: it is 46 metres long, 25 metres wide, 25 metres high and weighs 7000 tonnes – in other words, it is half the size of Notre Dame Cathedral in Paris, France. The CMS detector is a little more compact, but weighs a staggering 12 500 tonnes.

ATLAS and CMS have been conceived as general-purpose detectors suitable for the widest possible range of physics investigations, while ALICE and LHCb – the two smaller experiments – utilize specialized detectors designed to study very specific issues. They too, are operated by large international teams of up to 1000 scientists from all around the world.



The LHC accelerator with the four experimental halls deep under the earth outside Geneva

Germany – a strong partner

German researchers also play a fundamental role in the research programme conducted at the LHC. Altogether, research groups from 31 German universities, two Max Planck Institutes and three Helmholtz Centres – including DESY – are participating in the LHC experiments. The Helmholtz Alliances "Physics at the Terascale", which was established under the auspices of DESY, and "Cosmic Matter in the Laboratory" are also dedicated to physics research using the LHC. The German share of the financing for the total CERN budget is 20 per cent, making Germany the largest single contributor. Numerous German companies have built parts of the LHC and the detectors.

LHC: Large Hadron Collider

Proton-proton storage ring at CERN in Geneva
Can also be operated with heavy ions
Research operation: beginning in 2009
Length: 26 659 m
Proton collision energy: 14 teraelectronvolts (TeV)
Lead ion collision energy: 1150 TeV
Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM

> ATLAS
Multipurpose detector for proton-proton collisions
46 m long, 25 m high, 25 m wide; 7000 tonnes
Participation: over 2500 scientists from 37 countries

> CMS
Multipurpose detector for proton-proton collisions
21 m long, 15 m high, 15 m wide; 12 500 tonnes
Participation: over 3600 scientists from 38 countries

> ALICE
Detector optimized for heavy ion collisions
26 m long, 16 m high, 16 m wide; 10 000 tonnes
Participation: over 1000 scientists from 31 countries

> LHCb
Detector for proton-proton collisions, specialized in the measurement of particles with bottom quarks
21 m long, 10 m high, 13 m wide; 5600 tonnes
Participation: 700 scientists from 15 countries

RECORD HOLDER.

Making way for the LHC

Particles in a ring

At 10:28 a.m. on 10 September 2008, the first packets of protons shot across the finish line: the first particle beam had completed its lap around the 27-kilometre-long LHC accelerator buried beneath the earth near Geneva. DESY physicists are also participating in the commissioning of the most powerful accelerator of all time. The LHC crew is benefiting from the expertise of the HERA machine group, which is drawing on its many years experience of operating a superconducting proton accelerator to support the CERN team.

The LHC accelerator ring comprises superconducting magnets that hold the electrons on their 27-kilometre-long circular course, and accelerator structures in which the particles are brought to high energies. Focused into beams, the particles fly in opposite directions in two separate, ultra-high-vacuum beam pipes. More than a thousand magnets of various types and sizes guide the particle beams around the circular path. A total of 1232 dipole magnets, each 15 metres long and weighing 30 tonnes, deflect the particles; 392 quadrupole magnets between five and seven metres long focus the beams. The coils of the electromagnets are wound from superconducting cable, which carries electrical current without any resistance and thus without energy loss. This requires that the magnets be cooled with liquid helium to approximately minus 271 degrees Celsius – that's colder than in outer space. The entire control system for the LHC and its pre-accelerators is located in the CERN control centre. It is from there that the particle beams are brought to collision at four points around the accelerator ring. Installed at these points are the large detectors with which the collisions are recorded and analysed.

CERN facts and figure

CERN (*Conseil Européen pour la Recherche Nucléaire*), the European Organization for Nuclear Research in Geneva, is the world's largest centre for fundamental research in the field of physics.

- Founded: 1954
- 20 member states; Germany is a founding member
- Total budget for 2007: approximately 650 million euros, with 20 per cent provided by Germany
- Guest scientists at CERN: more than 8000 from 85 nations
- Largest accelerator: Large Hadron Collider LHC. Nearly 1000 German scientists are conducting research at the LHC.

The LHC – a superlative particle accelerator

> The largest machine in the world...

The Large Hadron Collider LHC at CERN in Geneva is the most powerful particle accelerator in the world. It measures 26 659 metres in circumference. The accelerator contains a total of 9300 magnets. The cryogenic distribution system of the LHC would qualify as the world's largest fridge. All the magnets are pre-cooled to minus 193.2 degrees Celsius (80 K) using 10 080 tonnes of liquid nitrogen, before they are filled with nearly 60 tonnes of liquid helium to bring them down to minus 271.3 degrees Celsius (1.9 K).

> The fastest racetrack on the planet...

At full power, trillions of protons will race around the LHC accelerator ring 11 245 times a second, travelling at 99.99 per cent the speed of light. Two beams of protons will each travel at a maximum energy of 7 teraelectronvolts (TeV), corresponding to head-to-head collisions of 14 TeV. Altogether up to one billion collisions will take place every second.

> The emptiest space in the Solar System...

To avoid collisions with gas molecules inside the LHC accelerator, the beams of particles travel in both beam pipes in an ultra-high vacuum – the pipes are thus as empty as interplanetary space. The internal pressure of the LHC is 10^{-13} atm, ten times less than the pressure on the Moon.

> The hottest spots in the galaxy, but even colder than outer space…

The LHC is a machine of extreme hot and cold. When two beams of protons collide, they will generate temperatures more than 1 000 000 000 times hotter than the heart of the Sun, concentrated within a minuscule space. By contrast, the surrounding magnets are even colder than outer space.

> The biggest and most sophisticated detectors ever built…

To detect and record the up to one billion proton collisions per second, physicists and engineers have built massive machines, whose advanced electronic systems measure the flight paths of the particles with a precision of just a few thousandths of a millimetre. Because the particle densities that occur during the collisions in the LHC are far greater than anything ever achieved before, the detectors must be designed for very high resolution. The number of output channels through which the information from the detectors is transferred to the outside world also exceeds that of existing systems many times over.

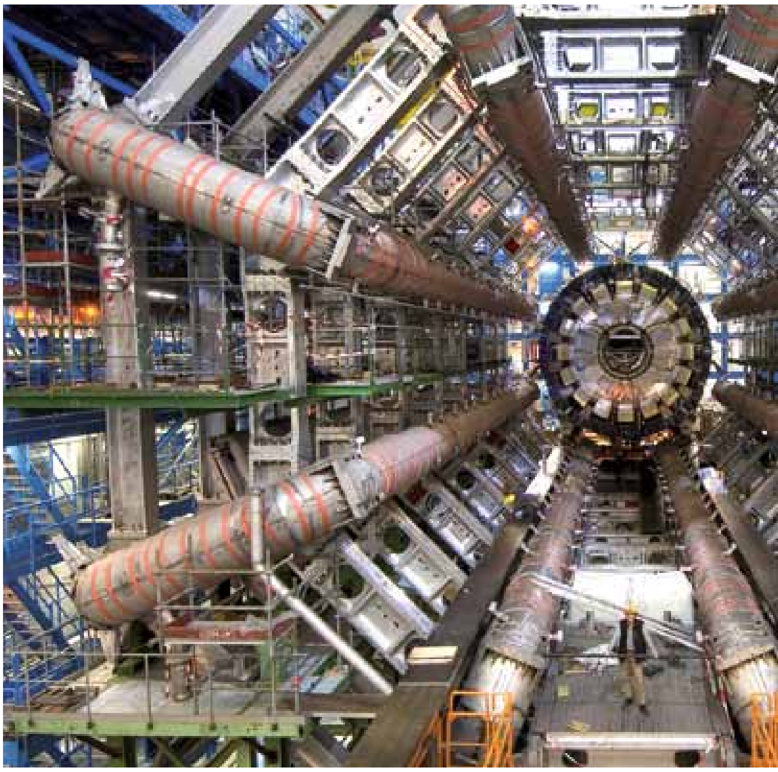
> The most powerful supercomputer system in the world…

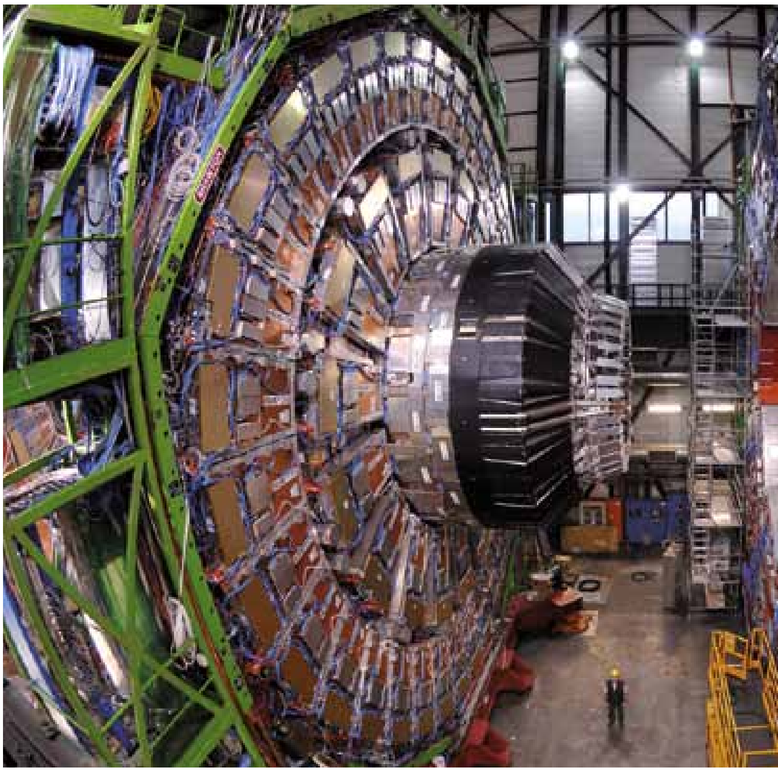
The data recorded by each of the big experiments at the LHC will fill several hundred thousand DVDs every year. To allow the thousands of scientists scattered around the globe to collaborate on the analysis over the coming years, tens of thousands of computers located around the world are being harnessed in a distributed computing network called the grid. Although the grid was developed for the LHC, it can also be used in other scientific fields in which large amounts of data must be processed.

Start-up of the LHC on 10 September 2008

ATLAS AND CMS.

The general-purpose detectors





Two giants for research

The DESY physicists are mainly participating in the two largest LHC experiments, ATLAS and CMS. These have been conceived as general-purpose detectors designed to investigate the largest range of physics possible. The researchers hope that ATLAS and CMS can provide answers to some of the key open questions regarding our understanding of the world (see pp. 8 and 48): Is the Higgs mechanism responsible for particles having mass? Is there a supersymmetric partner particle for each particle of the Standard Model? Is the dark matter in the universe made up of such superpartners? Could our universe exist in more than three dimensions of space?

ATLAS and CMS pursue the same physics goals – they are searching for the Higgs particle, supersymmetric particles and extra dimensions of the universe. They do this by measuring the paths, energies and identities of the particles produced during the collisions in the LHC. However, the two experiments have adopted radically different technical solutions and designs, in particular with respect to the structure of their magnet systems. ATLAS and CMS are thus independent of one another and can crosscheck each other's results – a vital aspect for the confirmation of any discoveries made.

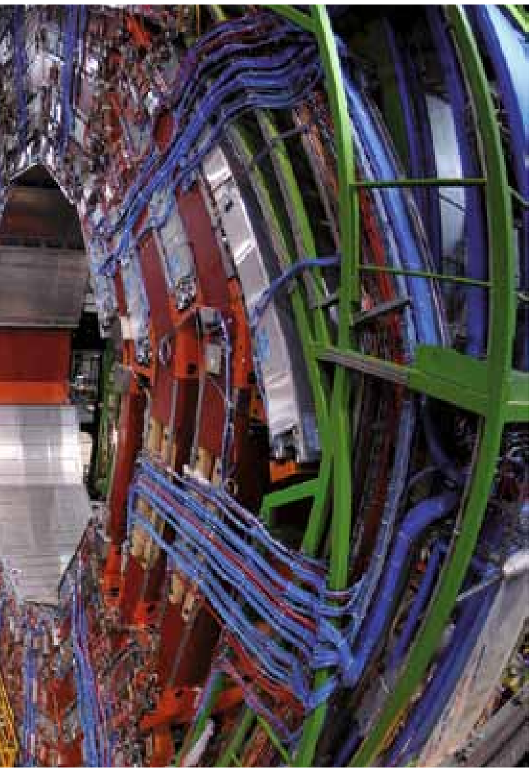
ATLAS – A Toroidal LHC ApparatuS

Measuring an impressive 46 metres in length and 25 metres in width and height, ATLAS is the largest detector ever installed at a particle accelerator. It comprises three sections. The inner tracker is used to measure the tracks of particles. In the middle are calorimeters for determining the energy of the particles. Located on the outside are the muon chambers. These are used to detect muons, the heavyweight relatives of the electrons. The defining feature of the ATLAS detector is its enormous magnet system comprising eight 25-metre-long superconducting magnet coils arranged to form a cylinder around the beam pipe through the centre of the detector. Within this cylindrical space, a homogeneous magnetic field is generated, in which the particles created in the collisions are deflected. ATLAS is the largest of the four LHC detectors, but only weighs half as much as CMS.

CMS – Compact Muon Solenoid

As the name suggests, the CMS detector is more compact and thus much smaller than ATLAS. Inside is a large solenoid magnet, whose cylindrical coil of superconducting cable encloses the central components of the detector. The particles flying out from the point of collision first encounter a silicon track detector and then the calorimeters, in which the energy of the particles is measured. The enormous weight of the detector – 12 500 tonnes – is due primarily to the massive steel yoke of the magnet. It comprises three rings,

The LHC detector ATLAS during construction



The LHC detector CMS during construction

whose interstitial spaces house gas-filled muon chambers. Detecting these particles is a focal point of the experiment. Unlike the other LHC detectors, CMS was not built directly at its subterranean location, but rather on the surface. The detector, which comprises 11 individual “slices”, was then lowered into the underground hall for final assembly.

DESY participation in the LHC

DESY groups from Hamburg and Zeuthen have been participating in the LHC and the ATLAS and CMS experiments, in particular, since 2006. They have made substantial contributions not only to the detectors, but also to the computer infrastructure for the analysis of the data and to the commissioning of the LHC accelerator itself. One example of an important DESY contribution is the establishment of a computing centre for ATLAS, CMS and most recently LHCb as part of the LHC Computing Grid, the global computer network for the evaluation of the LHC data (see p. 28). DESY operates a Tier-2 centre, whose large computing and storage capacity is available to scientists the world over for the analysis of the LHC data. Closely linked to the Tier-2 centre is also the National Analysis Facility at DESY, a computing complex that provides computer resources for physics analysis – in particular of ATLAS, CMS and LHCb data – to all German research groups working on LHC and ILC as part of the Helmholtz Alliance “Physics at the Terascale”.

The DESY researchers are also involved in various aspects of the ATLAS and CMS experiments. Some of them staff important, executive-level management functions in the large international teams of more than 2000 scientists, technicians and engineers operating the detectors. The DESY groups are working on the development, installation and operation of detector components, such as a luminosity monitor for ATLAS to measure the collision rate or a calorimeter for CMS, with which forward-flying particles can be detected. In addition to helping with the set-up of the grid computing for the analysis of the LHC data, the DESY researchers are also involved in the development of the software tools for the data acquisition and for the simulation, reconstruction and analysis of the collisions. Another focal point are studies of the physics at the LHC. Several members of the HERA machine group are also supporting the LHC team with the commissioning of the accelerator.

Furthermore, control centres are being built at DESY so that the operation and data taking of ATLAS and CMS can be monitored remotely. First up was the CMS Centre DESY, which went into operation in October 2008. Whereas the LHC experiments are run from local control rooms near the detectors for reasons of safety, the data acquisition can also be checked remotely. The proper functioning of the complex detectors can thus be monitored from CERN, from Fermilab in Chicago and now also from DESY. The researchers in Geneva, Chicago and Hamburg are in constant contact via a special audio and video link. Thanks to these control centres at DESY, the German scientists participating in ATLAS and CMS can take shifts for checking the data taking without having to travel to Geneva.

ALICE AND LHCb.

Big bang and antimatter

ALICE – A Large Ion Collider Experiment

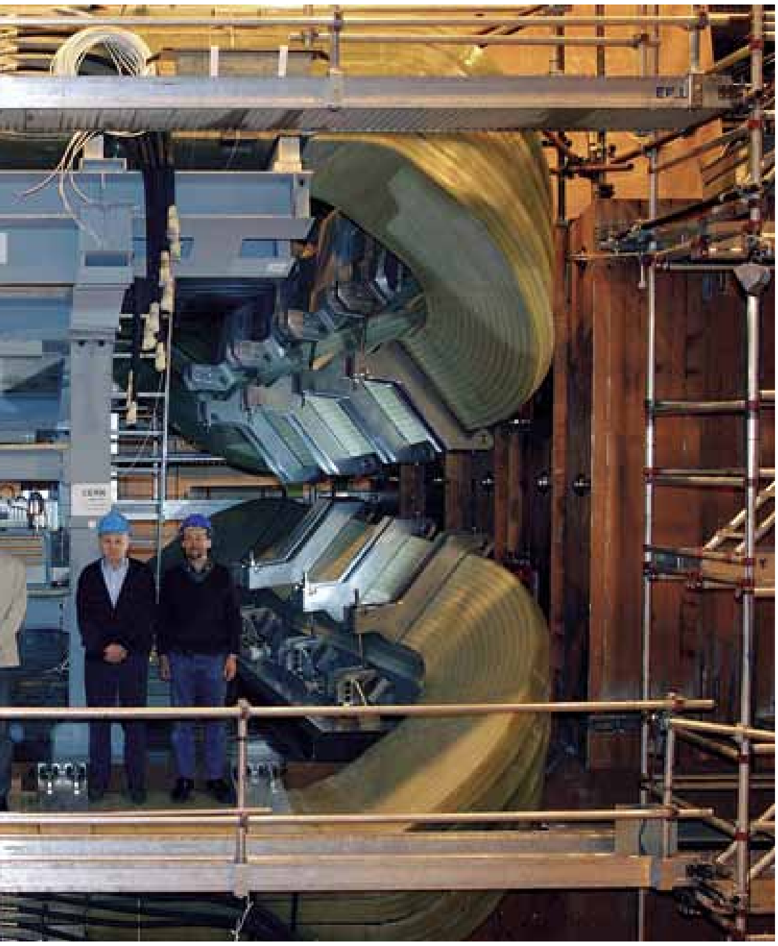
The physicists hope to use the ALICE experiment to study the state of matter immediately following the big bang. In this case the LHC accelerator will not be operated as usual with protons, but rather with lead ions that are more than 200 times heavier than the protons. These collisions between lead nuclei in the LHC generate temperatures more than 100 000 times hotter than those at the heart of the sun.

According to prevailing particle theory, the quarks and gluons that make up protons and neutrons, for example, should be able to move freely at such high temperatures and densities, whereas at lower temperatures they are “confined” in complex particles like protons and neutrons and cannot break free from one another. When lead nuclei collide in the LHC, their quarks and gluons are released, producing a state of matter that must have existed for a few millionths of a second after the big bang when the universe was still extremely hot: a quark-gluon plasma. The resulting quark-gluon cloud immediately expands, cooling within a fraction of a second to the temperature at which the quarks and gluons again join to form conventional particles of matter.

The ALICE detector will enable scientists to investigate how this quark-gluon plasma expands and cools, and thus observe how the particles that now make up the universe are formed. They hope to find answers to two fundamentally important and as yet unanswered questions about the strong force: Why are quarks and gluons always confined in composite particles and have never been observed individually (see p. 51)? And what is the origin of the mass of protons and neutrons? What is known for a fact is that protons and neutrons are composed of three quarks. Added together, however, the masses of these three quarks account for only one per cent of the mass of the proton or neutron. Where the remaining 99 per cent comes from is currently unknown. Could the mechanism that confines the quarks and gluons in the proton also be responsible for generating the majority of the mass of conventional matter? The ALICE experiment will help to answer these central questions.

The ALICE detector at the LHC during construction

The LHCb detector during construction



LHCb – Large Hadron Collider beauty

The researchers hope to use the LHCb experiment to determine why matter predominates over antimatter in the universe. The big bang should have produced equal amounts of matter and antimatter. Because matter and antimatter are mutually destructive when they interact, they should have completed annihilated one another, but this is obviously not the case. There must therefore be small differences in how matter and antimatter behave that explain why a portion of the matter – the portion of which we are composed – was left over. The physicists taking part in the LHCb experiment are investing these small differences between matter and antimatter using B hadrons, which are particles that contain b quarks (the “b” can stand for either “beauty” or “bottom” depending on your preference).

Like ATLAS and CMS, LHCb also searches for new particles that are heavier than the particles known to date. Whereas ATLAS and CMS are looking for particles created directly in the collisions, LHCb uses a different method. New particles can also be produced indirectly as virtual particles that only exist for an extremely brief time within the context of quantum mechanical energy uncertainty. Although these particles are so short-lived, they have an influence on other, observable processes. For example, such particles could cause the decay rates of B hadrons and their antiparticles to differ. The physicists are using the LHCb detector to search for such differences.

The advantage of the indirect search for new particles is that given the same centre-of-mass energies and same collision rate, such an approach can reveal the contributions of particles whose mass is many times greater than those detected in direct searches. This presupposes, however, that the decay processes – in this case of B hadrons – are theoretically predicted and measured with very high precision. Only if the decay rates predicted by the Standard Model are precisely known can the scientists interpret small deviations in the measurements as indications of new phenomena. Whether supersymmetry or extra dimensions – the researchers at LHCb expect that the new particles will make their presence known in the form of deviations from the Standard Model in the precision measurements of B hadrons. The indirect search for new particles with LHCb thus supplements the direct search with the general-purpose detectors ATLAS and CMS.

NETWORK.

The challenge of computer technology

Worldwide computer network

Each year, the LHC detectors will generate data amounting to around 15 petabytes (15 million gigabytes) – enough to fill hundreds of thousands of DVDs a year. Thousands of scientists around the world will analyse this flood of data – an enormous challenge with respect to data storage and computing power. To meet these needs, the LHC designers have turned to the concept of grid computing, in which computers distributed around the globe are linked together in such a way that they can be used as a powerful supercomputer by users from all over the world. The data from the experiments will thus no longer be stored and processed in just one place, but distributed to a series of computing centres with sufficient storage capacity, from where they will be transferred to other facilities and ultimately to the participating scientists.

Computing centres around the globe are cooperating with CERN to establish this gigantic computer network called the LHC Computing Grid (LCG). The grid comprises various levels, called tiers. The raw data generated by the LHC are first backed up on tape at CERN in Geneva, the Tier-0 centre. Following initial processing, these data are then distributed to 11 international Tier-1 centres for storage and reconstruction. These centres have the requisite storage capacity for large data volumes and are constantly connected to one another via the grid. One of these Tier-1 centres is the Grid Computing Centre Karlsruhe (GridKa) of the Research Centre Karlsruhe, which constitutes one of the primary central European nodes of the LCG.

The Tier-1 centres in turn make the data available to the Tier-2 facilities further down in the grid hierarchy. These facilities, which comprise either a single computing centre or an interconnected number of them, constitute the decisive level for the scientific analysis of the data using grid tools. DESY operates such a Tier-2 centre distributed across its

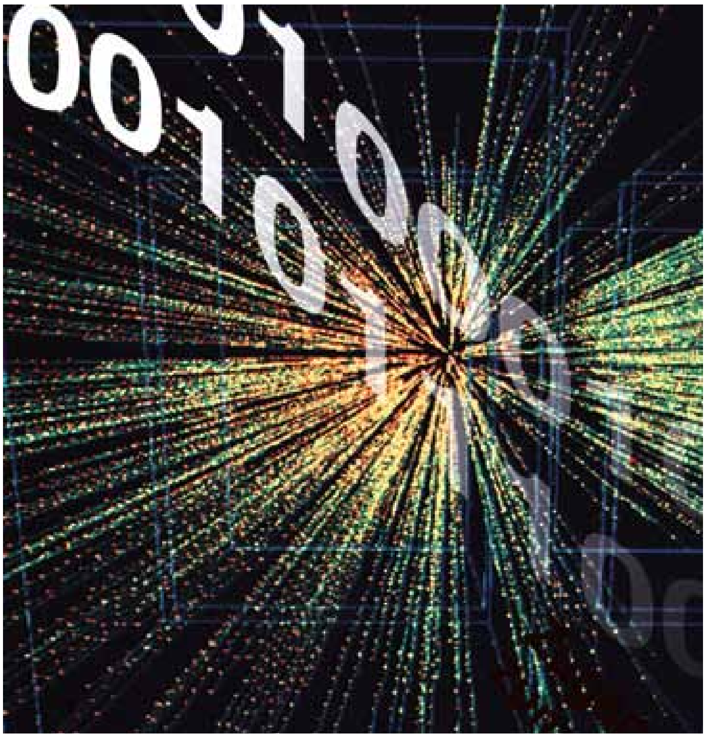
The CERN computer centre in March 2008

Hamburg and Zeuthen sites, providing large computing and storage systems for the LHC experiments ATLAS, CMS and LHCb. It is one of the largest of the more than 140 centres distributed around the globe and is used via the grid by research groups all over the world. The scientists access the LCG computing network via local computing centres at their institutions (Tier-3) or from the computers at their desks (Tier-4). This enables scientists all over the world to evaluate and analyse the stored data using the computing power of the LCG.

Analysis centre at DESY

To promote the exchange of information and collaboration within the field of particle physics in Germany is the stated goal of the new analysis centre of the Helmholtz Alliance “Physics at the Terascale” at DESY. The centre is intended to support particle physicists at German universities with the analysis of data from the LHC experiments and with preparations for the planned International Linear Collider ILC. The training of the physicists of tomorrow plays a major role here: the analysis centre supports the members of the Alliance with special training courses aimed at making and keeping their young staff competitive in the international research community. In addition to continuing education at such technical schools, young scientists and experienced physicists alike can spend a portion of their research time at the analysis centre to deepen their knowledge in certain fields.

Embedded in the attractive scientific environment at DESY with its outstanding infrastructure and high density of experts in the fields of experimental physics and theory, the analysis centre offers an optimal service enabling the members of the Alliance to broaden their scientific expertise. The infrastructure also includes the National Analysis Facility, a computing complex that is closely linked to the Tier-2 centre of the LHC Computing Grid at DESY. The National Analysis Facility makes computer resources for physics analysis available to all Alliance members. The analysis centre at DESY joins grid computing and detector and accelerator development as one of the central pillars of the Helmholtz Alliance “Physics at the Terascale”.



Technology transfer

There are many areas of life that rely on fundamental research. Medicine, communications, environmental technology and the entertainment industry – all benefit from the highly sophisticated accelerators, detectors and methods of particle physics.

Scientists involved in basic research are concerned with gaining new insights – applications are secondary. Yet the equipment and techniques they need for their experiments are often so complex that the researchers have to develop them themselves. Many of these technologies and processes that have been newly developed for basic research find their way into everyday life. For example, many medical investigative procedures and therapies would never have been possible without developments in particle physics. Companies too often contribute to developments in the field of particle physics and are then able to transfer this new technology into other areas and thus open up new fields of business. Although the LHC was constructed purely as a project for basic research, it can already boast a number of products that have found their way from the laboratory to everyday life.

Physicists are also in great demand on the job market. That’s because they can think in a focused and analytical way and solve complicated problems creatively and efficiently. Many of them speak more than one language and are at home in international situations – abilities they have acquired during their studies and while working as members of international research teams. CERN as well as other research institutes and universities in Germany and around the world train thousands of young people every year, who then go on to benefit the world of business with the knowledge and skills they have gained from working in research.

UNCHARTED TERRITORY.

ILC
The project for the future of particle physics

Whereas the proton accelerator LHC will fling open the door to the terascale for the first time and offer exciting initial insights into this uncharted territory, physicists will only be able to solve the big mysteries of the universe in combination with a second, precision machine – a linear accelerator in which electrons and their antiparticles, positrons, collide at the highest energies. DESY is playing a major role in the development of one such linear accelerator, the International Linear Collider ILC. The ILC will complement the discoveries of the LHC and reveal the features of the terascale in exquisite detail.

Mysterious universe

In the past century, physicists have explored the fundamental components of the universe, trying to explain the origin of mass and probing the theory of extra dimensions. And in recent years, experiments and observations have pointed to evidence that we can only account for a surprising four per cent of the universe. Scientists believe that the remaining 96 per cent consists of mysterious dark matter and dark energy, revealing a universe far stranger and more diverse than they ever suspected. The global particle physics community is in agreement that an electron-positron accelerator – such as the proposed International Linear Collider ILC – will produce the breakthrough to an understanding of how the universe arose and acquired its current form.

In contrast to proton accelerators such as the LHC in Geneva, in which composite particles collide with one another, the collisions at the ILC will be between point-like electrons and their antiparticles, positrons, which are also point-like. They annihilate each other and become pure energy, from which new particles can be created. Since the initial conditions of the particle production are precisely known and no “fragments” of the colliding particles remain, the results are much easier to interpret than the results from the LHC. The ILC is thus a precision machine that brings within reach discoveries which could stretch our imagination with new forms of matter, new forces of nature, new dimensions of space and time and bring into focus Albert Einstein’s vision of a grand unified theory.

Make visions become reality

Thanks to its high energies and unprecedented precision, the ILC will give physicists a new cosmic doorway to explore energy regimes beyond the reach of today’s facilities. The proposed electron-positron collider will ideally complement the proton-proton collider LHC. Together they could unlock some of the deepest mysteries of the universe. With the LHC’s discoveries pointing the way, the ILC would provide the missing pieces of the puzzle.

Consisting of two linear accelerators that face each other, the ILC will hurl some ten billion electrons and their antiparticles, positrons, toward each other at nearly the speed of light. Superconducting accelerator cavities operating at temperatures close to absolute zero give the particles more and more energy until they smash together at the centre of the 35-kilometre machine. The particle beams collide 14 000 times every second at record electron energies of 500 billion electronvolts (500 GeV). These collisions create an array of new particles that could help us to answer some of the most fundamental questions of our century. The current baseline design allows for an upgrade of the International Linear

Superconducting cavity resonators will be used to accelerate particles in the ILC.

ILC: International Linear Collider

- Electron-positron linear accelerator
- At planning stage
- Location still to be decided
- Length: approx. 35 km
- Electron-positron collision energy: 500 to 1000 gigaelectronvolts (GeV)
- Two moveable experiments at one collision zone
- Participation: 2000 scientists from more than 24 countries

Collider to a 50-kilometre, one-trillion-electronvolt (1 TeV) machine during the second stage of the project.

Pioneering technology

The International Linear Collider ILC is to be constructed and operated as a global project. Worldwide, there were several proposals for such an accelerator of the future, which differed in their choice of accelerator technology. After an intense assessment, the committee that represents particle physicists from around the world decided that the planned linear collider will be realized using superconducting accelerator technology. This technology has been developed jointly by DESY and its international partners – the TESLA Technology Collaboration – and successfully tested at the TESLA test facility in Hamburg. The same superconducting technology is also employed for the European XFEL X-ray laser facility, which is currently under construction in Hamburg – an outstanding example of the successful synergies provided by the multiple use of a completely new technology.

SUPERCONDUCTIVITY.

Powering the accelerators of the future

Pioneering research for the ILC

DESY is a major partner in the project to develop the accelerator technology for the proposed ILC. Back in 2004, when the relevant committee announced which technology was to be used for the 35-kilometre-long facility, the decision fell in favour of the superconducting radio frequency technology that had been developed and tested, under the leadership of DESY, for the TESLA project. This technology is already being used in a similar form for the 300-metre-long free-electron laser FLASH, which has been in operation at DESY since 2005, and for the European XFEL, a 3.4-kilometre-long X-ray laser currently being built as a European project in Hamburg. In other words, DESY remains excellently qualified to continue in its role as a leader in the development of superconducting accelerator technology.

DESY researchers in Hamburg and Zeuthen are also involved in the development of many other important elements of the ILC accelerator – mainly as part of international projects, including the TESLA Technology Collaboration and EU projects such as EUROTeV and ILC-HiGrade, which are being coordinated by DESY. Such work includes development of damping rings and polarized positron sources; studies on beam diagnostics, beam dynamics, beam stabilization and luminosity optimization; measurement of ground motion and establishing a global accelerator network to allow remote monitoring and control of the accelerator.

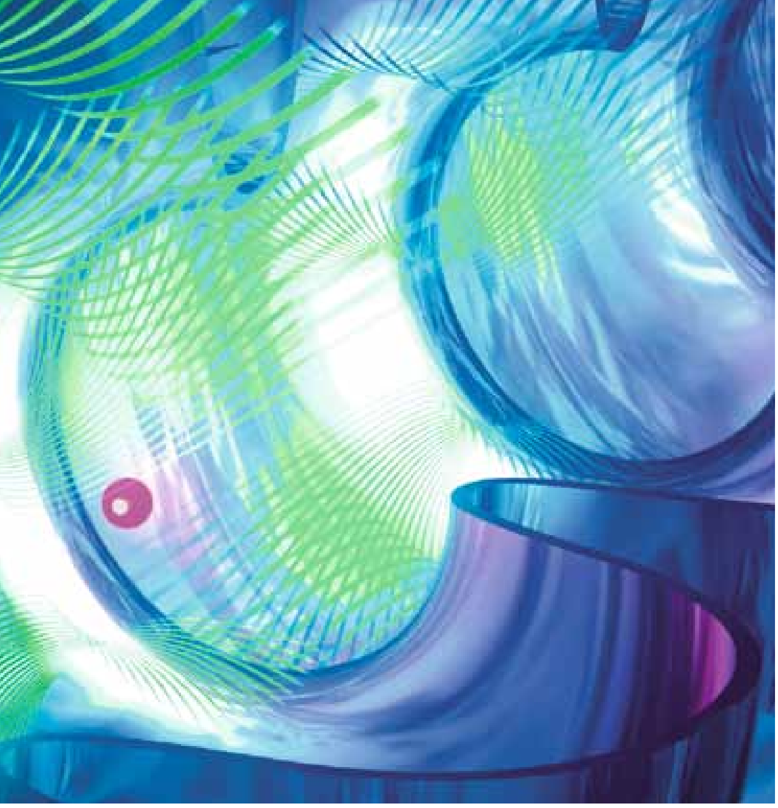
Experience with operating FLASH and the construction and subsequent operation of the European XFEL also give DESY crucial insights, for example into the challenges involved in developing highly sophisticated accelerator components to technological maturity in cooperation with partners in industry, and in being able to mass produce such parts in line with required quality standards. The ILC project will also benefit from the experience DESY will gain during tunnel construction for the European XFEL and installation of equipment inside. At DESY, in Hamburg and Zeuthen, there are currently over 200 people working on FLASH, the European XFEL and preparations for the ILC. Many of them are involved in all three projects, generating important synergy effects that set DESY apart from other research centres participating in the ILC project.

Niobium resonators for highest field strengths

The electrons and positrons in the ILC will be accelerated by means of electromagnetic fields that oscillate within special nine-cell accelerator structures made of the metal niobium. These “cavity resonators” are superconductive – i.e. when cooled to an operating temperature of minus 271 degrees Celsius with liquid helium, they lose all electrical resistance. This means they conduct electricity with almost no loss whatsoever, thus providing an extremely efficient and energy-conserving means of acceleration. As a result, practically the total electrical power is transmitted to the particles.

One of the resonators’ main performance criteria is the strength of their accelerating field, the gradient. Thanks to intensive development work, particularly at DESY, this value has increased substantially during the last two decades. Whereas the superconducting cavities installed in the accelerators in operation in 1992 were capable of gradients of between five and eight megavolts per metre (MV/m) at most, the nine-cell resonators intended for use in the ILC are now delivering gradients of up to 40 MV/m in individual tests and around 30 MV/m when operating as groups of eight within accelerator modules. The aim is to be able to accelerate the particles in the ILC with gradients as high as 35 MV/m. Just how the gradient can be increased to this level in a reliably reproducible way is being intensively studied also at DESY.

The processes for manufacturing and treating the surface of the niobium cavities play a vital role here. Together with international partners, DESY researchers are currently investigating the use of electropolishing to achieve a mirror finish on the inner surfaces of the cavities. This helps to eliminate any unevenness that could lead to a breakdown of



Computer simulation of particle acceleration in the superconducting cavities

superconductivity. Another idea is to produce the cavities from large-grain niobium crystals, or even from single-crystal niobium rather than polycrystalline niobium, as is currently the case. Both feature a much more evenly structured crystal lattice that provides considerably fewer places for contaminants to gather and thereby diminish the cavities' performance.

Accelerator modules on the test bench

As in FLASH and the European XFEL, the ILC is likely to feature eight cavities per accelerator module. In addition to the cryogenic systems needed to cool the cavities to the requisite temperature of minus 271 degrees Celsius, these modules also contain a host of other important high-tech components that must deliver the highest performance while being perfectly matched to one another. A new cryomodule test bench at DESY now makes it possible to test and optimize the entire 12-metre-long accelerator modules for FLASH, the European XFEL and the ILC without having to install them in the actual FLASH facility and thus expend valuable FLASH user time for module testing.

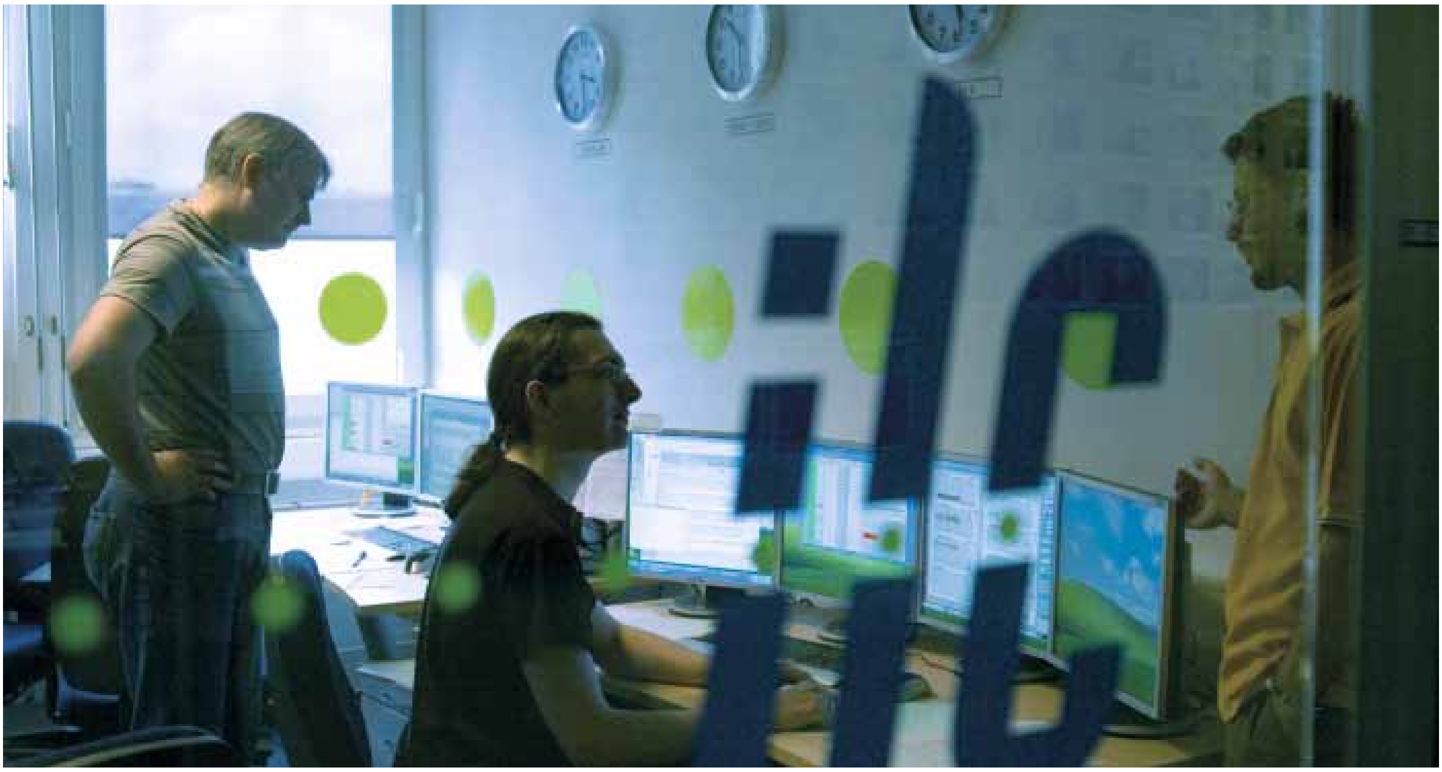
In one test procedure, for example, one of the modules was cooled to minus 271 degrees Celsius and then warmed back to room temperature ten times in succession in order to examine the behaviour of its inner components under such extreme conditions. Even minimal movement of the accelerator components as a result of temperature changes can impair the particle beam's quality. As little as a fraction of a millimetre can be enough. In addition, a series of crash tests was carried out in order to simulate a variety of worst-case scenarios, particularly vacuum leaks, under controlled conditions. The aim here was to ensure that the modules meet European regulations on pressure vessels and that, should the worst happen, any problems will remain confined to the inside of the module.

To prepare for series production of the accelerator modules for the European XFEL and later for the ILC, DESY is now ensuring that the extensive module construction know-how it has accumulated in recent decades is shared out among project partners. Given that 100 modules are needed for the European XFEL, and almost 2000 for the ILC, teams from around the world are already working hard to acquire the knowledge and skills needed to assemble these sophisticated pieces of equipment, each of which consists of 1200 individual parts that must be put together with the utmost precision and under stringent conditions of cleanliness. Numerous researchers and industry representatives have already travelled to DESY to observe the assembly process. With the help of the highly detailed construction manual produced by DESY, scientists at Fermilab in the USA have already successfully assembled a module. The experience that DESY, other research establishments worldwide and industry will gain from the launch of series production for the accelerator modules for the European XFEL will also be of great benefit for the ILC project.

Inspection of a superconducting niobium cavity at DESY

REMOTE OPERATION.

Control room to the world



Discussion in the newly opened ILC control room at DESY

Enabling global access

Even today the ILC is already a product of unique global cooperation, with about 2000 people from more than 25 nations currently taking part in the development work. Hundreds of physicists, technicians and engineers are involved in test experiments, and individual components for the various pieces of the facility are being produced across the globe. At the end of the day, however, the 35-kilometre-long accelerator will be built in only one country, whichever that may happen to be. This raises complex questions. How can everyone be involved on an equal basis, so that project partners will not feel excluded from operation of the facility? And what is the best way to ensure that a malfunctioning component is repaired as quickly as possible when all the experts responsible happen to be at a conference on the other side of the world?

One solution to these problems is the establishment of a Global Accelerator Network (GAN), a worldwide complex of control rooms located in various countries that will enable remote monitoring and operation of the accelerator and the experiments. The idea is that GAN members will be able to access and control the huge accelerator and its detectors from any authorized computer, and provide direct support to colleagues at the facility in the event of a problem. This would also spell an end to the exhausting night shifts that are common practice in the world of particle physics, since the responsibilities could be shared out in such a way that control rooms in America, Asia and Europe would be on duty only during daytime hours. Assuming an overlap of one hour for the handover from one region to next, each shift would only last nine hours, and that during the normal working day – the kind of conditions most particle physicists can only dream of at present.

Pilot tests with ELETTRA

Back in 2005, the GAN working group of the EU project EUROTeV demonstrated the feasibility of remote control for an accelerator facility. Using various software tools, scientists at DESY succeeding in injecting an electron beam into the ELETTRA accelerator ring in Trieste, Italy, more than 1000 kilometres away. With the help of simple webcams, “remote desktops” and two-way audio links, they were able to safely store the beam under the watchful eyes of staff present in the Trieste control room. All the data communications involved were transmitted via secure links.

As a user survey conducted by EUROTeV shows, the standards required of such a remote-control system are very high indeed. Ideally, users should be no longer even aware of their remoteness from the facility. However, achieving such transparency and seamless control requires the use of radically simplified user interfaces, as they now start to become available.

A direct link to Fermilab

The newly opened ILC control room at DESY uses such a simplified principle. Equipped with two computer workstations, images from three webcams, and three clocks displaying the times in Hamburg, Chicago and Tokyo, scientists at DESY can now monitor equipment at CERN in Geneva or Fermilab in Chicago from the comfort of their own control room. Since May 2008 the international CALICE group, which is developing calorimeter prototypes for one of the ILC detectors, has been using the set-up to monitor and control its test-beam experiment at Fermilab in Chicago and to analyse the data thus recorded. Thanks to a permanent video link, which provides a window onto the lab in Chicago, scientists from Fermilab and DESY can now work together just as if they were in the same room.

This also means they can join forces to resolve technical issues. Using the webcams, scientists in Hamburg can zoom in close to the experiment and examine it in detail to provide fellow researchers at Fermilab with helpful tips concerning the cause of the problem, whether a broken cable or a wrongly activated switch. In fact, scientists at DESY do not even need to be in the control room. This is because the new system provides each member of the CALICE group with access to the experiment at any time and from any location, including inspection of its current status via a web-based electronic logbook. The only requirement is a computer with Internet access.

New forms of cooperation

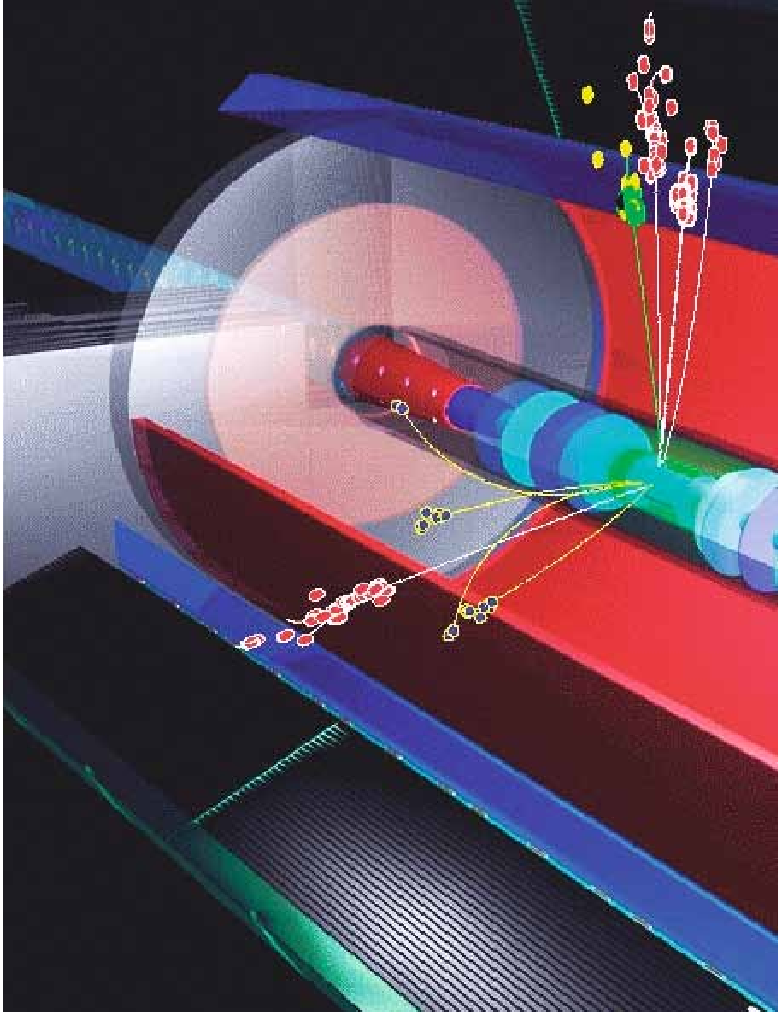
The fact that the complete system is web-based represents a major innovation compared to former control systems, which required special technical equipment. As a result, they were expensive and complicated to install, and could be used only for limited tasks. As a globally active team, however, the CALICE group required an easy means of linking its 220 members around the world. The result is a simple-to-install and inexpensive system that enables each team member to control the experiment at any time and provide help, if required, or take direct action in the event of a problem.

As might be expected, this type of cooperation demands a certain familiarization. Not everyone feels truly comfortable with the idea of being under constant observation by people right around the world. For similar reasons, cooperation via videoconference works best when the people involved have already met in person beforehand. At the same time, it is important to think carefully about which control options are to be made generally available and which are to be restricted to the control room.

For members of the CALICE group, life would be very much the poorer without their new control system. Since its launch, it has rapidly advanced to become the most-used auxiliary tool within the group and has given rise to a whole new dimension of collaboration. Other groups and projects are also set to use the ILC control room at DESY in the future, and there are plans to install a similar system for monitoring purposes and control of the European XFEL X-ray laser facility in Hamburg. Such new web-based control systems promise to revolutionize the nature of virtual cooperation in a whole variety of areas – as did the World Wide Web, which was originally devised at CERN in order to facilitate the exchange of data between particle physicists working around the world. A few years down the road, it is quite possible that such systems will be just as much a part of our everyday lives as the Web is now.

DETECTORS.

High-precision detectors for the ILC



Computer simulation of a particle collision in a future ILC detector

Detector technology of the future

Regardless of the power and precision of an accelerator, without the right kind of detectors to track and record the particle collisions in detail, it is little more than a useless piece of high-tech. The electron-positron collisions at the ILC will enable extremely precise measurements at the terascale – unexplored territory for particle physics. To ensure that the scientific potential of the ILC is fully exploited, the two detectors to be installed at the facility must be sensitive enough to do justice to this extreme precision in all its aspects.

For a number of years now, research and development work has been in progress around the world in order to produce viable proposals for the ILC detectors. Here too DESY is playing a major role and currently coordinates, for example, the EU project EUDET, which involves 31 European institutes from 12 countries and 24 associated institutes from around the world. The principal purpose of EUDET is to make important research infrastructure available that would otherwise be too expensive for individual labs. This includes a precision instrument for checking the measuring accuracy of prototype detectors as well as readout electronics and a range of universal software. DESY groups in Hamburg and Zeuthen are also conducting research and development work with partners from abroad for various detector components – including a vertex detector, time projection chamber, forward calorimeter, hadronic calorimeter and polarimeter – as well as developing the software required for the complex simulation and reconstruction methods of the forthcoming ILC detectors.

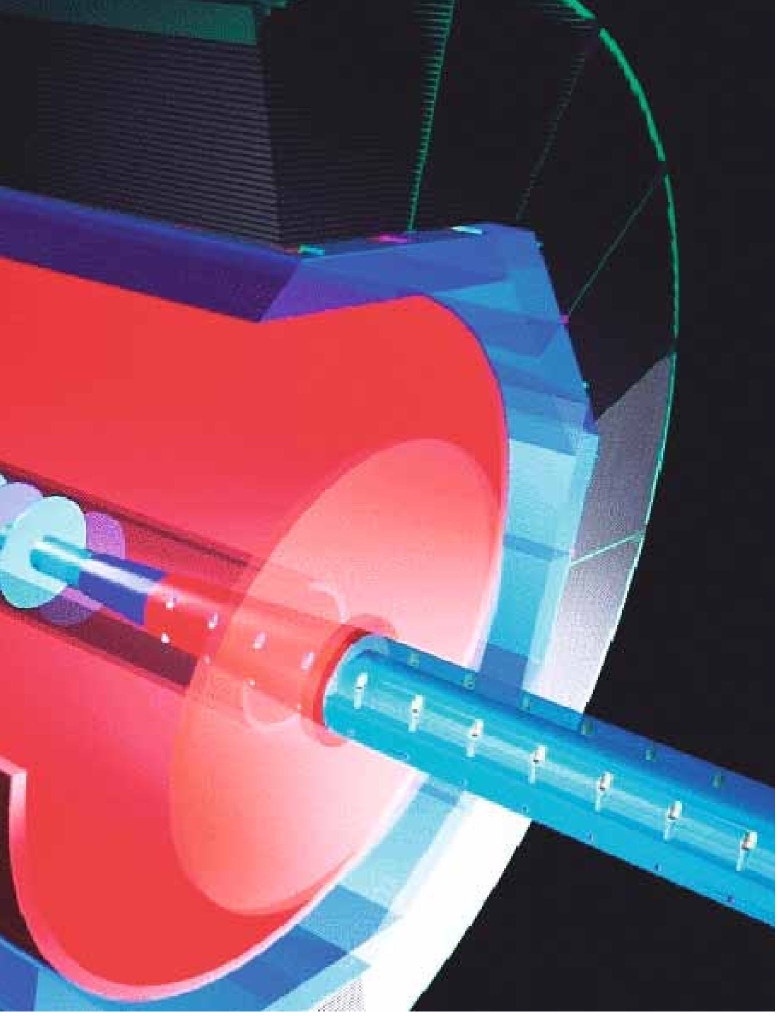
Going with the flow

A concept of central importance for the future ILC detectors is "particle flow". In order to do justice to the precision of the electron-positron collisions in the ILC, the detectors must be able to track in three dimensions each individual particle as it flies through the various detector layers. Today's tracking detectors are capable of registering each individual particle of the jets of particles produced in the collisions. The calorimeters, however, which determine the energy of the particles, can only measure the jets as a whole. For a calorimeter to be able to deliver 3D images of each individual particle, it must itself become a kind of tracking detector. This can only be achieved by an exceptionally finely segmented calorimeter, i.e. one that consists of a great number of individual sensors that are as small as possible, which make it possible to determine the location and direction of the particles with extreme precision. The detector concept under development at DESY combines an exceptionally efficient and precise tracking detector system with such finely segmented, high-granularity calorimeters.

Measuring particles in 3D

The tracking detector system consists of a time projection chamber and a silicon tracker, which together deliver more than 200 single-point measurements for each particle track. As a result, the particle paths can be reconstructed with an accuracy enhanced by a factor of ten – a quantum leap in exactitude. Major challenges here involve the use of new microstructures for gas amplification, which offer greater accuracy, most particularly in conjunction with the powerful magnetic fields required for the ILC detectors. These detectors also have to be very lightweight to minimize disturbance to the measurements made by the calorimeters in the surrounding detector layers.

Regarding the calorimeters, DESY researchers are concentrating in particular on the development of extremely finely segmented systems to detect particles from the hadron



family, for example within the framework of the international CALICE group. The resulting prototypes are then tested and calibrated in test beams at DESY in Hamburg, CERN in Geneva and Fermilab in Chicago. The purpose of the tests is to show whether a calorimeter with five million channels – something only realizable with the use of the very latest photosensor technology – is indeed a practicable option, and if so, what changes need to be made to the prototypes to achieve this ambitious target. This will enable researchers to determine which concept is best suited to the needs of the ILC. In initial tests, the DESY prototype for a hadronic calorimeter fulfilled the high expectations of the researchers. It features an extremely fine segmentation of just 3 x 3 centimetres, making it more precise than any of its predecessors.

Researchers working on the development of the forward calorimeters for the ILC detectors are facing other challenges. These calorimeters are located very close to the beam pipe and have to withstand an annual radiation dose of several million grays if they are to perform according to requirements. Under the leadership of DESY in Zeuthen, the international FCAL group is investigating a variety of prototype forward calorimeters, also taking a close look at sensors made of synthetic diamond. Such diamond sensors are being used for the first time in the LHC experiments. The FCAL team in Zeuthen has assumed responsibility for the assembly, commissioning and readout software of one of the beam monitors in the CMS experiment, which are used to measure the quality of the particle beams in the LHC. This is a perfect example of how research focusing on new detector technologies for future experiments can feed into development of special components for today's detectors.

Research infrastructure for the ILC

The purpose of the EU project EUDET, which is being coordinated by DESY, is to provide important research infrastructure for the development of the ILC detectors. Examples here include a special superconducting magnet from the KEK Research Centre in Japan, which was originally used with a stratospheric balloon to search for antimatter from space. This magnet has exceptionally thin walls, weighs a mere 400 kilograms and requires neither fixed helium pipes nor power cables. When filled with helium and charged by means of an external power source, it runs fully autonomously for up to two weeks. As part of the test-beam infrastructure at DESY, the magnet now effectively serves as a miniature version of the future ILC detector magnets. Inside this magnet, researchers can install prototypes of detector components – such as a small version of the tracking chamber and the vertex detector – and thus test them under precisely defined conditions.

Further examples of EUDET infrastructure include a special "telescope" that has been initially installed at DESY. This telescope is used not to observe the stars but rather to gauge the measuring precision of detector prototypes. Much like a calliper gauge fitted with silicon detectors – in the middle of which the prototype under investigation is installed – the telescope can determine the position and/ or path of each beam particle to an accuracy of three micrometers. Developers can then compare the data from the telescope with that from their prototype and thus determine whether their detector is working properly. If the data do not correspond to those of the telescope, then they know something is wrong. The EUDET telescope is an authentic joint-European production: the chips come from France, the readout system from Italy, the data acquisition software from Switzerland, the trigger from the UK and the mechanical parts from DESY in Germany. DESY was also responsible for system integration, which ensured that the individual contributions could be combined into a working whole.

Thanks to its many years of experience and accumulated know-how in the field of accelerator experiments, DESY has become a major international centre for detector development. With its attractive infrastructure, it provides groups from home and abroad with ideal conditions for research, development and testing. Such projects also dovetail perfectly with the Helmholtz Alliance "Physics at the Terascale", the aim of which is to pool Germany's expertise in the field of particle physics (see p. 10) and strengthen it on a lasting basis.

LIGHT WEIGHT.

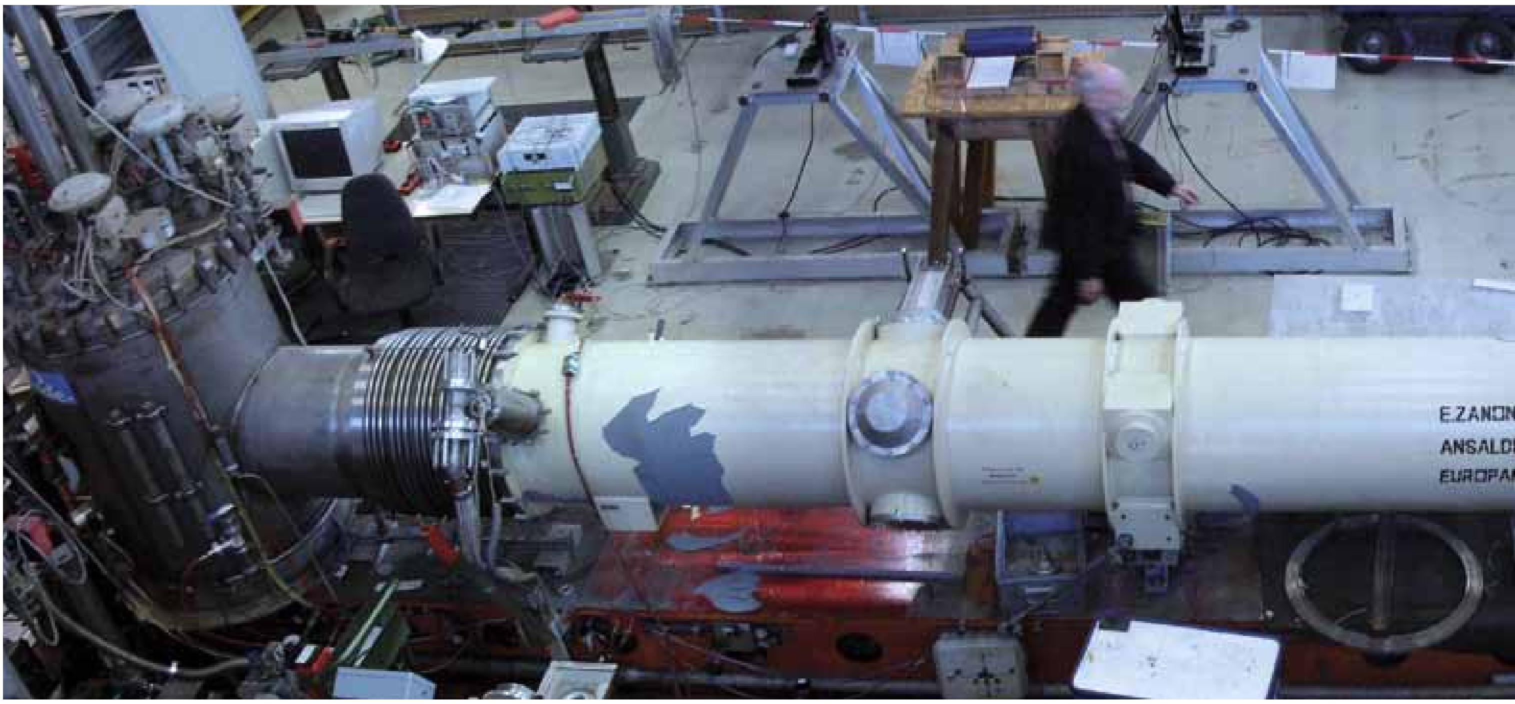
ALPS
Searching for lightweight particles

Researchers at DESY are interested not only in extremely heavy particles, which have to be generated by means of large high-energy accelerators; very light particles at the lower end of the energy scale can also point the way toward unknown physics phenomena. The ALPS experiment, which is tiny compared to the vast LHC and ILC facilities, is currently helping DESY researchers to track down such lightweights of the subatomic world.

Particle physics at the lower end of the energy scale

In the case of large high-energy accelerators such as the LHC in Geneva or the planned ILC linear collider, physicists are searching for the heavyweights among subatomic particles – particles that had previously escaped them because the energies reached by former accelerators were never high enough to generate particles of such a mass. Most of the theories that take us beyond the Standard Model of particle physics predict the existence of new particles that are around 1000 times heavier than protons. However, the most recent

Using a decommissioned HERA magnet, physicists at the ALPS experiment are looking for extremely light particles that could point the way to new physics.



theoretical works, along with some still poorly understood experimental observations, suggest that the “new physics” also could include a host of extremely light particles.

These so-called WISPs (Weakly Interacting Sub-eV Particles) rarely react with matter and are therefore seldom generated, which means that their tracks would simply be drowned out by the flood of standard reactions in large high-energy accelerators. To detect these hypothetical WISPs at the lower end of the energy scale, it is therefore necessary to use other means. These include the experiment ALPS (Any Light Particle Search), which has been running at DESY since the summer of 2007.

Light through a wall

The ALPS experiment involves physicists from DESY, the Hamburg Observatory, the Hanover Laser Centre and the Max Planck Institute for Gravitational Physics. Their seemingly absurd proposal is to make “light shine through a wall”. To achieve this, they first direct a laser beam through a powerful magnetic field generated by a decommissioned dipole magnet from the HERA ring accelerator. In the event that WISPs do actually exist, some of the photons (particles of light) in the laser beam should disappear and change into these mysterious lightweight particles. Installed in the middle of the magnet is a wall that stops the laser beam. The theory is that any WISPs produced would be able to pass through the wall – since they react so rarely with other particles, solid matter is no obstacle for them. Once they re-enter the magnetic field beyond the wall, the WISPs could then change back into particles of light, which would then show up in a photon detector. The light from the laser beam thus would have effectively passed through the wall.

David and Goliath

Yet the expected yields from such photon regeneration experiments are extremely low. At best, scientists predict that one in a billion photons will change into a WISP; and of those, only one in a billion will ever change back into a photon. The physicists working on the ALPS experiment are currently using a laser with a power of almost 15 watts – the equivalent of around 15 000 laser pointers. They are confident that such a set-up is already sensitive enough to enable them to detect WISPs lighter than one millielectronvolt. Meanwhile, it is hoped that installation of a so-called optical cavity will increase laser power to 300 watts initially and then potentially to over 1000 watts. This will make the ALPS experiment the world’s most sensitive facility for detection of WISPs and thereby, scientists hope, yield new insights into the unknown territory of low-energy particle physics.

It may well turn out that the ALPS physicists with their decommissioned HERA magnet will be quicker to deliver some long hoped-for signs of new physics than the scientists working on hugely expensive accelerator facilities. In any case, the hunt for extremely lightweight particles in the low-energy region ideally complements the large-scale experiments conducted at the highest energies. In combination, the results of each approach will make a vital contribution toward increasing our knowledge of the elementary building blocks of the universe and the way in which they interact with one another.

SPACE MESSENGERS.

IceCube and CTA
Windows on the universe

The DESY scientists also conduct research in astroparticle physics, a research field that combines methods and questions from astrophysics, cosmology and particle physics. Various kinds of particle from the cosmos constantly reach the Earth – particles that can provide insights into events happening in the depths of the universe. The DESY researchers at the Zeuthen location use two of these cosmic messengers, neutrinos and high-energy gamma rays, to uncover the secrets of stellar explosions, cosmic particle accelerators – such as the surroundings of black holes – or dark matter.

Pulsars also act as cosmic particle accelerators. The image shows the immediate region surrounding the pulsar in the Crab Nebula.

Mysterious cosmic rays

The Earth is constantly bombarded by particles from the far reaches of the cosmos: protons, helium nuclei and heavier elements such as iron nuclei rain down incessantly on the atmosphere. High up at an altitude of 20 kilometres, they set off whole avalanches of secondary particles which penetrate the entire depth of the atmosphere to finally speed even through us humans. If these particles are electrically charged, they ionize the matter they pass through. For millions of years, they have thus been contributing to the alteration of genetic material – cosmic rays are thus one of the motors driving evolution, the process which eventually also spawned mankind.

Some of these particles from space reach vertiginous energies – up to ten million times higher than those delivered by the LHC, the most powerful accelerator humanity has ever built. This corresponds to the energy of a tennis ball hit with full force, concentrated on a single elementary particle. But where are the sources of these high-energy projectiles? How does nature succeed in accelerating particles to such high energies? Are these particles messengers from the immediate surroundings of black holes, which swallow matter like giant maelstroms, hurtling energy into space in the form of extended matter jets in the process? Or could other astronomical

One quarter of the light sensors for the neutrino telescope IceCube were made at DESY in Zeuthen. The installation in the photograph suggests the geometrical arrangement in which the sensors are frozen, deep in the Antarctic ice.

objects also act as cosmic accelerators? Can cosmic rays provide insights about the mysterious dark matter?

Windows on the universe

To investigate these questions, the researchers from DESY in Zeuthen are cooperating with colleagues from all over the world to construct the largest particle detector on Earth: IceCube, a superlative neutrino telescope at the South Pole. In the future, they will also be hunting for high-energy electromagnetic radiation, so-called gamma rays, from outer space with the planned gamma-ray telescope CTA (Cherenkov Telescope Array). In addition, theoretical work is carried out on this subject in both DESY locations, Hamburg and Zeuthen.

The DESY research is a major element of the Helmholtz Association's overall strategy in the field of astroparticle physics. The Helmholtz Association is investigating the high-energy universe through three windows: With IceCube, DESY is exploring the terra incognita of the neutrino universe. In future, it will be looking at the already staked-out map of gamma-ray sources with highest precision using CTA. In the Argentinean pampas, the Research Centre Karlsruhe operates the Pierre Auger Observatory, an air shower observatory designed to detect charged cosmic rays. One universe – three messenger particles which open up three different views on the cosmos: according to the principle of multi-messenger astronomy – astronomy using different messenger particles – the research programmes at the two Helmholtz centres complement each other in an optimal way.

IceCube

Neutrino telescope in the ice of the South Pole, complemented by a detector field on the ice surface (IceTop)

- Completion: 2011
- Volume: one cubic kilometre
- Depth in the ice: between 1450 and 2450 metres
- 80 strings, each of which has 60 optical modules
- 4800 optical modules in total
- Size of IceTop: one square kilometre
- 80 IceTop detector stations
- Participation: more than 200 scientists from 8 countries

ICECUBE.

Tracking ghostly particles

Neutrinos as heavenly messengers

At DESY, astroparticle research is primarily conducted at the location in Zeuthen, where scientists have been carrying out this kind of work for the past two decades. They are particularly interested in neutrinos – extremely light particles that pass through everything in their path almost unhindered. Neutrinos are created in a variety of ways, such as through nuclear fusion inside the sun or as a result of stellar explosions known as supernovae. The particles strike the Earth practically unnoticed. Although around 60 billion neutrinos from the sun pass through every square centimetre of the Earth's surface every second, they hardly react with their surroundings. That's why the ghostly particles can only be detected with the help of elaborate experiments, such as large tanks in mines and measuring devices in lakes, oceans and the everlasting ice at the South Pole.

Neutrinos provide important information about events in the cosmos. In the same way that certain phenomena can be made visible with light, other phenomena can be "seen" with the help of neutrinos. Paradoxically, the fact that the ghostly particles very rarely interact with their environment makes neutrinos ideal cosmic messengers. That's because particles that can hardly be detected can penetrate even the thickest layers of matter almost unhindered. Neutrino measurements revealed, for instance, that the theoretically predicted fusion reactions actually occur deep within the sun, and that the interiors of collapsed stars, from which light cannot escape, have temperatures of 40 billion degrees Celsius.

Neutrinos reach the Earth on a direct path. The most energetic of the particles which the researchers are looking for come, for example, from the centres of distant galaxies, millions or even billions of light-years away. By contrast, light beams or gamma radiation from these galaxies easily get caught in nebulae on their way to Earth. Charged particles, meanwhile, are deflected by cosmic magnetic fields, whereby they lose the information about their original direction, so their actual source can no longer be determined. Neutrinos, on the other hand, are not affected by nebulae or magnetic fields. This means these heavenly messengers are almost impervious to influences and can provide us with information from regions of space from where almost no other signal reaches the Earth.

Telescopes for neutrinos

Due to the vast distances involved, high-energy neutrinos from the far reaches of outer space only rarely reach the Earth. In order to track down such particles, therefore, researchers have to construct neutrino telescopes hundreds or thousands of times bigger than the detectors in shafts or tunnels used to detect solar neutrinos. Such gigantic instruments are submerged deep in water or ice. Together with colleagues from many other countries, DESY researchers are hunting for these elusive particles with neutrino telescopes in Lake Baikal and at the South Pole.

The neutrino telescope AMANDA is located in Antarctica, deep in the polar ice. It is currently being extended to form IceCube, the world's largest particle detector, which is scheduled for completion in 2011. The researchers' objectives in detecting the neutrinos from the far reaches of space are to investigate the origin of cosmic rays and to plant the first flags on the as-yet blank map of the high-energy neutrino universe. They also plan to use the neutrino telescopes to observe the rare supernova explosions and to search for particles of dark matter or even more exotic particles such as magnetic monopoles.

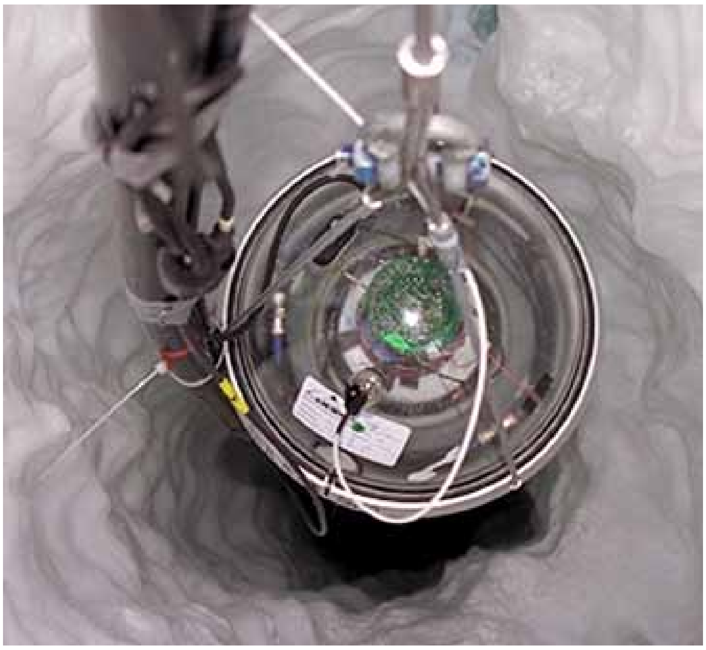
Members of the neutrino telescope AMANDA's crew at the lowering of a string

Cosmic tracks in the eternal ice

The neutrino telescope IceCube consists of several thousand glass spheres with light sensors – called optical modules – that are strung on long cables like pearls, and melted almost 2.5 kilometres deep into the polar ice of the Antarctic. The thick ice shield screens the sensors from interfering signals. Thanks to the crystal-clear ice, the particles' direction of origin can be determined. When a neutrino reacts with an atomic nucleus a muon is created. In water or ice, this particle emits what is known as Cherenkov radiation. The electronics in the glass sphere record the light cones of the Cherenkov radiation and thus the path of the muon. The direction of flight of the neutrino responsible for the event can be calculated from the sensor data sent to the measuring station on the surface.

Remarkably enough, neutrino reactions produce not only optical, but also acoustic signals. However, the tiny popping noises are only produced by extremely high-energy neutrinos. Whether or not the neutrinos at the South Pole can also be detected acoustically is currently being investigated using the SPATS South Pole Acoustic Test Setup.

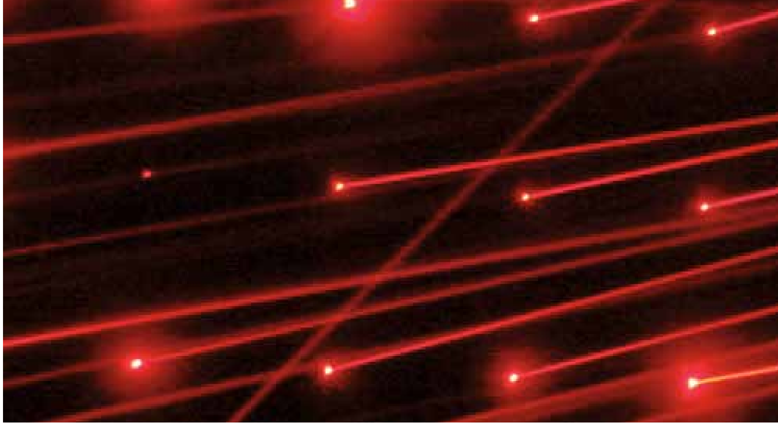
IceCube will encompass a volume of one cubic kilometre, making it the world's largest particle detector. It will be around 30 times as sensitive as its predecessor AMANDA, whose optical sensors have now become part of IceCube. In February 2008, the IceCube detector was half-completed, and it is already taking data at this stage. In addition, the neutrino telescope is being enhanced by a further detector field known as IceTop. Measuring one square kilometre in area, IceTop will comprise 80 detector stations located directly above IceCube's light sensors. The scientists intend to use IceTop to observe extended air showers triggered in the atmosphere by high-energy cosmic rays. One quarter of IceCube's detector modules have been produced in Zeuthen. The Zeuthen-based researchers are also major participants in the analysis of the data from IceCube and IceTop.



The IceCube detector consists of strings, each of which has 60 light sensors attached and is melted into the ice between depths of 1450 and 2450 metres. A total of 80 such strings will have been installed by 2011.

CTA.

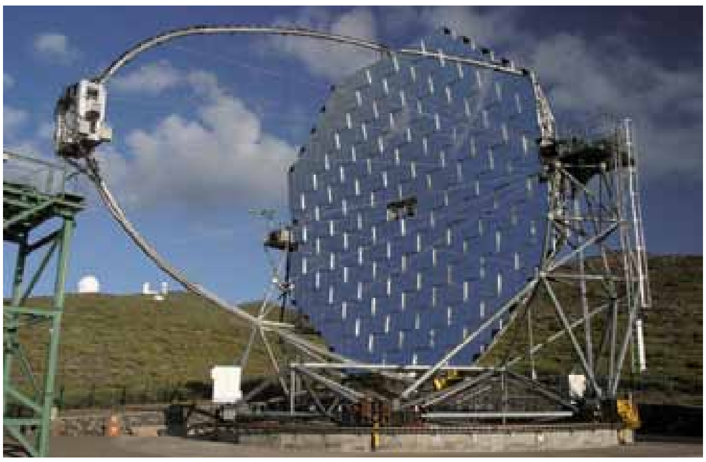
A sky full of gamma rays



Cosmic information in multipacks

The complete map of the high-energy heavens will not be revealed until we make consistent use of all the information supplied by the cosmos. The possible messengers from the universe include electromagnetic radiation – referred to as gamma radiation at high energies – and charged cosmic particles, neutrinos and, in future, perhaps also gravitational waves. In line with the principle of multi-messenger astronomy, the DESY researchers are relying on several of these heavenly messengers.

For example, a young scientists' group in Zeuthen is not only participating in the neutrino telescope IceCube, but also in the gamma radiation project MAGIC on the island of La Palma in the Canaries. Gamma-ray telescopes register the characteristic light from particle showers triggered by high-energy cosmic gamma radiation in the Earth's atmosphere. The telescopes consist of huge systems of mirrors that focus the atmospheric light from these air showers onto fast cameras capable of resolving events on the scale of billionths of a second. This enables the direction of the shower – and thus the direction of origin of the gamma ray that caused it – to be determined. Telescopes of this type are built on high mountains, as far as possible from sources of light that would interfere with the results, for example on La Palma in the Atlantic Ocean (MAGIC) or in Namibia (H.E.S.S.).



The gamma-ray telescope MAGIC on La Palma, Canary Islands

The sky in the light of gamma radiation

In recent years, the gamma-ray telescopes have opened up previously unimagined insights into the far reaches of the universe. To date, the discovery of around 75 cosmic gamma-ray sources has been published. Most of these sources coincide with known objects, which are also visible in other wavelength regions. In this way, it was first possible to demonstrate that stellar supernova explosions really do act as cosmic accelerators, boosting particles to high energies in their shock waves. The gigantic magnetic and electric fields of pulsars – fast-rotating neutron stars – are also obviously cosmic particle accelerators, as are the regions around the black holes at the heart of active galaxies.

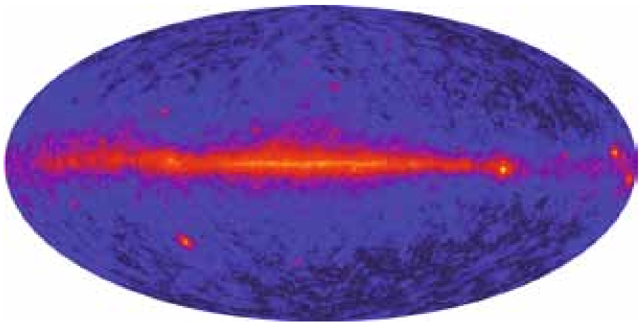
The researchers also have discovered a series of "dark" gamma-ray sources which have not been observed to date in any other spectral region. In particular, these sources emit neither X-rays nor radio waves, both of which arise when electrons are accelerated to high energies. It is possible that these sources represent a previously unknown type of heavenly body which only accelerates protons. As protons and nuclei make up 99 per cent of the charged cosmic radiation which constantly bombards the Earth, these mysterious gamma-ray sources could offer the researchers valuable information on the origin of cosmic rays.

Next-generation gamma-ray telescopes

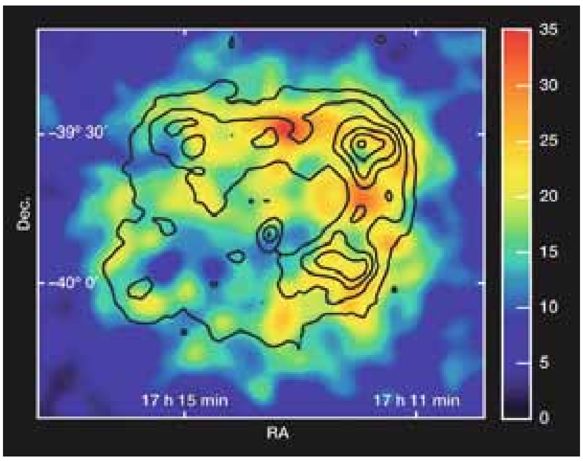
The 75 sources published so far on the gamma-ray map of the sky are probably only the tip of the iceberg. Totally new phenomena could be discovered here, using telescopes with ten times the sensitivity of today's facilities. With such instruments, the researchers could also decode what mechanism in cosmic sources millions of light years away is capable of accelerating particles to create such high-energy light. Telescopes like these would make it possible to study the spatial structure and temporal changes of a large number of sources in detail and so obtain a complete astronomical picture over the entire electromagnetic spectrum.

To achieve a tenfold increase in gamma-ray sensitivity over a wide energy range requires more than 50 telescopes with diameters of between six and 25 metres arranged over an area of at least one square kilometre. An observatory

of this type is currently in preparation. Starting in 2012, the gamma-ray telescope CTA (Cherenkov Telescope Array) is to be constructed by an international consortium in order to look for cosmic high-energy accelerators with previously unavailable sensitivity. CTA will be able to record around 1000 sources and thus raise the field of gamma-ray astronomy to the level of astronomy with radio waves or X-rays. What's more, CTA will also search for signs of dark matter and perhaps also help us to better understand the nature of the mysterious dark energy in the cosmos. DESY physicists are currently participating in optimization calculations, the design of the gigantic reflecting telescopes and the conception of an operations and data centre as part of the prototype study for CTA.



The first picture of the gamma-ray sky from the Fermi Gamma-ray Space Telescope (previously known as GLAST), which was launched into space on 11 June 2008. The image shows the glowing gas of the Milky Way, flashing pulsars and a glowing galaxy at a distance of billions of light-years.



The first image of a supernova as seen in the light of high-energy gamma radiation, recorded by the gamma-ray telescope H.E.S.S. The colour scale specifies the intensity of the gamma radiation, the lines indicate the intensity of the X-ray light. The image proves that the ring-shaped shock waves of such supernovae can act as cosmic particle accelerators.

The dark matter puzzle

Numerous experimental results suggest that most of the cosmic matter in existence is not the same stuff of which we are made – not protons, neutrons and electrons – and not even the other particles known to us, which we have artificially created in accelerators. This dark matter is as ghostly as the neutrinos, and until now, has only been observed in terms of its gravitational effect. The best current candidates for dark matter are WIMPs – Weakly Interacting Massive Particles – with masses suspected to be 100 or 1000 times that of the proton.

It may be possible to artificially create such WIMPs in the LHC at CERN. In parallel with these efforts, researchers are also looking for the tiny signals that would be produced by WIMPs colliding with atomic nuclei in subterranean experiments. However, IceCube and CTA could also detect indirect signs of WIMPs, as these particles collect in heavenly bodies and the particles' occasional mutual annihilation reactions should emit neutrinos or gamma rays. The researchers are thus advancing on one of the most exciting problems of physics from three sides.

THOUGHT FACTORY.

Theory
The hunt for the Theory of Everything

Theoretical particle physics strives to piece together the big picture that underlies the host of experimental findings. Without such theory, the best experiment would be worthless. Theorists at DESY use numerous mathematical tools to explain the world of elementary particles and its physical laws. They not only apply these tools with the help of pencil and paper, but also using high-performance computers developed especially for this purpose. A close connection between experiment and theory is absolutely vital in this regard. It is only by working closely together that theorists and experimental physicists will be able to unravel the mysteries of nature and – so the scientists hope – ultimately to work out a comprehensive theory of all particles and forces.

Hand in hand

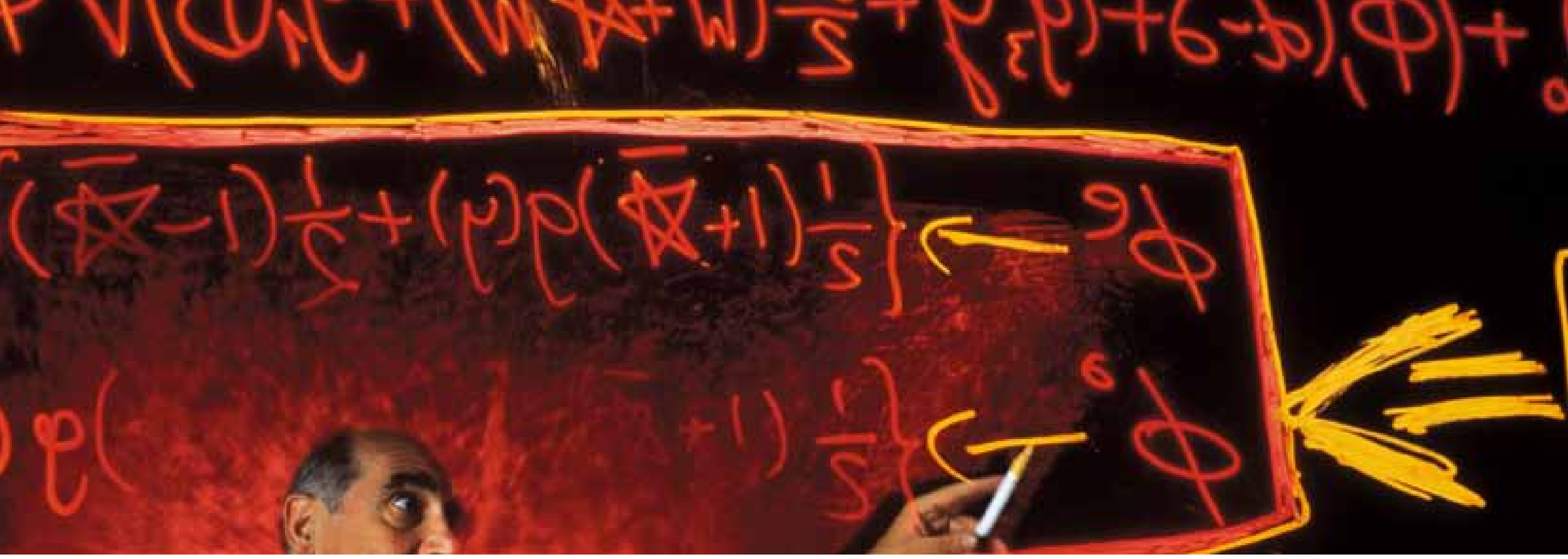
The extremely successful Standard Model, the current main theory of particle physics, also emerged from the intense interplay of theory and experiment. For instance, the theory describing the strong interaction – quantum chromodynamics – predicted that the force between the quarks should be transmitted by so-called gluons. These “glue” particles that hold the quarks together were discovered at DESY’s PETRA accelerator in 1979. The existence of antimatter or neutrinos was also first postulated by theorists and then confirmed by experimentalists.

Then again, particle physics experiments also frequently uncover phenomena that go beyond the scope of known theory and thus entail its revision. In 1987, for example, physicists at DESY’s DORIS accelerator discovered that particles called B mesons can transform into their antiparticles, and at a surprisingly high rate. From this observation it could be deduced that the mass of the sixth quark – the top quark – which was still missing at the time, must be much higher than previously assumed. The “bubbling soup” of quarks and gluons in the proton, discovered at DESY’s HERA storage ring (see p. 14), also triggered a host of new theoretical developments that are used to expand and refine our description of the strong interaction.

The theorists at DESY explore the many facets of the Standard Model and aim to obtain new insights embedding the model into a comprehensive theory of matter and forces – ideas which are of highest interest for the experiments at the LHC in Geneva and the planned linear collider ILC. The main fields of interest are fundamental questions regarding the origin of mass and the unification of the forces of nature, which eventually also has to include gravity.

The Standard Model…

One special focus of the exploration of the Standard Model is on quantum chromodynamics (QCD), the theory of the strong interaction that describes the innermost structure of protons and neutrons. The fundamental questions of QCD cannot be calculated using standard methods but require new techniques, methods of string physics or the use of supercomputers with extremely high computing power. Such



high-performance computers were developed by DESY in cooperation with institutes in Italy and France, and are being used by the researchers at the John von Neumann Institute for Computing (NIC) and by the theorists in Zeuthen.

As a central challenge within the Standard Model, the DESY theorists are exploring the Higgs mechanism, which is believed to give the particles their mass and constitutes the decisive remaining problem of the model. Another major focus is the physics of B mesons (particles containing the second-heaviest quark of the Standard Model, the bottom quark), which provides insights into the different behaviour of matter and antimatter with respect to the laws of nature. This fundamental asymmetry of matter and antimatter is a precondition for solving one of the most important mysteries of cosmology, the question of why there is more matter than antimatter in the universe today.

…and beyond

Although the Standard Model of particle physics is extremely successful, it leaves essential questions unanswered. Physicists therefore explore various possibilities to extend the model and embed it within a comprehensive theory that provides answers to these questions. One theoretically well founded and physically attractive extension is supersymmetry, which endows each particle with a novel partner particle. Theorists at DESY look for mechanisms that are responsible for the large masses of those superpartners. They also investigate how these particles can be discovered at the LHC, the ILC and in cosmological experiments, and how their profile can be determined.

String theory is probably the most convincing candidate for a unified theory of matter and forces that is known today. It is based on the fundamental idea of describing elementary particles as tiny, oscillating strings rather than point-like entities. In close connection with supersymmetry, string theory brings particle physics and gravity together in one unified concept. For reasons of mathematical consistency, supersymmetric string theories can only be constructed in a ten-dimensional spacetime. This means that six of these dimensions must be "curled up" so small that we have not been able to directly observe them so far. Along with physicists from the University of Hamburg, the theorists at DESY are exploring a range of issues, including the fascinating mysteries of string theory itself. At the same time, they are also striving to shed new light on some of the most fundamental aspects of physics, such as the question of the origin and evolution of the universe.

The research programme of the DESY theorists also involves many cosmological problems that are closely related to particle physics: What is the structure of space and time at the smallest scales? Could tiny black holes be created in particle collisions in accelerators or in the atmosphere, and how could they be detected? Are there super-heavy partner particles of the light neutrinos which could contribute to the asymmetry of matter and antimatter in the universe? The DESY theorists are investigating a whole range of these questions that inextricably link the microcosm with the structure and history of the universe.

Theory at DESY

Standard Model physics:
- Higgs mechanism, perturbation theory methods
- Quantum chromodynamics (QCD), string and computer methods

Physics beyond the Standard Model:
- Supersymmetry
- String theory

Cosmology:
- Matter-antimatter asymmetry in the universe
- Dark matter

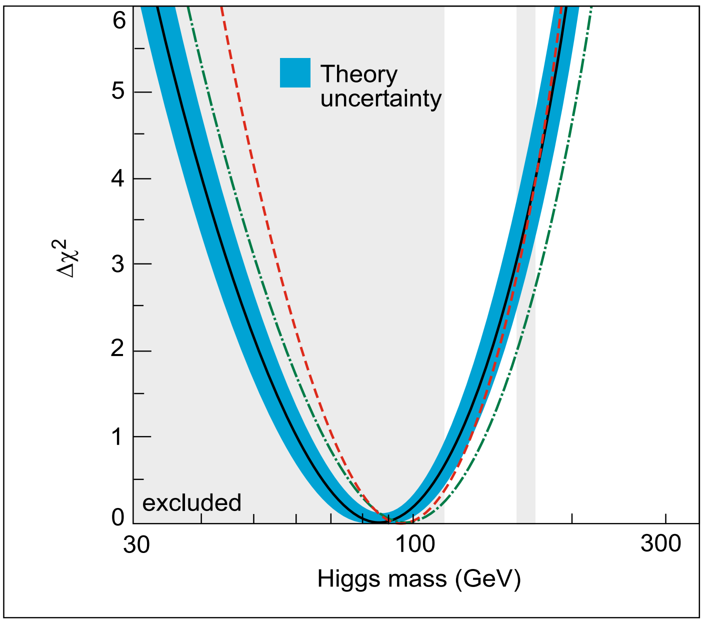
LHC AND ILC.

Collider physics

A model with gaps

Our understanding of the laws of nature in the microcosm has made tremendous advances in recent decades thanks, in particular, to experiments at high-energy accelerators. The results have been used in close interplay with theory to develop an alluringly simple picture of the basic building blocks of matter and the forces acting between them, which is summarized in the Standard Model of particle physics. The model has not yet been fully fleshed out experimentally, however: the mechanism that gives rise to the mass of the fundamental particles has not yet been demonstrated experimentally, and the neutrinos have so far also been reluctant to share their secrets fully.

Although theoretically consistent, the Standard Model leaves fundamental questions unanswered. For example, is it possible to unify all natural forces including gravity? What is the nature of dark matter? And what is the origin of the imbalance between matter and antimatter in the universe? Experimental physicists and theorists alike hope that with their terascale energies (teraelectronvolts), the next-generation particle accelerators LHC and ILC will enable decisive steps to be taken toward a comprehensive theory of matter and forces while also linking the microcosm and cosmology.



Using analysis programs co-developed by DESY theorists, the theoretical bounds for the mass of the Higgs particle can be calculated from precision data obtained at the LEP accelerator at CERN. Mass values in the trough of the parabola are the most probable. (The grey areas have already been ruled out experimentally. The upper limit is at approximately 160 GeV.)

Insight into the fundamental forces

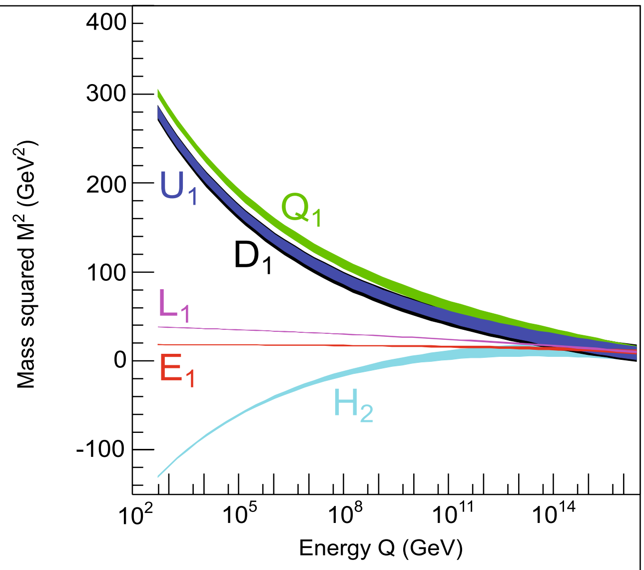
With the accelerators PETRA and HERA, which were used to experimentally investigate the strong force, and the analyses of the theory groups, which link the experimental results to fundamental physics principles, DESY has played a major role in the development, in particular, of the Standard Model description of the strong interaction. In 1979, for example, collision events with three particle "jets" were discovered at PETRA. It was these events that enabled the gluons to be established as the carriers of the strong force between the quarks – just as theory had predicted. The surprising results obtained with HERA, not only in regard to the large number of gluons in the proton, but also the distribution of their spins (see pp. 14 and 18), enabled us to refine our understanding of how protons are constructed of quarks and gluons.
The analysis of the coupling between quarks and gluons impressively confirmed the asymptotic freedom of QCD, i.e. the energy dependence of the strong force, which becomes progressively weaker in the transition region to high energies (see p. 16).

DESY has also made decisive contributions to the understanding of the electroweak interaction – the unified electromagnetic and weak force. The investigation of particle decays with heavy quarks, for example, confirmed the theoretical predication that the different behaviours of matter and antimatter observed in the laboratory can be attributed to complex mixing between quarks and antiquarks. It was an impressive solution to a years-old mystery.

The Higgs mechanism

One of the most important hypotheses co-developed in recent years by DESY theorists has to do with the Higgs mechanism. The Standard Model explains the mass of the fundamental particles as the interaction energy with the Higgs field, which extends evenly over the entire universe. A particle with characteristic properties is associated with this field. Whether the Higgs mechanism is indeed responsible for the generation of mass stands and falls with the experimental discovery of this Higgs particle. Precision measurements carried out at the former LEP electron-positron accelerator at CERN can place narrow bounds on the mass of the Higgs particle within the Standard Model (see fig. left).

Once the mass of the Higgs particle has been determined, all of its other properties can be predicted theoretically: its production mechanisms at accelerators, its lifetime and its decay properties. Theoretical physics has therefore



In theories that include gravity, the masses of the supersymmetric partners of quarks (D_1, Q_1, U_1), leptons (E_1, L_1) and also the Higgs bosons (H_2) can unify naturally at high energies to a universal value, much like the unified coupling strengths of the forces. Precision measurements at the LHC and the ILC will make it possible to theoretically extrapolate the masses to high energies, enabling the experimental investigation of the central question of universality.

generated a very precise profile of this particle that will enable a targeted experimental search to be conducted at the LHC in the years ahead. Several of the characteristic properties of the Higgs particle can already be studied at the LHC, but a high-precision electron-positron accelerator like the ILC is required before all facets of the Higgs mechanism can be investigated as the mechanism clearly responsible for the generation of mass. Concerted analyses at the LHC and ILC, particularly as developed by the DESY theorists, will ultimately be able to provide conclusive answers to our questions about the origin of particle mass.

Supersymmetry

The electromagnetic, the weak and the strong force can be unified naturally if a supersymmetric partner particle is associated with every particle of the Standard Model. Each particle with integer spin is paired with a particle with half-integer spin and vice-versa. This novel spectrum of particles makes it possible to establish a bridge between the region of lower energies in which the Standard Model applies and the extremely high energies at which the fundamental forces of nature unify into a primordial force.

Theoretical studies have restricted the masses of the particles in this new supersymmetric world to the terascale. The properties of the superpartners can be predicted in detail within this framework, so that unique signatures can be used to discover the superpartners at the LHC and for the comprehensive investigation of the theory of supersymmetry at the ILC. If supersymmetry occurs in nature with particle masses in the theoretically expected range, the LHC and ILC will open the door to a fascinating new world. In recent years, DESY theorists have been involved in the development of these concepts for the LHC and the ILC. These tools will make it possible to determine whether the masses of the supersymmetric particles unify at extremely high energies in the same way as the coupling strengths of the forces (see fig. left). This will enable the development of a clear picture of supersymmetric matter at high energies, in that fundamental region in which the roots of both particle physics and cosmology lie.

In most models the lightest supersymmetric particle is stable or long-lived, making it an excellent candidate for the dark matter in the universe. If the tracks of this particle can be found at the LHC, and its properties determined at the ILC, an amazing riddle extending from particle physics to cosmology would be resolved (see p. 54).

Alternatives?

The Higgs particle would be the first fundamental particle discovered in nature without spin. Would it be the only one? According to supersymmetry, there should be several particles of this type. In contrast, alternative theories negate the existence of the Higgs particle and instead postulate new interactions. Others reduce the unification scale – those extremely high energies at which gravity begins to interact with the forces of particle physics – to the terascale range. This would put additional spatial dimensions of the universe within experimental reach, and implies that accelerators like the LHC could even produce microscopic black holes.

The experiments at the LHC will soon reveal which of these comprehensive theories of matter and forces – super-symmetry or possible alternatives – nature prefers. Whatever the experimental answers to our theoretical questions turn out to be, in the years ahead high-energy physics will provide decisive insights into the structure of the universe.

SUPERCOMPUTERS.

High-performance computing in particle physics

Installation of an apeNEXT system at DESY in Zeuthen

Physics on the lattice

The strong force acting between the quarks plays a central role in particle physics and must be considered when interpreting nearly all particle physics experiments. But how can its influence even be calculated at all? The very distances at which the confinement (see box) characteristic of the strong force occurs are where the established mathematical models used for decades to solve equations on paper fail. Fortunately, shortly after the discovery of the fundamental mathematical equations associated with quantum chromodynamics (QCD) – the currently accepted theory of the strong force – a fitting solution was found: lattice gauge theory. In this approach, the physicists use a trick that enables them to solve the equations with ever greater precision with the help of very high-performance computers. The idea behind lattice gauge theory is that space and time – which in reality are continuous – can be replaced by a lattice of individual cells. The fact that physics phenomena then take place only on this lattice and no longer in the lattice spaces simplifies the calculations. However, solving the equations still requires supercomputers with extremely high computing power.

Supercomputers in Zeuthen

Although the mathematical structure of lattice gauge theory was worked out in large part at DESY in Hamburg in the 1980s and early 1990s, the activities are now focused at DESY in Zeuthen, where several European collaborative projects are being coordinated. Simulations of lattice gauge theory are performed here in close cooperation with the John von Neumann Institute for Computing (NIC), which was jointly founded by DESY and the Research Centre Jülich. The researchers in Zeuthen also perform development work for the massively parallel supercomputers used for the computations.

The number of lattice cells plays a decisive role in lattice gauge theory: the more cells considered in the calculations, the more precise the results. The precision of the computations is therefore enhanced not only by the further development of mathematical and numerical methods, but also by the enormous advancements in computing speed. Today multimillions of cells can be simulated on supercomputers comprising thousands of individual processors. The DESY physicists in Zeuthen developed the

APE high-performance computers tailored for the numerical problems of particle physics in collaboration with the *Istituto Nazionale di Fisica Nucleare* (INFN) in Italy and the University of Paris-Sud in France.

High-performance computers for research

Because the crucial factor for such computations is the performance of the greatest possible number of floating point operations, the decisive performance criteria for the computers used is measured in floating point operations per second (flops). Today's peak computer power of multiple teraflops (1 teraflop = 1 000 000 000 000 flops) cannot be achieved by a single processor; instead a large number of processors are interconnected by means of a fast network. Despite their great complexity, these massively parallel computers must be capable of many weeks of fault-free continuous operation. Low power consumption and a compact design, to say nothing of high efficiency when it comes to lattice gauge theory simulations, are critical factors for cost-effective operation. The APE computers excel in this latter discipline with efficiencies of over 50 per cent in some cases, even when 1024 processors are all working together, for example.

The innovative concepts developed by DESY, INFN and the University of Paris-Sud for the APE computers have even influenced the architecture of what are currently the world's fastest computers, which are built by IBM. Development continues non-stop in this area as well. The DESY physicists are working together with the Universities of Regensburg and Wuppertal in addition to IBM on a computer for demanding quantum chromodynamics computations. This new computer, which will be powered by thousands of intelligently linked processors of the type Sony uses in its PlayStation 3, will shatter the existing records for energy and cost-efficiency.

Of glueballs and unified forces

Quantum chromodynamics poses numerous challenges for the theorists and their high-performance computers. For example, it has long been known that the world of hadrons should also include glueballs. These are particles that consist almost entirely of gluons – the small "glue" particles that hold the quarks together in conventional hadrons. Experiments have not yet succeeded in identifying glueballs unequivocally, however, because they are very difficult to differentiate from complicated bound states of quarks and gluons. Detailed computations by the theorists and highly precise experiments are needed to confirm the existence of glueballs. A comparison of theoretically predicted and experimentally determined particle masses can provide valuable starting points here. Final certainty can hardly be achieved without a precise analysis of the possible production and decay mechanisms of such glueballs, however. These computations also require the use of appropriate supercomputers, such as the ones being co-developed in Zeuthen.

Ever greater precision of QCD computations is also important for theoretical investigations into the unification of the fundamental forces of nature (see p. 17). Indeed, these computations will make it possible to determine the exact strength of the strong force. This is ultimately the only way that theorists will be able to predict the energies at which the strong force unifies with the electromagnetic force and the weak force.

The mysterious strong force

Particles from the hadron family – like protons and neutrons, the building blocks of atomic nuclei – consist of quarks that are held together by gluons, the exchange particles of the strong force. No one has ever observed an individual quark, however. This phenomenon has been attributed to confinement, a special property that differentiates the strong force from the other forces of nature. Gravity, for example, is barely noticeable if two bodies are far enough apart, which is why we can send spaceships to distant planets. The strong force, on the other hand, retains an enormous power of attraction – no matter how great the distance – when an attempt is made to separate two quarks. It is as if the quarks were joined by a spring. As long as they are close together, the spring remains relaxed and only has a minor effect. If an attempt is made to move them apart, however, the spring tension becomes increasingly noticeable. The quarks are thus essentially confined in the hadrons.

This confinement cannot be easily explained within the framework of quantum chromodynamics (QCD), the currently accepted theory for the strong force. Predictions based on QCD computations are reliable as long as the quarks are close together and the effect of the strong force is weak. But hadrons can also be brought into more extreme situations involving larger separations between their constituent quarks, such as in the collisions at HERA and the LHC. The strong force between the quarks most likely played a major role in the early universe as well. Efficiently describing the strong force at large distances continues to be a significant challenge. Widely differing approaches such as lattice gauge theory and recent developments in string theory (see next page) are being pursued to meet this challenge.

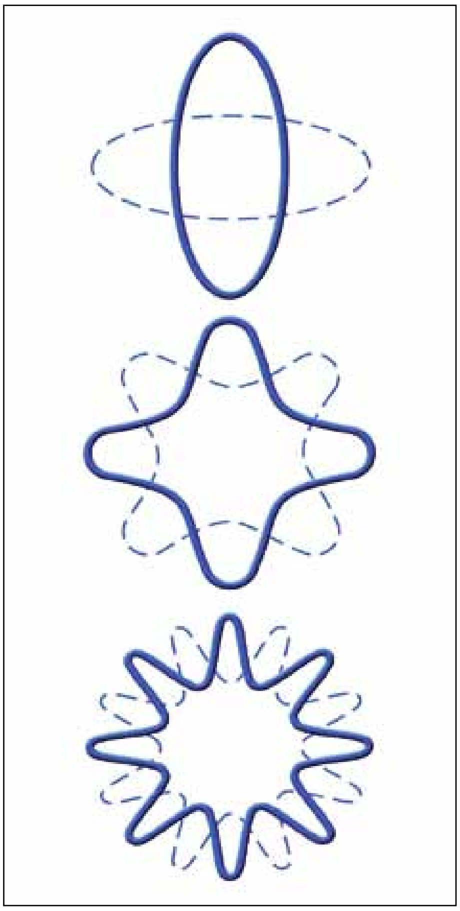
STRINGS.

String theory and collider physics

Quarks from strings?

The strong force, which is of fundamental importance especially when it comes to understanding proton collisions at the LHC, acts almost as if the individual quarks were connected to one another by elastic threads. In fact, theorists attempted early on to explain the properties of hadrons, i.e. particles made up of quarks and gluons, on the basis of vibrations of one-dimensional strings. Such attempts led to the first string theories in around 1970. The application of these theories to the strong force, however, initially met with little success.

It took nearly 30 years of intensive research before the string theorists achieved a long-awaited breakthrough in the description of hadronic physics. According to string theory, the basic building blocks of nature are not point-like particles, but instead behave much more like one-dimensional strings. To keep the whole thing mathematically consistent, the string theory's universe must extend into ten spacetime dimensions. However, some of these dimensions can be "curled up" in such a way that we do not directly perceive them as viable dimensions of space. The possibility of creating a universe from such elementary strings has attracted a lot of attention, in particular because string theory resolves the long-known theoretical inconsistencies between quantum physics and Albert Einstein's general theory of relativity.



In string theory, particles are no longer considered to be point-like objects. Instead, they are viewed as tiny strings that can vibrate in characteristic patterns. The various states of oscillation correspond to the various particles.

A question of perspective

A world of strings would be barely distinguishable from our four-dimensional universe – at least if we don't look that closely. In particular, strings can also form objects similar to black holes. Because they are extremely well suited to the study of the quantum aspects of gravity, there was intensive investigation of black holes in the 1990s. During the course of these studies, the string theorists made a remarkable discovery. They found that quantum chromodynamics, i.e. the theory of quarks and gluons in a three-dimensional space, by no means provides the only possible description of hadronic physics. The researchers actually discovered entirely new models by means of which hadronic physics can be explained as a string theory in a five-dimensional spacetime. (Five spatial dimensions of the nine-dimensional string universe thus have to be curled up.) This may seem odd at first glance, as it suggests that we cannot categorically differentiate whether our real world is four- or five-dimensional – it all depends on whether we view it as a world of particles or a world of strings!

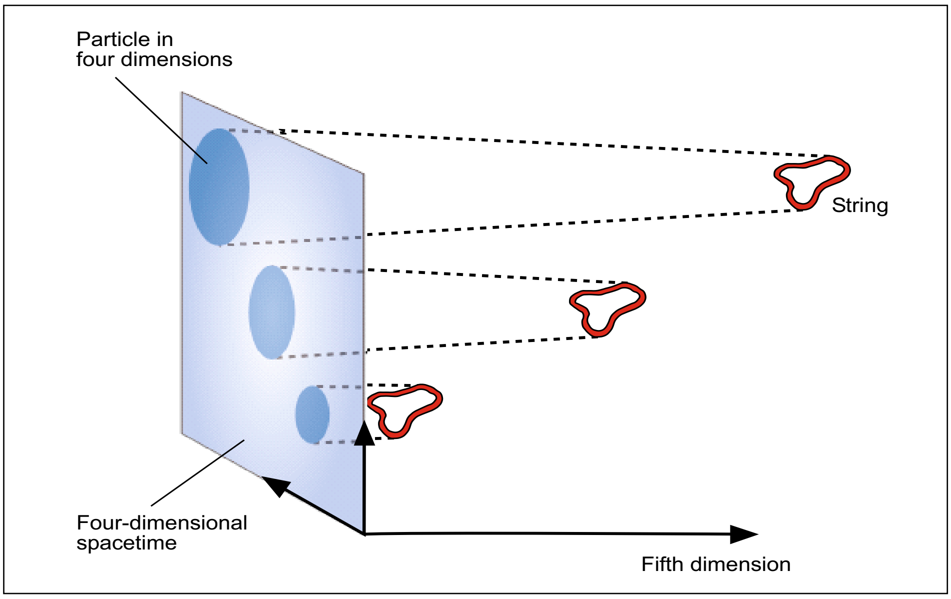
As surprising as the existence of two completely different descriptions of one and the same reality may appear to be at first, the phenomenon is not actually all that unusual. Something similar happens with a photograph, for example, which can either be recorded via the chemistry of conventional film or as a sequence of bits – zeros and ones – in modern digital cameras. Although the image itself is the same, its representation in the camera could hardly be more different. The two representations can, of course, be converted from one form to the other using the appropriate technology.

String theory on the rise

Each of the two known representations of hadronic physics – quantum chromodynamics or rather one of its supersymmetric relatives and string theory – has its own merits. Quantum chromodynamics offers highly-developed tools for the investigation of hadronic systems that are working well as long as the distance between the quarks is small. With the intuitive image of the strong interaction as a spring force, it is reasonable to expect that the methods of string theory can be used to make predictions in the range of the otherwise inaccessible large distances between quarks, and using nothing more than paper and pencil. The intermediate range of medium quark distances currently remains the domain of the supercomputers of the lattice gauge theorists. There are now a few spectacular examples, however, in which string theory computations were able to be performed for any distance between the quarks without any assistance from high-performance computers.

Recent experiments at heavy ion accelerators indicate that string theory does indeed describe large distances between the quarks very efficiently. When two heavy ions collide, the numerous quarks and gluons in their nuclei from a droplet of “quark-gluon soup”, which eventually evaporates in the form of a large number of hadrons. Before evaporation occurs, however, the droplet behaves very much like a fluid, whose viscosity can be measured experimentally. It has since become clear that the quark distances prevailing in such droplets are too large to allow a reliable calculation of the viscosity using the conventional approximation methods of quantum chromodynamics. On the other hand, the predictions of the string theory models agree relatively well with the experimental data.

Currently it is still very difficult to compute the properties of hadrons with the help of string theory. Whereas the computational techniques of quantum chromodynamics have undergone decades of intense refinement, a lot of work must still be done before string theory reaches a corresponding level of development. The string theory group at DESY is tackling this exciting challenge in cooperation with numerous partners all over the world.



A whole new perspective: particles in our four-dimensional spacetime are the holographic image of a five-dimensional world made up of strings. In principle, the hologram and the original image contain the same information but encode this information in very different ways.

PARTICLE COSMOLOGY.

The interface of particle physics and cosmology

Mysterious universe

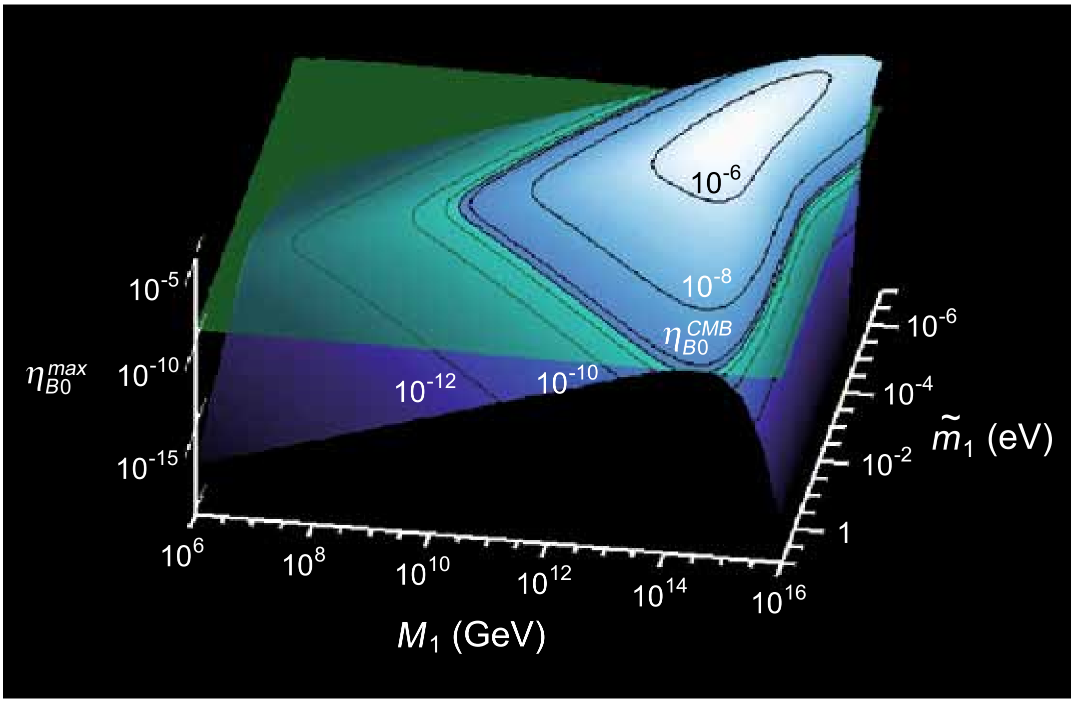
One of the greatest successes of modern cosmology was the determination of the energy density of the universe based on measurements of the light radiated by supernovae and the analysis of the cosmic microwave background radiation. The composition of this energy density was a complete surprise. The matter with which we are familiar from planets, stars and interstellar gas – and of which we humans are also composed – accounts for only four per cent of the total. In other words, 96 per cent is “dark”, that is, it neither absorbs nor emits light. In all observations so far, this dark fraction has manifested itself only indirectly through its gravitational effect. Of this dark fraction, 23 per cent behaves like dark matter, which like visible matter forms spatial structures. The predominate fraction of 73 per cent – dark energy – is spatially homogenous. It evenly permeates all of space rather than forming structures, and its negative pressure tends to accelerate the rate of expansion of the universe.

The question of the origin of visible matter and the nature of dark matter and dark energy is closely linked to particle physics and its theoretical foundation, quantum field theory. Indeed, interactions that violate certain laws of conservation and symmetries – as they were discovered in accelerator experiments – are a prerequisite for the accruement of a tiny surplus of matter relative to antimatter in the early universe. This, in turn, is the reason why matter exists at all in today’s universe. Supersymmetric extensions of the Standard Model of particle physics predict the existence of new elementary particles such as the neutralino, axino or gravitino, which are candidates for the primary components of dark matter. Dark energy, on the other hand, could be generated by quantum effects of the gravitational field or other fields.

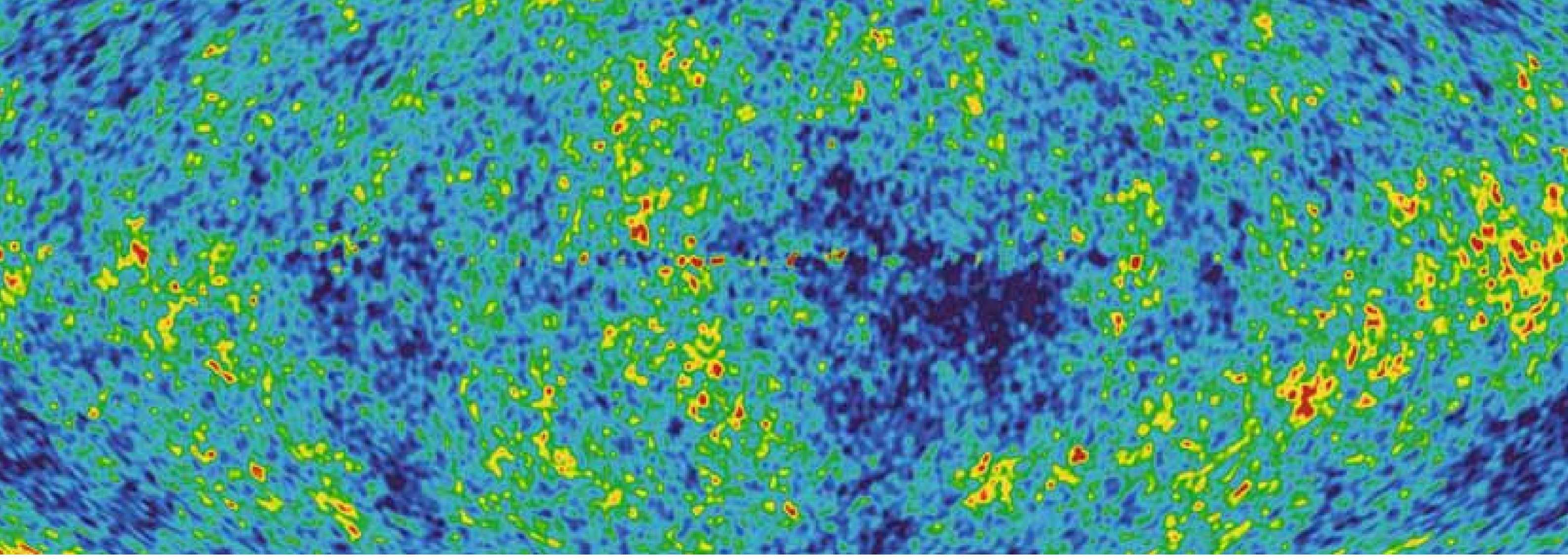
The correlation between particle physics and cosmology that is attracting so much interest today has long been part of the research programme of the DESY theory group. The far-reaching significance of ideas developed here in the late 1980s was not realized until a decade later. They include leptogenesis as an explanation of the matter-antimatter imbalance in the early universe or certain extensions of the theory of gravity, which today play an important role in the discussion about the nature of dark energy.

More matter than antimatter

In the early universe, quarks, antiquarks, leptons, antileptons and photons were present in roughly equal densities. Today, in contrast, an imbalance between matter and antimatter is observed – the so-called baryon asymmetry. In the early universe, this asymmetry corresponded to a tiny surplus of quarks compared to antiquarks, and a correspondingly tiny surplus of leptons compared to antileptons. Such



Theoretical studies of leptogenesis: the figure shows the computed baryon asymmetry as a function of the mass M_1 of the decaying heavy neutrinos and an effective mass $\tilde{m}_1$ of the light neutrinos. The computed value must agree with the baryon asymmetry ($\eta_{B0} = 6 \times 10^{-10}$) determined from the cosmic microwave background radiation (CMB). According to the theoretical analysis, the matter-antimatter asymmetry in the early universe for a typical mass of $M_1 = 10^{10}$ GeV was produced at a time $t = 10^{-26}$ s after the big bang.



Temperature fluctuations of the cosmic microwave background radiation, recorded by the WMAP space probe.

an asymmetry can be produced by the decay of heavy neutrinos. These heavyweights generate the very low masses of the light neutrinos – as observed in neutrino oscillation experiments – through their quantum mechanical mixing with these light neutrinos. The key here is that the decay of the heavy neutrinos violates CP symmetry, resulting in different abundances of leptons and antileptons.

The magnitude of the resulting baryon asymmetry depends on the properties of the neutrinos, their masses and mixing. This is also the subject of detailed studies by the DESY theory group. Theoretical analyses show, for example, that the matter-antimatter asymmetry in the early universe for certain typical neutrino masses was produced 10^{-26} seconds after the big bang. This reveals a fascinating correlation between neutrino physics and the infancy of the universe. It is extraordinarily remarkable that the experimental evidence of the existence of neutrino masses, which was obtained from neutrino oscillation experiments, and the leptogenesis mechanism derived from theoretical studies are quantitatively consistent. This has led to numerous investigations that suggest the existence of additional processes, especially in supersymmetric theories, whose discovery could further our understanding of the matter-antimatter imbalance in the universe.

Dark matter

One mathematical concept that goes beyond the Standard Model of particle physics is supersymmetry, which assigns every particle a supersymmetric partner particle. In many supersymmetric extensions of the Standard Model, the lightest of these new superparticles (lightest supersymmetric particle or LSP) is electrically neutral and stable. A popular candidate for the LSP is the neutralino, a superpartner of the photon, Z boson and the Higgs particle. In this case, we should see characteristic events that appear to violate the law of conservation of energy in the experiments at the LHC, since a fraction of the total energy escapes from the detectors unobserved in the form of neutralinos. Neutralinos from dark matter could also scatter off normal matter via the weak force and thus be detected directly in laboratory experiments.

The investigation of the leptogenesis mechanism suggests an additional possibility. Dark matter could also be composed of gravitinos, the supersymmetric partner particles of gravitons, which mediate gravity in the same way that photons carry the electromagnetic force. Under certain conditions, the gravitons could decay into conventional particles, in particular photon-neutrino pairs. Experimental evidence supporting this hypothesis could be provided by gamma-ray telescopes and by the LHC. Indeed, the photon flux generated inside and outside the Milky Way has a characteristic energy spectrum, which can be measured using satellite-borne experiments. In the 1990s, the satellite-based gamma-ray telescope EGRET observed an anomaly in the photon flux that can be explained by the effect predicted by the gravitino hypothesis. If this hypothesis really is true and dark matter is comprised of gravitinos, the Fermi Gamma-ray Space Telescope (formerly known as GLAST) launched in June 2008 should also detect a signal in the next few years. Furthermore, we can expect characteristic decays of other heavy superparticles to be discovered at the LHC. The mystery of dark matter could very well be solved within the next five years, marking another important milestone in the search for a Theory of Everything.

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