POINTING THE WAY.

How HERA is helping to shape the future of physics

For 15 years, electrons and protons collided inside the HERA particle accelerator, which lies deep in the earth beneath Hamburg. Data taking at HERA ended in the summer of 2007. This is thus a perfect occasion to take a backward look at Germany's largest research instrument, which has written physics history, and look ahead at what HERA still has to offer. After all, the evaluation of the recorded measurement data, which will be completed sometime in the next decade, will give us a comprehensive overall picture of the proton and the forces acting within it – with a precision that won't be matched by any other particle accelerator in the world for years to come.

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
Member of the Helmholtz Association

Inside the HERA tunnel: The normally conducting magnets of the electron ring are located beneath the proton accelerator with its superconducting magnets (beige).

CONTENTS.



TEAM WORK.

The whole is greater than the sum of its parts

Every major research project is an expedition into unmapped territory and, like every expedition, the project can succeed only if individuals commit themselves to it, develop new ideas and motivate their fellow team members to join them in overcoming the technical and scientific challenges involved.

The challenge of HERA

Three individuals, representative for all those who contributed to the project, should be mentioned in connection with HERA: Bjørn H. Wiik, who suggested the basic concept behind the electron-proton storage ring and headed the proton ring construction project; Gustav-Adolf Voss, who contributed his extensive experience in the construction of accelerators and built the electron ring; and Volker Soergel, who as Chairman of the DESY Directorate, played a key role in the project's success during the planning and construction phases.

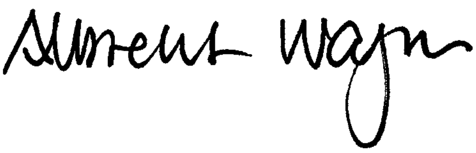
HERA was also a pioneering experiment with regard to international cooperation. Partners from many other countries financed a quarter of the total costs, in particular through the construction of important components. HERA could not have been realized without our partners.

An accelerator is only as good as the experiments that are conducted at it. Approximately 1000 scientists from all over the world were involved in developing, constructing and conducting the four major HERA experiments. They are now helping to extract new knowledge from the flood of data these experiments recorded. Their wealth of ideas and strong personal commitment have played a major role in HERA's success.

This brochure is dedicated to all of the people who have made such an extraordinary contribution to HERA and who will continue to do so in the ongoing process of evaluating the data it has generated.

"Those who have finally reached the top of a mountain after a long climb are rewarded by a view of the world that they have never seen before. And that's exactly how we feel after 15 years of research at HERA. We are pleased to note that the knowledge we have gained through HERA is already being passed on in physics textbooks and is expanding our understanding of the forces that hold the world together at its core."

Prof. Dr. Albrecht Wagner
Chairman of the DESY Directorate



Prof. Dr. Rolf-Dieter Heuer
Director for Particle Physics

RACE COURSE.

How Hamburg received a racecourse that's renowned throughout the world

Hamburg's most prominent racecourse was frequented not by top athletes but by billions of particles, all of which are much tinier than an atom. Deep in the earth beneath Hamburg, electrons and protons collided at extremely high energies in a gigantic round particle accelerator. The Hadron-Electron Ring Accelerator HERA went into operation at DESY in 1992. Research operation was concluded at the end of June 2007 and the accelerator was switched off. This is therefore a perfect occasion to take a backward look at the history of Germany's largest research instrument, review 15 years of remarkably successful research, and look forward to see what HERA still has to offer. After all, the evaluation of the recorded data will keep particle physicists on the edge of their seats well beyond 2010.

An ambitious plan

As DESY's physicists set about planning the future back in the 1970s, one thing was clear: the next project had to be unique. It had to open up new ways of studying the microcosm and explore uncharted territory that was inaccessible to the world's other accelerator centers. Physicists at the other research centers in Japan, Switzerland and the USA were using particles and antiparticles for their experiments: electrons and positrons, protons and antiprotons. At DESY, it was decided to adopt a new, fundamentally different accelerator strategy in order to build a "super electron microscope" for protons – a machine that would allow physicists to gaze into the innermost structure of matter.

The Hadron-Electron Ring Accelerator facility HERA was born, the worldwide first and only storage ring facility accelerating two different types of particles. Here, in a 6.3-kilometer-long tunnel located deep below Hamburg, lightweight, point-like electrons collided with hydrogen nuclei – i.e. protons from the hadron family – which are nearly 2000 times heavier.

Pioneering technology

When an electron collides with a proton inside the HERA accelerator, the electron acts like a tiny probe that scans the inner structure of the proton. The higher the energy of the particle collision, the deeper physicists are able to gaze into the proton, and the more details are revealed. To achieve these high-energy collisions, both particle types have to be accelerated separately and then directed to collide with each other head-on. This concept requires two distinct accelerators, each one of them a technological challenge in itself.

No one had ever tried to build such a facility before. Even though electrons had been fired into protons at rest during the early phase of research at DESY, everyone had since concentrated on the physics of electrons and positrons, and was therefore totally inexperienced when it came to constructing a proton accelerator. But it all worked out: HERA was formally approved on April 6, 1984, and the facility celebrated its symbolic startup right on schedule on November 8, 1990. At the ceremony, Hamburg's Science Senator Professor Ingo von Münch spoke of a financial "bull's eye," for despite the enormous technological challenges, the HERA team had succeeded in keeping to both deadline and budget.

The "father" of HERA: Bjørn H. Wiik, who went on to become director of DESY, in the HERA tunnel. Back in 1971, Wiik had the groundbreaking idea to accelerate electrons and protons separately and smash them into one another head-on. His plan was to construct a huge electron microscope for protons. His concept was brilliant; his work laid the foundation for HERA's subsequent success.

Hannelore Grabe-Çelik

In 1985, Hannelore Grabe-Çelik, a trained technical drawer, was asked to coordinate HERA's installation. Just what the job would entail became clear when she was greeted at the underground construction site with the remark, "A woman underground brings bad luck." But she succeeded, and equipped with her energy, humor and unshakable optimism, she still organizes everything from the installation of PETRA III to the HERA party.

HERA was my biggest job ever. I've been working for 40 years now at DESY, and the accelerator rings are my children: I started out with the planning of PETRA, and I'll finish with PETRA III. I took "my boys" underground in 1986. It was exciting to work there for almost five years as the only woman among some 200 men, who took a while to get used to things. By deciding what entered the tunnel when (and, more importantly, how), we made sure the work never came to a standstill. I also served as the complaints desk and the interface with DESY. I was the one the companies complained to if they found hip flasks in the water pipes or shopping carts in the tunnel. But we solved all the problems and celebrated our many successes.

After installing hundreds of kilometers of cable, 24 800 grates, magnet modules for electrons, superconducting magnets for protons and a host of large and small components, we mounted the last proton magnet with a drum roll on September 19, 1990.

We had finished the job!

A construction project of superlatives

The civil engineering work for HERA was a hard job. Four underground halls had to be excavated, each of them seven stories deep. Between them, the tunnel boring machine HERAKLES wound its way through Hamburg's sandy soil, 10 to 25 meters deep underground. The machine, which is six meters in diameter and roughly as long, is a huge steel drill of the kind used to construct railway and subway tunnels. The entire 6.3-kilometer-long tunnel in which the two HERA accelerators are installed was thus excavated underground. Without risks to persons and property, HERAKLES chewed its way under residential and commercial areas, roads and parks.

On August 19, 1987, the laser-controlled tunnel boring machine broke through the wall of the HERA South Hall. Exactly 28 months after it had set out from the opposite side of that hall, it closed the loop again with a deviation of only two centimeters, i.e. well within the allowed margin of ten centimeters. On its way below the Bahrenfeld harness course, various residential and commercial areas, and the Hamburg Volkspark, HERAKLES had removed around 180 000 cubic meters of soil.

Two accelerators for HERA

As soon as HERAKLES had finished the first tunnel section between the HERA South and West Halls, the installation crew took over. First came cable support racks, electric wires, water pipes, and light and ventilation systems; then it was the turn of the first magnets of the electron storage ring. As HERAKLES reached its starting point again in August 1987, nearly half of the electron accelerator had been installed in the tunnel. One year later, the facility accelerated its first electron beam.

Then came the most critical part, the construction of the proton accelerator with its newly developed superconducting magnets and its sophisticated helium cooling system. All in all, around 650 superconducting magnets were delivered to DESY from companies in Germany and Italy. They stayed for 80 hours on average in the magnet test hall at DESY before being installed above the electron ring inside the tunnel. The last proton magnet was in place on September 19, 1990. In the night of April 14-15, 1991, the HERA team succeeded in storing protons in the machine for the first time. On October 19, 1991, HERA delivered its first electron-proton collisions.

A huge pinion-type cutter: The HERAKLES tunnel boring machine cleared the way for HERA.

Large-scale cryogenics: HERA's 2500-m² refrigeration hall

Europe's largest refrigerator

At the high energies reached by HERA, it takes very powerful magnetic fields to make the heavy protons follow the curve of the accelerator ring. In fact, these fields must be three times as strong as those attainable using normal iron yokes and copper coils. The only practical way to produce such strong fields is with the aid of superconductivity – the ability of selected materials to conduct electricity without losses at extremely low temperatures.

The design for the 650 superconducting magnets of the HERA proton ring developed by DESY to the series-production level was an immediate success – so much so, that it has meanwhile been adopted worldwide. HERA's superconducting magnets operate at a temperature of minus 269 degrees Celsius – one degree above the deep-freeze temperature of outer space. To keep things properly cool throughout the 6.3-kilometer length of HERA, DESY built what was then, in 1986, Europe's largest refrigeration plant. Inside the 2500-square-meter hall, helium gas is cooled until it condenses into a liquid, which is fed into the HERA ring. Here it flows through the magnets, bringing them down to their operating temperature. As far as Europe's industry was concerned, the construction of HERA was a unique opportunity. For the first time, companies were able to gain experience of superconductivity and low-temperature technology on a large scale.

A tremendous multicultural event

HERA's construction was a tremendous multicultural event: a total of 11 countries contributed to the construction of HERA – a first in the history of particle research. Previously it had been common practice to build the massive detectors within the framework of an international collaboration. The accelerators themselves always remained the responsibility of the host institute. However, the international interest in HERA was so great that institutes from France, Italy, Israel, Canada, the Netherlands and the USA supplied and paid for major parts of the facility or conducted important tests. Great Britain, Poland, the then Czechoslovakia, Switzerland, the People's Republic of China and German institutes from the GDR and the FRG sent specialists to assist with the work.

No fewer than 45 institutes and 320 companies (with contracts worth over 25 000 euros) participated in the construction of the facility. In total, more than 20 percent of the funds required for HERA came from abroad. The same holds true for around 60 percent of the four HERA experiments. This "HERA Model" of international cooperation worked so well that it now serves as a role model for large international research projects.

An exciting weekend: first electron-proton collisions at HERA (19.10.1991)

MICRO LAB.

Huge detectors and the world's smallest laboratory

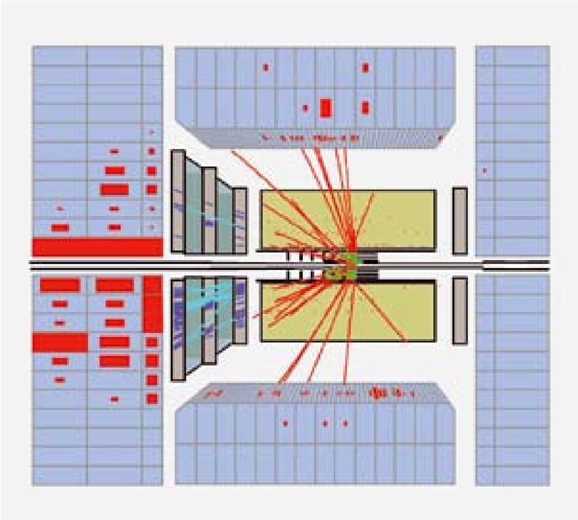
The 6.3-kilometer-long HERA storage ring at DESY is the only one in the world in which different types of particles – here protons and electrons or their antiparticles, the positrons – are accelerated separately and then brought to collision. In such electron-proton collisions, the proton acts as a microscopic laboratory in which various problems of modern particle physics can be investigated in detail. As a super electron microscope, HERA provides physicists with the world's sharpest view of the proton. Through the HERA experiments, they can precisely investigate the inner structure of the proton and the fundamental forces of nature.

The sharp eyes of HERA

The HERA storage ring passes through four immense underground halls, one at each point of the compass. Here, seven stories below the earth, are the detectors used by international research teams to investigate the most minute building blocks of matter. The huge detectors were in operation until mid-2007, and between them they have recorded a gigantic amount of data. Active data taking has now been completed, but the HERA experiments are continuing: the evaluation of the data will be providing exciting insights into the inner structure of the proton and the fundamental forces of nature well beyond 2010.

In 1992, the first two HERA experiments went into operation: H1 in the North Hall and ZEUS in the South Hall. Both experiments observe 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 has been located in the East Hall since 1995. It uses the HERA electron beam to investigate the intrinsic angular momentum – the spin – of protons and neutrons. From 1999 to 2003, the HERA-B experiment used the proton beam from the storage ring in HERA's West Hall to shed light on the properties of heavy quarks.

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.



A flood of images

The detectors installed in the underground chambers of the HERA ring work like giant high-performance cameras. They are as tall as a three-story building, weigh half as much as the Eiffel Tower, and are packed with hundreds of thousands of electronic components. They can register ten million digital images of particle collisions every second. Immediately after the events are recorded, the electronic equipment automatically selects the best fifty images – second by second. This means that in a normal year of operation of HERA, the H1 and ZEUS experiments alone produce more than 100 million pictures of particle collisions, all of which then have to be precisely analyzed using computers. The events recorded by the experiments are evaluated by large international teams of scientists.

HERA: Hadron-Electron Ring Accelerator

Storage ring facility for particle physics
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 tons
> ZEUS experiment
Data taking: 1992–2007; HERA South Hall
Universal detector: 12 m x 11 m x 20 m; 3600 tons

> HERMES beam-target experiment
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 tons

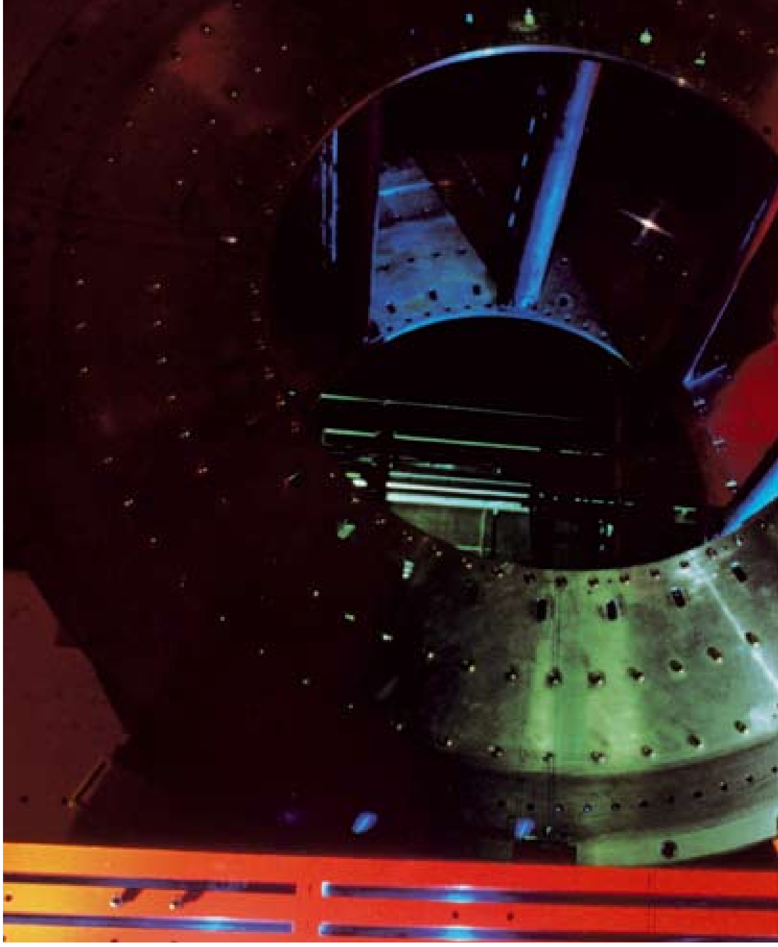
> HERA-B beam-target experiment
Investigation of the properties of heavy quarks
Use of the proton beam
Data taking: 1999–2003; HERA West Hall
Detector: 8 m x 20 m x 9 m; 1000 tons

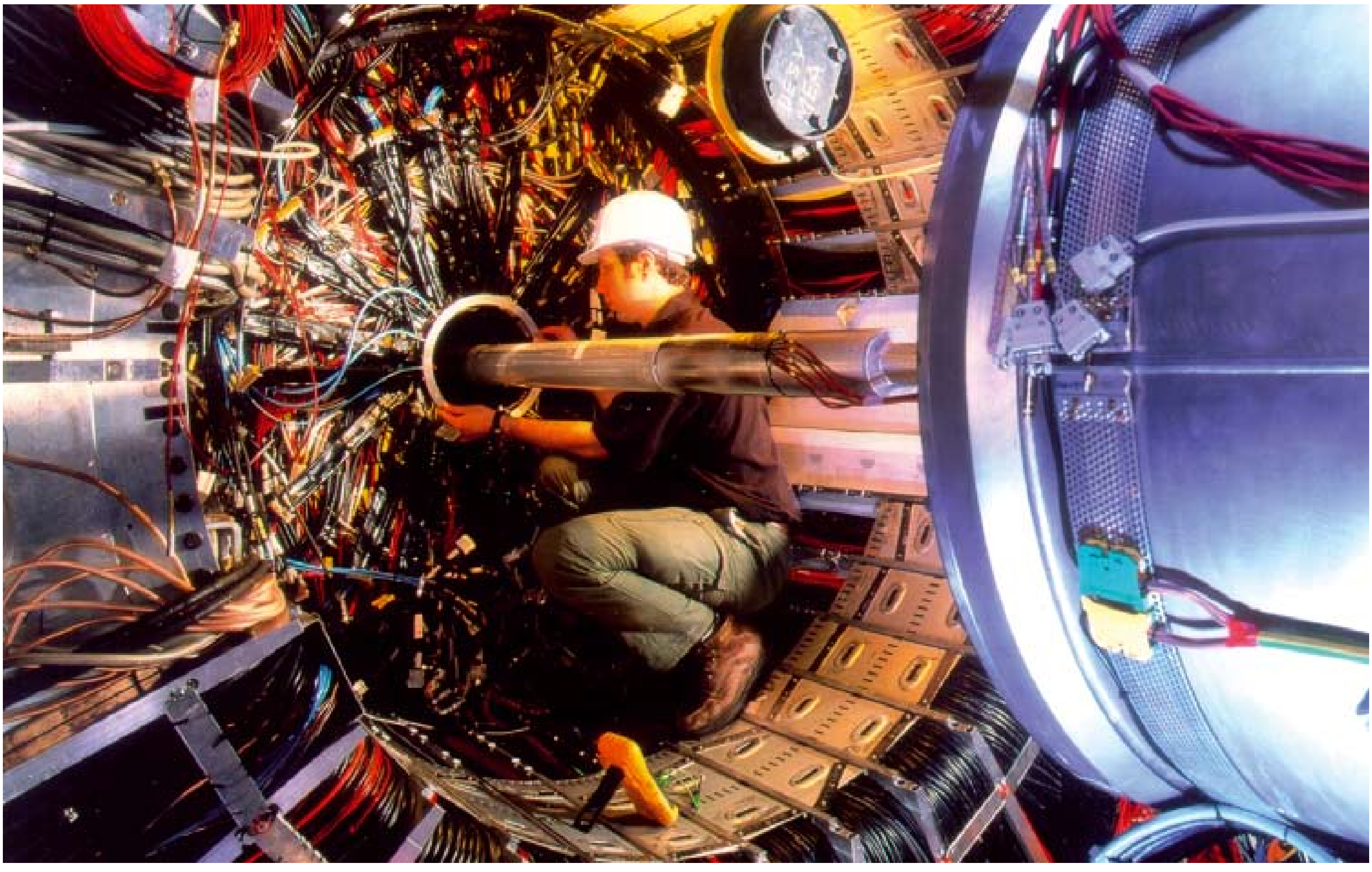
H1 AND ZEUS.

Particles on a collision course

The colliding-beam experiments H1 and ZEUS took data from 1992 to 2007. Right in the center 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 is about ten times greater than that of similar experiments in the past. The super electron microscope HERA thus provides the physicists with the world's sharpest view of the proton's interior.





Quark-gluon soup

More than 30 years ago, physicists discovered that the proton is made up of three quarks. The quarks are held together by the strong force. The gluons, the carriers – or mediating particles – of this force, were discovered at DESY in 1979. For an extremely short time, a gluon can split into a pair consisting of a quark and an antiquark, which can in turn emit gluons, and so on. The proton was thus found to contain a bubbling "sea" of quarks, antiquarks and gluons that spontaneously emerge and disappear again. As the results from H1 and ZEUS show, the inner life of the proton is in fact a lot more turbulent than was previously supposed. The HERA physicists have found many more quark-antiquark pairs and gluons there than expected. And it turns out that the more closely they look, the more particles they see. Quarks, antiquarks and gluons form a simmering "soup" inside the proton. Theoretical and experimental physicists are working together intensely to figure out the recipe.

Back to the primordial force

The H1 and ZEUS experiments impressively confirmed one of the central predictions of the currently accepted particle theory, also known as 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, the weak force is much weaker than the electromagnetic force at low energies. However, the two forces become equally strong at the highest collision energies HERA can provide. H1 and ZEUS were therefore able to provide direct evidence that the two forces have the same origin: the electroweak force, into which the two forces unite at energies not reachable in the laboratory. The HERA experiments were thus able to directly observe the effects of the first step toward the grand unification of the four fundamental forces of nature.

HERA and the Nobel Prize

H1 and ZEUS have enabled the physicists to precisely measure the strength of the strong force acting between the quarks. For the first time, a single experiment consistently demonstrated over a wide range of energies that the strength of this force changes. Moreover, it does so in the opposite manner from the other forces of nature: 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 odd behavior of the strong force had been theoretically predicted by the physicists David Gross, David Politzer and Frank Wilczek in 1973 – and their prediction was impressively confirmed by HERA 20 years later. In recognition of their discovery, Gross, Politzer and Wilczek received the Nobel Prize in Physics in 2004.

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.

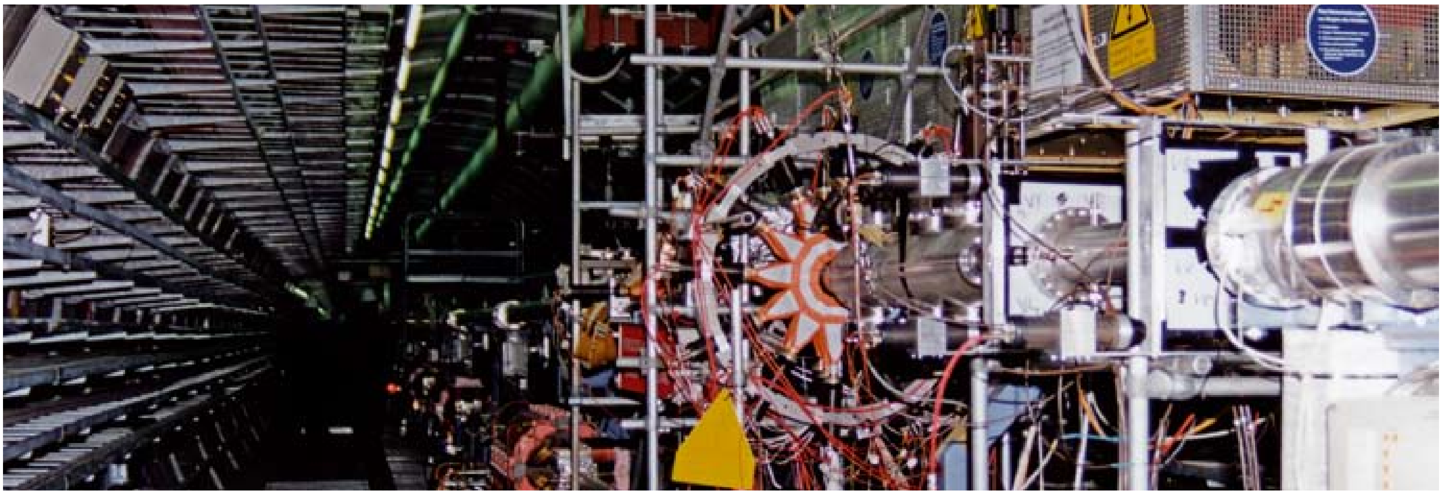
Today, physicists assume that shortly after the big bang, when the whole universe was still a minuscule fireball of incredibly high energy, a single primal force controlled all interactions. Experiments at particle accelerators such as HERA allow us to study forces and particles with the utmost precision. 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.

Eckhard Elsen

The particle physicist Eckhard Elsen was the spokesperson of the H1 experiment at HERA from 1999 to 2002. Although he is now coordinating many of the lines of responsibility for the planned International Linear Collider ILC, he has been "on shift" at H1 until the very last day of the data taking.

With analyses entering the high-energy regime at HERA in late 1996, we observed an excess of events in the mass spectrum that some physicists interpreted as leptoquarks. This would have revolutionized particle physics. We recorded 12 events (with only five expected), and everyone in the collaboration was very excited. We worked at top speed to analyze the data, interpret it and determine the statistical significance of this observation. Everyone contributed, and enthusiasts and skeptics alike worked in a spirit of selfless competition. The team working on our rival experiment ZEUS also observed indications of an excess of events. When we finally issued a careful statement, it caused a sensation in the physics world and the news even made it into the New York Times. Not until a few years later, when we had recorded much more data, were we able to show that "our leptoquarks" were merely a statistical fluctuation. Nonetheless the H1 team benefited from the experience: because of this quirk of nature, we developed an intense collaboration style that still characterizes our work today.

Members of the international ZEUS collaboration in front of the open detector. Complex and costly endeavors such as today's particle physics experiments cannot be undertaken any more on a purely national level. The detectors are designed, constructed and operated by large international teams with members from many different countries.



HERA-B.

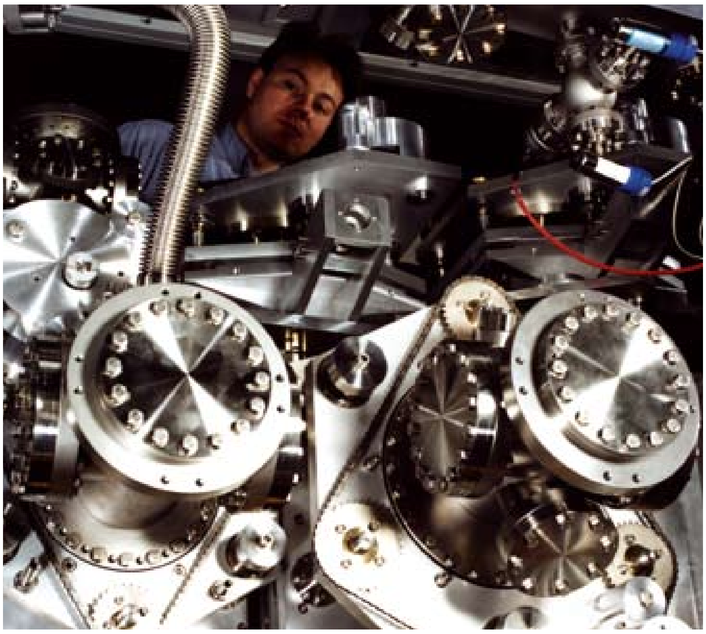
Groundbreaking work

The HERA-B experiment took data from 1999 until 2003 using HERA's proton beam. The protons hit a target of thin wires, thereby producing a cascade of particles. Very rarely, these included a few pairs of particles made of heavy quarks – so-called B mesons, whose decays are recorded by the detector. HERA-B was originally designed to investigate the question as to why the universe is composed primarily of matter, although the big bang produced matter and antimatter in equal quantities. This puzzle may be studied particularly well using B mesons.

To study this question, the particle physics centers KEK in Japan and SLAC in the USA built specialized electron-positron storage rings (so-called B factories) with one detector each. DESY decided to use HERA's proton beam and to build the HERA-B detector. This was quite a technological challenge because, compared to the electron-positron detectors, not a single prototype existed for HERA-B. Therefore completely new methods of detection had to be developed and tested. In particular, it was necessary to not only come up with detector components with unprecedented radiation hardness, but also develop an electronic data acquisition system capable of dealing with a flood of signals every second that is as large as all the information passing through Deutsche Telekom's entire network.

In the year 2000 it became evident that the experiments at the two B factories would reach their goal more quickly. The HERA-B group therefore decided to use their detector to investigate other physics questions, for instance how particles made of charm quarks are produced within atomic nuclei and how they interact with nuclear matter. The developments achieved for HERA-B are nonetheless pioneering work for future experiments where similar harsh conditions will pertain, e.g. experiments at the LHC proton accelerator at CERN in Geneva.

In the target chamber of the HERA-B experiment, the high-energy protons from HERA collided with thin metal wires, producing a whole cascade of particles. The particle decays the physicists were hunting for are extremely rare, however. The detector therefore had to process a tremendous amount of particle tracks before one of these decays occurred. Because of this huge particle flux, the radiation hardness of the detector components and the electronic data acquisition system had to meet extremely high technical standards.

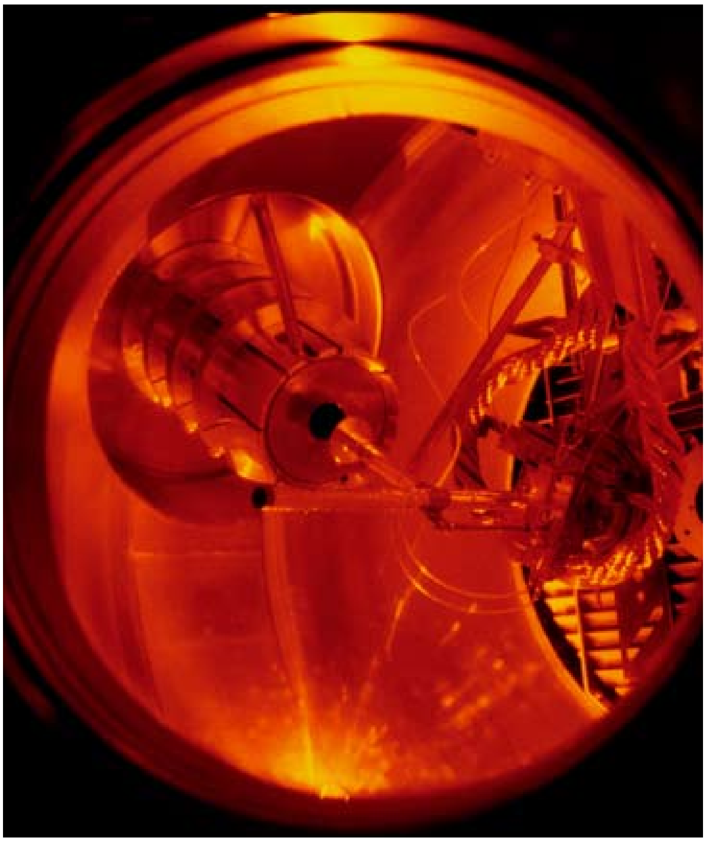


HERMES.

The right spin

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, they 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.

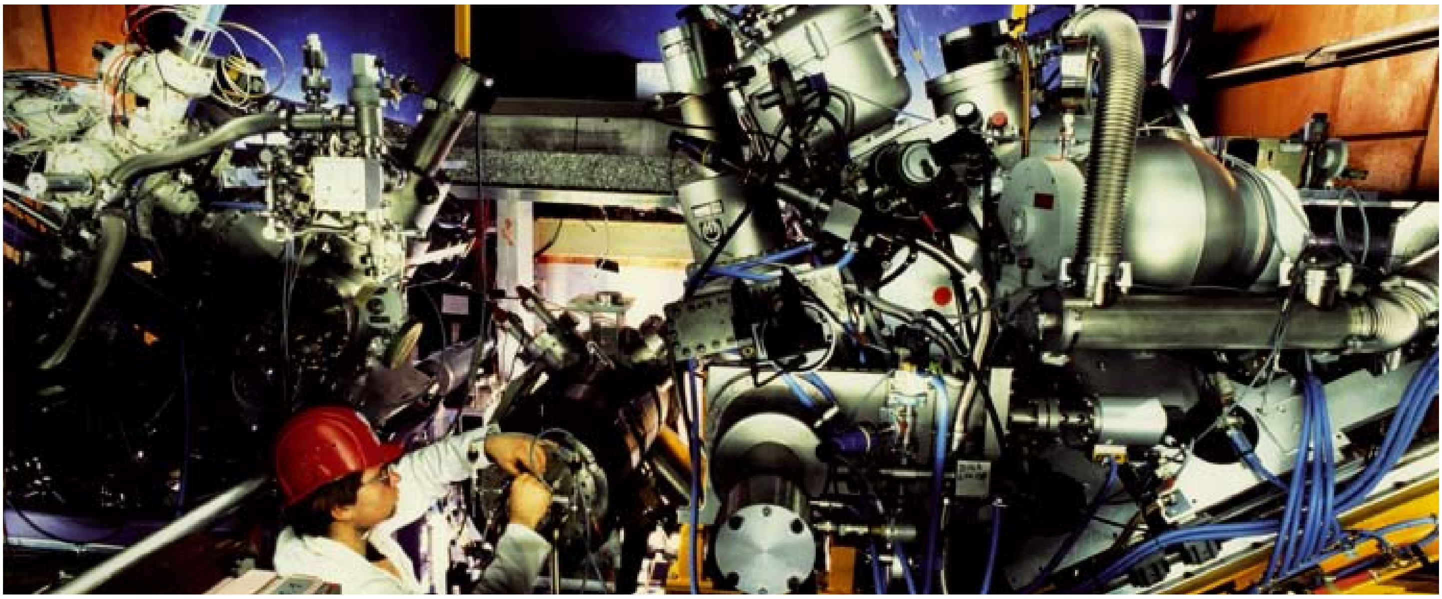
Scientists working on HERMES observe what happens when electrons from the HERA storage ring fly through a gas-filled cell and collide with the atoms of that gas. The key feature is that both the electrons from HERA and the gas atoms are polarized, i.e. their spins are aligned in a specific direction. 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.



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.

The spin puzzle

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. HERMES can lend a hand here. The experiment's special concept enables physicists to separately measure the contribution made by each different type of quark to the total spin. In addition, HERMES is among the first experiments in the world that delivered direct evidence of gluon spin. The results yielded so far show that the quark sea makes a minimal contribution to the overall spin of a nucleon, while the gluons also seem to add little to the total. This is an important milestone on the way toward the solution of the spin puzzle – for it means that not only the spin of the quarks and the gluons but also their orbital angular momentum must play a major role in causing the spin of the nucleon. The latest research carried out at HERMES therefore focuses on this issue.



Assembly work on the target chamber of the HERMES experiment: Inside this chamber, the polarized high-energy electron beam of HERA passes through a gas-filled cell. Here, the particles collide with the protons and neutrons in the atomic nuclei of the gas, which are polarized as well. The reaction products are then detected in the HERMES spectrometer (in the background behind the target area). To the left of the target chamber is the atomic beam source, to the right a polarimeter used to measure the polarization of the gas nuclei.

Elke Aschenauer

Elke Aschenauer, a particle physicist, has been working on the HERMES experiment at HERA since 1996 and was its spokesperson from 2003 to 2006. Even though she is now leading a new experiment at Jefferson Lab in the USA, she says she's „of course still a member of the HERMES team."

What I especially like about HERA is the pleasant atmosphere; we're almost like a big family. Academic titles are much less important than skills and experience, and that has opened up opportunities for many doctoral students and postdocs that they would never have had at other experiments. At times there wasn't a single professor on the HERMES management team and nobody at the experiment was older than 40! That's another indication that there's always an opportunity for young people at HERMES.

HERA was the first project to offer the opportunity to experiment with polarized positrons and electrons at high energies. Our biggest challenge at HERMES was the attempt to measure all of the components of the nucleons' spin. One of our most exciting results was the set of measurements of the quarks' contribution to the spin of the nucleons, which we were even able to break down according to the different types of quarks. I think it's especially impressive that a lot more was accomplished at HERMES than we had ever planned. Thanks to our findings, we have made a major impact on the physics programs of other experiments, and we will continue to do so through our data evaluation in the future. That's why I'm eagerly anticipating all the findings we still don't really have a grasp of yet – but I'm sure there will be some real eye-openers.

SCALING THE PEAKS.

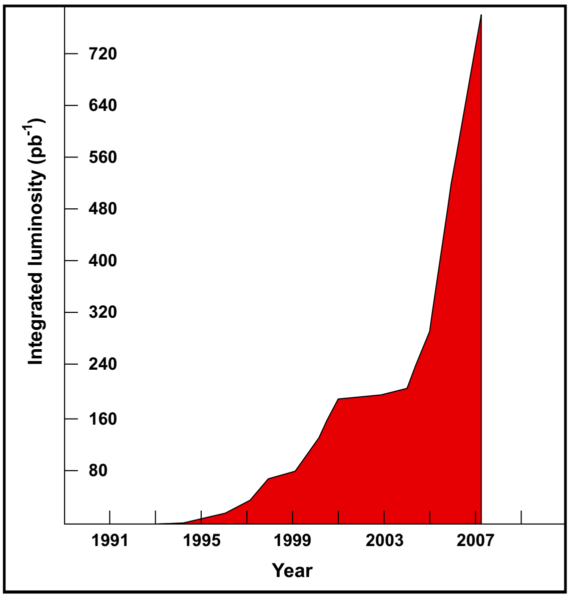
At the top of the luminosity peak

HERA underwent extensive remodeling between September 2002 and May 2001. The purpose of these ambitious alterations was to increase the “hit rate” (luminosity), i.e. the number of particles that collide with one another, by a factor of four. By providing the experiments with access to rare processes, this upgrade thus further sharpened HERA’s gaze on particles and the forces acting between them. Working together, the accelerator crew and the experiment teams mastered all the challenges posed by the upgrade and helped HERA’s luminosity soar to previously unreached heights.

Upgrading for more power

A total of 120 technicians, scientists and engineers worked for nine months on the conversion of HERA. Altogether, 480 meters of vacuum system had to be replaced, and almost 80 magnets were newly designed and fitted, each of which measures between one and four meters and weighs up to seven metric tons. The new magnets reduced the cross sections of the particle beams accelerated by HERA immediately before their collision to a third of their previous size – i.e. from one hundredth of a square millimeter to just three thousandths of a square millimeter. This level of precision required an extensive remodeling of the two interaction zones where the particles collide. The reduction of the beam cross sections considerably increased the probability that the electrons and protons accelerated in HERA would actually collide. As a result, the particle physicists were able to observe even rare processes with a high enough frequency to make their observations statistically valid. However, the flood of uninteresting processes increased as well. HERA’s detectors, which are as large as houses, were therefore also technically improved so that they could more quickly and effectively assess which particle interactions are really interesting.

Another innovation opened up many promising research perspectives for the HERA physicists: after the upgrade, not only the HERMES experiment but also the H1 and ZEUS experiments were able to use polarized electrons for their studies. For this purpose, the north and south sections of HERA were equipped with new spin rotators – sophisticated magnet systems that flip the spin of the electrons into their direction of flight; in technical terms, the particles are “longitudinally polarized.” Thanks to this polarization, the physicists working on H1 and ZEUS were able to look closely at previously inaccessible aspects of the proton’s structure.



Hitting new heights: The luminosity integrated over the operating time of HERA demonstrates the excellent performance of the storage ring facility.

A difficult start

It takes more than just the push of a button to commission a machine that is as technically complex as HERA, with its two accelerator rings, four experiments and thousands of corresponding high-tech components. When an accelerator facility is new or has been extensively remodeled, it often takes weeks

or months of meticulous adjustments, optimizations, setbacks and advances before the accelerator crew can routinely create ideal conditions for all the experiments.

Accordingly, successfully recommissioning HERA after its major luminosity upgrade was an extreme challenge. When the accelerator was switched on again, unexpectedly severe backgrounds made it almost impossible for the H1 and ZEUS collider experiments to take data. Close collaboration between the HERA machine crew and the experiment teams, aided by external and internal advisory committees, allowed one problem after the other to be identified, understood and solved. In the process, changes were made to the beam collimation system, the vacuum system and the detectors. Finally, early in 2004, the improvements were such that H1 and ZEUS were able to take data at the originally planned HERA beam currents.

HERA flying high

From then on, all systems were go. The HERA machine crew could concentrate on steadily increasing the beam currents, while the experimenters could focus on taking data efficiently. At the beginning of the summer shutdown in 2004, HERA had already exceeded the highest luminosity delivered during its first phase of operation, and it had become the first storage ring in the world to provide longitudinally polarized high-energy positrons in colliding-beam mode. In 2005, the specific luminosity increased considerably beyond the design value. Thanks to their untiring optimization work, the HERA crew was able to improve the facility's availability, peak luminosity and background conditions year by year and thus ensure ideal measuring conditions at highest luminosity for the HERA experiments in both positron and electron operation.

Ferdinand Willeke

Ferdinand Willeke, known to his colleagues as "Mr. HERA," has headed the MHE group at DESY, which is responsible for operating the facility, since 1994. In summer 2007 he moved to Brookhaven National Laboratory in the USA, where he will be in charge of the accelerator systems for the light source NSLS-II.

To provide luminosity for the experiments, we have to master challenging accelerator physics issues and complex operating processes at HERA and the entire accelerator chain. Our biggest challenge is to

organize everything so that HERA runs reliably, efficiently and without interruptions. We can be proud that all processes at HERA have run very well. But from time to time we had to cope with a dry spell, for example when electrons started attracting dust particles. To solve that problem we installed a completely new vacuum pump system. And after the luminosity upgrade, we had background problems that made it necessary to improve the collimators in the H1 and ZEUS detectors. However, the luminosity operation at HERA was extremely successful, considering the reservations people initially had concerning operations with such different types of particles.

I think that all of the groups and individual colleagues who participated in the experiments at HERA can be proud that they succeeded in operating a facility as complex as HERA with such tremendous efficiency: HERA achieves up to 80 percent of the theoretically possible value! The success of a facility like HERA is the result of many small forward steps distributed over the past 20 years. Mastering each of these steps, such as the first stored beam and the first luminosity, is a success that is a pleasure to think back on.

WORLD VIEW.

HERA makes physics history

The simmering particle soup in the proton, the running coupling constant of the strong interaction, and the connection between the electromagnetic and weak force – all of these deep insights provided by HERA into the microcosm have found their way into the physics textbooks. The journey of discovery is far from over, however. Whereas the analyses carried out to date have illuminated many individual aspects of the sub-atomic world, the evaluation of all the data recorded will ultimately provide a precise and comprehensive picture of the proton, whose theoretical interpretation still presents several challenges.

HERA: a precision machine

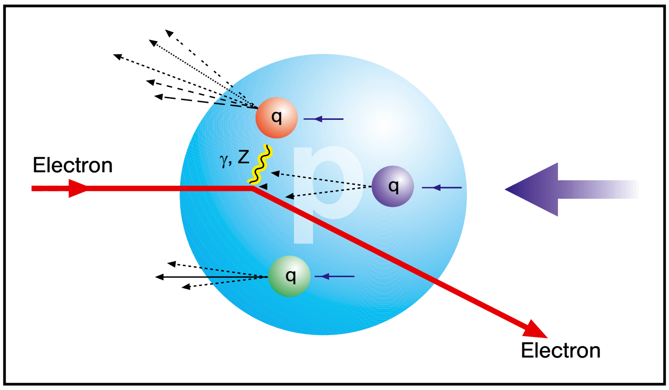
The Hadron-Electron Ring Accelerator HERA is unique. It is the only accelerator worldwide in which tiny electrons collide with protons, which are 2000 times heavier, at the highest energies. Here, the electron acts as a point-like probe that “illuminates” the interior of the proton, without participating itself in the strong interaction. The strong force controls the interactions between the quarks and gluons, the building blocks of the proton. HERA was designed to precisely measure the internal structure of the proton and the forces that reign there – particularly the strong interaction. As the physicists say: HERA is a “precision machine for QCD” – a super electron microscope for studying quantum chromodynamics, the theory of the strong interaction.

The electron’s antiparticle, the positron, is also used as a probe at HERA. Moreover, since the facility’s upgrade in 2000-2001, it has become possible to longitudinally polarize the electrons and positrons – in other words, set their spin in either the direction of flight or the opposite direction – not only for the HERMES experiment but also for the H1 and ZEUS collider experiments. As a result, physicists at HERA can now conduct their research with an extensive variety of tools. In fact, they have all the instruments they need to study the most diverse aspects of the proton and the forces of nature.

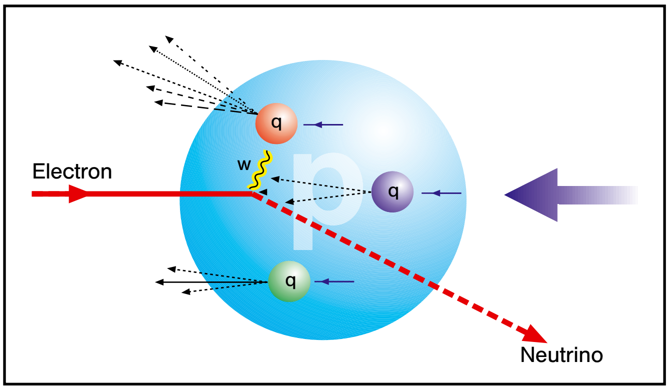
Thanks to the use of the point-like electrons and positrons as probes, HERA achieves a high level of precision for investigations into the strong force. This is because these particles interact with the quarks in the proton via the electroweak force and thus remain unaffected by the strong interaction. In other words, the electrons and positrons act as neutral observers with regard to the strong force. This offers a key advantage over what will soon be the world’s most powerful accelerator – the LHC proton-proton collider at the CERN research center in Geneva. Although the LHC’s probes – the protons – have a much higher energy than those at HERA, they are held together by the strong force. This makes it much more difficult to use them to resolve structures in the proton. The results achieved at HERA, many of which are already part of the basic knowledge presented in physics textbooks, will therefore remain valid and unchallenged for quite some time.

Particle reactions at HERA: neutral current and charged current

When an electron strikes a proton in the H1 or ZEUS detector, it can collide with one of the quarks (q) from which the proton is formed. The electron then transfers energy and momentum to the quark by emitting either a photon as the carrier of the electromagnetic force or a Z or W particle as a carrier of the weak force. The struck quark is ejected from the proton, producing a particle bundle, or jet. The two remaining quarks continue to travel in their original direction and also produce particle jets.



Should the electron emit a photon or a Z particle (top) during the collision, the electron itself is deflected and becomes visible in the detector. Because the transferred force particles are neutral, this type of reaction is also known as a "neutral current". If, in contrast, a W particle is transferred (bottom), the electron is transformed into a neutrino, which passes through the detector without a trace. This reaction is known as a "charged current", due to the presence of a charged force particle.



Martin Berg

Martin Berg is an expert on emptiness: a vacuum technologist, he joined DESY in 1983 and has worked at HERA throughout his entire career. His next project will be PETRA III.

I still vividly remember our Open Day in June 1986. My daughter Sophie was just four weeks old, and despite my wife's vehement protests I brought Sophie down with me in her carrycot to HERA's West Hall, which at the time was just a huge underground excavation. Over the years, my family has grown up and HERA has also grown older. I'm a bit sad that we had to switch it off. HERA was a big milestone for DESY, not only because all of the groups connected with it worked together so harmoniously and effectively, but also because of the outstanding science we were doing. I hope that the scientific findings coming out of HERA will receive the attention they deserve and that particle physics will continue to thrive at DESY.

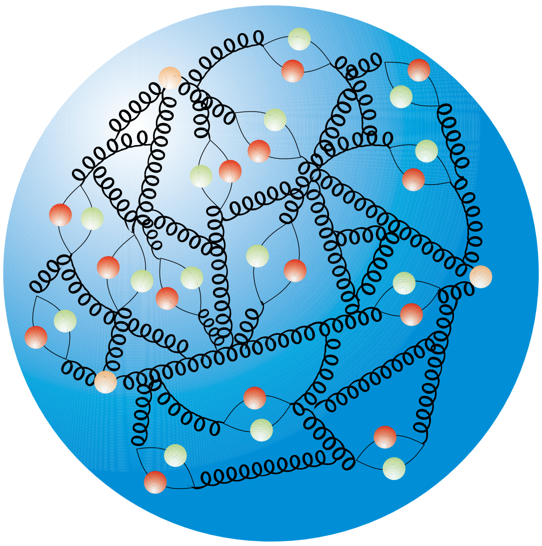
INNER STRUCTURE.

Insights into the depths of the proton

Anyone wishing to understand how the strong force works has to first understand the structure of the proton. That's because protons are made up of quarks and gluons which are subject to the strong force. What's more, the energy contained in the field of these particles determines the proton's mass. That makes protons ideal laboratories for studying the strong force.

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. When HERA started up in 1992, scientists only had vague notions of what they expected to find in the depths of the proton. It was known that the quarks in the proton emit gluons – the particles that stick the quarks together – and that these gluons in turn create other gluons or pairs of quarks and antiquarks. However, it was generally assumed that apart from the three valence quarks that are responsible for the charge of the proton, there were only very few quark-antiquark pairs and gluons in the proton. With the help of HERA's extremely high energy, the H1 and ZEUS experiments pushed forward to increasingly shorter distances and smaller momentum fractions and measured the structure function F_2 over a range that spans four orders of magnitude of the kinematic parameters x and Q^2 – two to three orders of magnitude more than were accessible to earlier experiments (see box). What the physicists discovered during these tests came as a great surprise: the HERA measurements show that the interior of the proton is like a thick, bubbling soup in which gluons and quark-antiquark pairs are continuously emitted and annihilated again. The smaller the momentum fractions x are to which the HERA microscope is set, the more quark-antiquark pairs and gluons are seen in the proton. This high density of gluons and quarks in the proton, which increases at small momentum fractions x, represented a completely new and until then uninvestigated state of the strong force.

Valence quarks, sea quarks and gluons

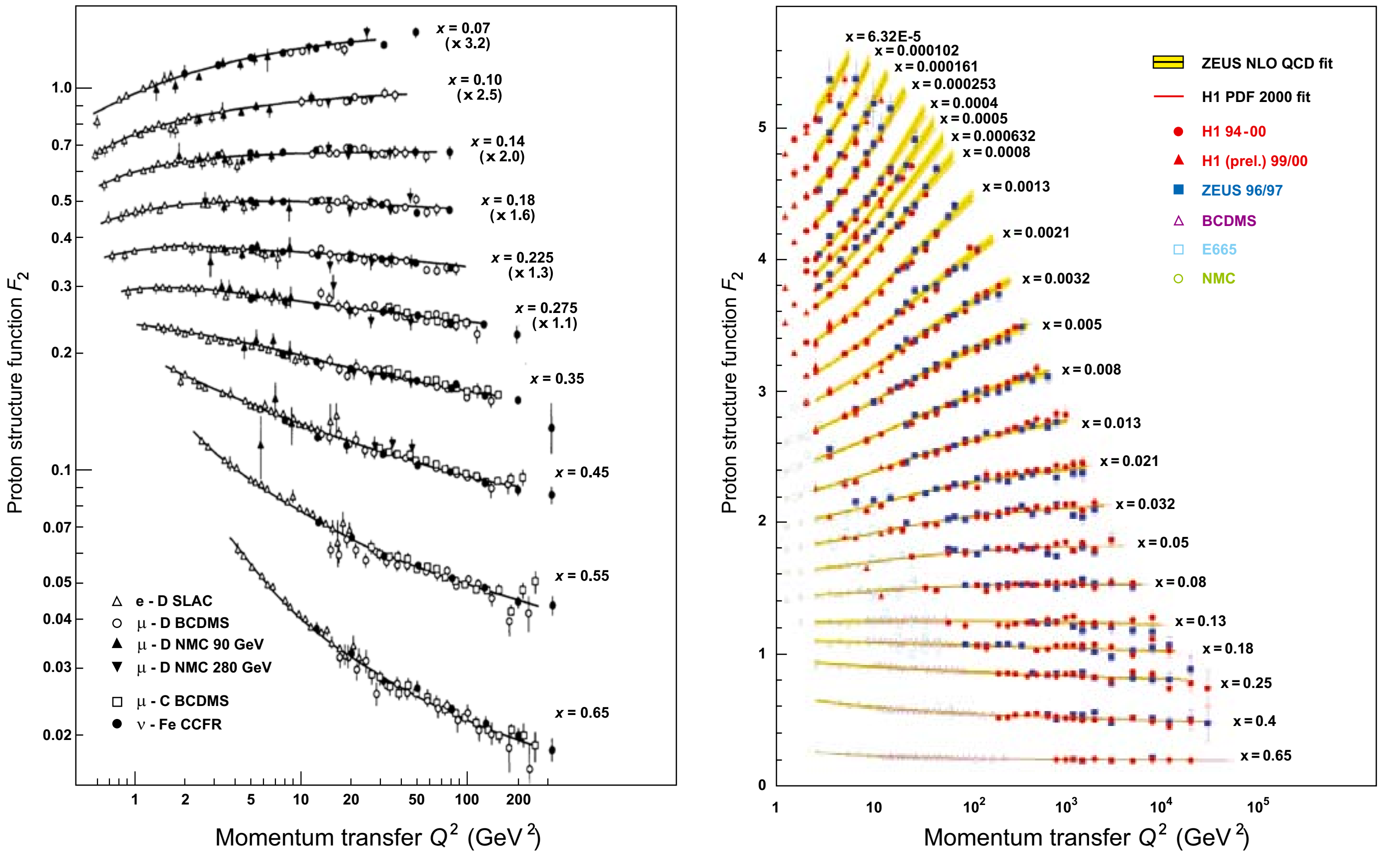


The super electron microscope HERA makes the proton's detailed structure visible. There are three valence quarks inside the proton, which are bound together by the exchange of gluons. Quantum theory allows the gluons to transform into quark-antiquark pairs for an extremely short time. Alongside the valence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

The kinematic variables x and Q^2

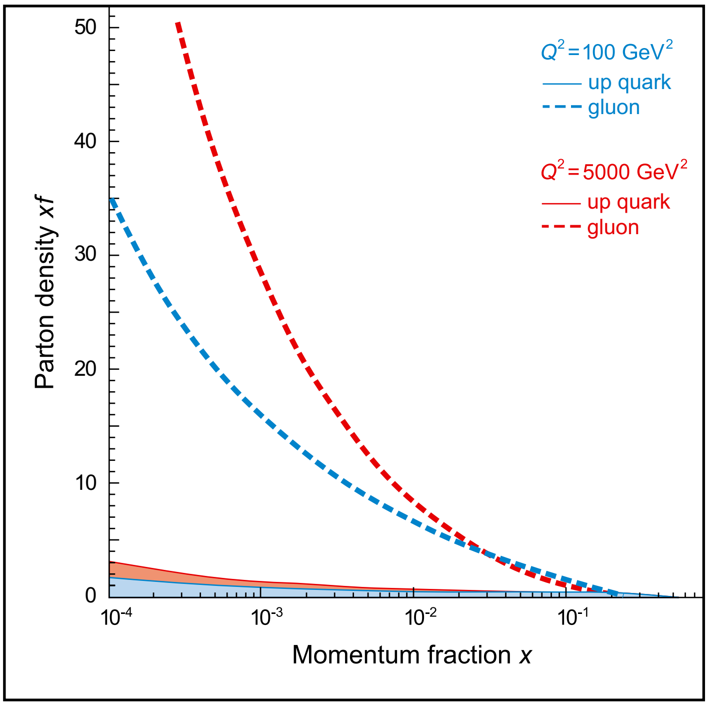
- **Momentum fraction x: the fraction of the proton's momentum carried by the quark with which the electron collides.**
- **The momentum transfer Q^2, also called the resolution parameter, is the square of the momentum transferred in the collision between the collision partners. It is a measure of the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

The structure function $F_2\ (x,Q^2)$ of the proton as a function of the resolution Q^2 for various momentum fractions x. Particularly noticeable is the rapid increase of F_2 with Q^2 at decreasing values of x. A comparison of the HERA measurements (right) with the data from 1992 (left) shows the considerable increase in precision and the accessible kinematic range.



Nobel Prize Laureate Frank Wilczek on the HERA measurements

"The most dramatic of these specific experimental tests, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later."



Parton density distributions of the up quarks and gluons as a function of the momentum fraction x at two different resolutions Q^2. The gluon density increases dramatically with improved resolution (higher value of Q^2). (The down quarks behave similarly to the up quarks.)

Structure functions as a key to the proton

The proton's structure can be described with the help of so-called structure functions, each of which covers different aspects of the interaction between the electron and the proton. Although it is not yet possible to calculate how these structure functions look in detail, scientists have already found out how changes in the resolution change the structure functions. In other words, if the structure function at a particular resolution has been determined in experiments, it is possible to predict, for example, how the structure changes when the resolution is doubled.

The proton's structure is determined by the quarks and gluons (collectively known as "partons"). If the density distribution of the partons is known, this fact can be used to calculate the corresponding structure functions. In experimental physics, however, researchers can only use the opposite approach, in which they measure the structure functions to determine the parton distribution functions (PDFs) that describe the density of the various quarks and gluons in the proton as a function of the momentum fraction x at a particular resolution Q^2.

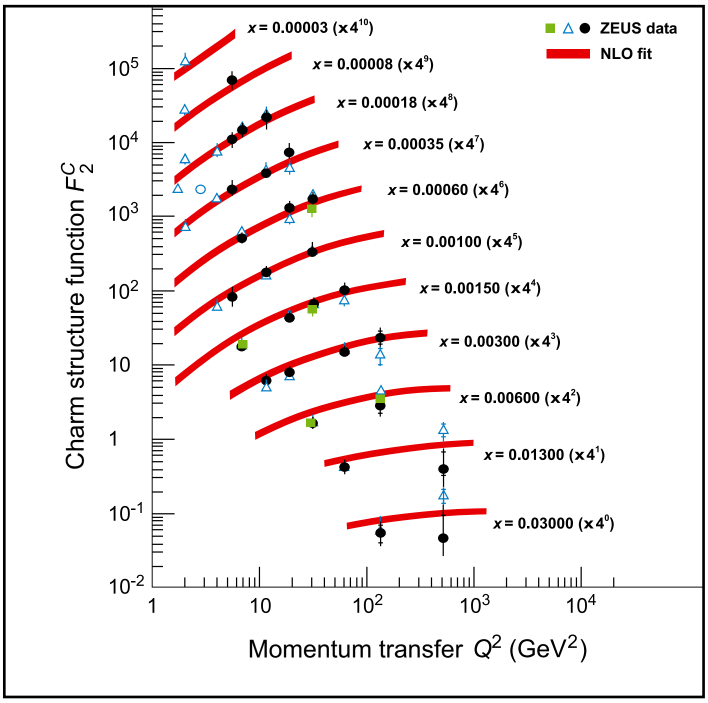
The structure functions listed here apply to neutral current scattering processes, in which a neutral force particle (a photon or a Z boson) is exchanged between the electron and the quark. In this case, the dominant share of all processes is described by the structure function F_2. The charged current scattering processes in which the reaction involves a charged W boson can be described in an analogous manner.

- The structure function F_2 provides insights into the distribution of the quarks and antiquarks in the proton, depending on the resolution Q^2 and the relevant quarks' and antiquarks' momentum fraction x of the proton's total momentum. The structure function F_2 provides an overview of the quarks and antiquarks in the proton, without distinguishing between valence quarks, sea quarks and antiquarks (see box p. 22).

- The structure function $x \cdot F_3$ describes the share accounted for by the weak interaction, and in particular by the interference effects between the photon and the Z boson. This structure function is therefore sensitive to completely different parton combinations than F_2 and thus helps scientists to further resolve the proton's structure.

- The structure function F_L reflects the behavior of gluons when the momentum fractions x are small. If there were no gluons, this structure function would vanish.

HERA is the world's only particle accelerator at which scientists are able to measure all three structure functions in detail. As such, the physicists at HERA have access to a complete set of tools for examining the proton and the forces at work within it.



The structure function $F_2^C(x,Q^2)$ of the charm quark in the proton as a function of the resolution Q^2 for different momentum fractions x. The dependence of F_2^C on x and Q^2 is similar to that measured for F_2, which is dominated by the light quarks.

Charm and other quarks

The structure function F_2 encompasses all types of quarks within a proton: the valence quarks, which give the proton its identity, as well as the large numbers of sea quarks and antiquarks, which are created as virtual quark-antiquark pairs as a result of Heisenberg's uncertainty principle before disappearing again after an inconceivably short period of time. As was discovered by the H1 and ZEUS experiments, the proton not only contains 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 in the proton for the first time and separately measure their structure functions. The results showed that charm quarks account for 20 to 30 percent of the structure function in some areas, while the bottom quarks account for 0.3 to 1.5 percent. It appears that all types of quarks are produced to the same extent at extremely high collision energies, when even the mass of the heavy quarks becomes irrelevant. Once the remaining data have been evaluated, the physicists at HERA will be able to state these results even more precisely. An exact understanding of the mechanisms that generate heavy quarks is particularly important for the physics program at CERN's LHC accelerator.

Following the upgrade of HERA to increase its luminosity, H1 and ZEUS were also able to use longitudinally polarized electrons and positrons for their investigations. This boosted the sensitivity of the two HERA experiments for the structure function $x{\cdot}F_3$, which describes the interference effects between the electromagnetic and weak interaction within the proton. These effects are normally difficult to measure, but their intensity increases with the polarization of the particles, which thus makes them clearly visible. The polarization therefore provided the physicists at HERA with a welcome additional tool for probing deeper into the proton's parton structure.

Shortly before HERA's operating time came to its end, the accelerator was operated for several months at reduced proton energy (460 and 575 GeV instead of the usual 920 GeV). Measurements at different collision energies but under otherwise identical kinematic conditions explicitly filter out the contributions of the third structure function F_L which provides information on the behavior of the gluons at small momentum fractions x. These measurements are without parallel and particularly important for understanding quantum chromodynamics (QCD), the theory of the strong force. Before they had obtained these results, scientists had to use relatively arbitrary assumptions when interpreting measurement data.

CRASH COURSE.

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. In such a situation, you would normally expect a proton to “burst apart” into many new particles. Instead, the proton remains completely intact in approximately 10 to 15 percent of such cases, despite the intensity of the collision. This would be like discovering that no marks or scratching occur in 15 percent of all head-on vehicle collisions!

Such phenomena were familiar at low energies, and were generally described using the ideas of diffractive physics, which had been developed for just that purpose. The phenomenon was explained by means of a so-called 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, which was unsatisfactory from a theoretical point of view, simply did not hold up. For example, in the case of large momentum transfers – in the so-called hard diffraction range – it failed completely. 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 color-neutral, as is observed in the experiment. Could this phenomenon therefore possibly have something to do with the high proportion of gluons in the proton at small x? As soon as a sufficient amount of data on these spectacular events had become available, the experimental physicists from H1 and ZEUS attempted to conduct a structural analysis similar to the one they had carried out for simple electron-proton scattering. The result was clear: the color-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. A comprehensive understanding of QCD should make it possible to explain this measurement data. It is therefore important that the HERA data in this area should be analyzed and evaluated from all conceivable points of view so that the theoretical interpretations can be appropriately assessed.

Colored quarks

In the Standard Model, the strong force is caused by an abstract particle property called color charge. Quarks for instance exist in the colors red, green and blue, antiquarks in antired, antigreen and antiblue. However, only color-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 color and the corresponding anti-color. Only colorless combinations like these exist as free particles – no single-color particle has ever been observed.

Allen Caldwell

Allen Caldwell, particle physicist and director at the Max Planck Institute for Physics in Munich, started working on the ZEUS experiment in 1987, serving as its spokesperson from 1997 to 1999. With his various MPI groups, he is still involved in the HERA physics.

The HERA results are for me truly fascinating – they have led to a radically different picture of matter at short distances. We now see that at short distances and small x, which corresponds to short time fluctuations, the physics is dominated by gluons. The extremely high density of gluons leads to novel and previously unexpected effects, such as a high rate for diffractive processes even at high Q^2. The HERA data is at once simple in its behavior, yet leads to profound questions about the fundamental structure of matter. The theoretical understanding is still in development, but in my estimation will likely result in radically new ways of understanding matter at short distances.

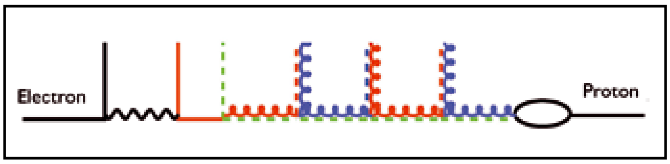
Today, driven by the HERA data, theorists discuss the possible presence of an underlying "color glass condensate" at the heart of all matter. Others discuss the possible deep connection between diffractive processes and gravitational interactions, seeing links between string theories and supersymmetric versions of QCD. The most important results from HERA – the observations of the strong rise of the structure functions at small x and the large diffractive cross section – therefore represent a beginning to a wholly new understanding of nature, and that is truly exciting.

In addition to the continued theoretical developments, ideas are currently under serious discussion for further experimental programs which should extend the reach of the HERA data, and perhaps bring us closer to a new paradigm for understanding nature.

A question of perspective

Electron-proton interactions at HERA can be interpreted in different ways. The standard approach views the electron as a probe that "illuminates" the structure of the proton. However, it is also just as reasonable to regard the electron as the carrier of the structure.

The figure below, for example, depicts the scattering of an electron off a proton at very high energies. The straight line on the left represents the electron, while the oval shape on the right is the proton. Also shown are a photon (wavy line), quarks (red line and green dashes) and gluons (two-colored spirals).



The scattering can be viewed as follows: the electron emits a photon, which scatters off a quark originating from the proton. The quark is the final product in a long chain of virtual emissions consisting primarily of gluons. However, the scattering process can also be viewed in the following alternative manner: the electron emits a photon, which splits into a quark and an antiquark, one of which emits a chain of virtual gluons. One of these gluons then interacts with the proton. It cannot be definitively determined which particle the emission chain belongs to.

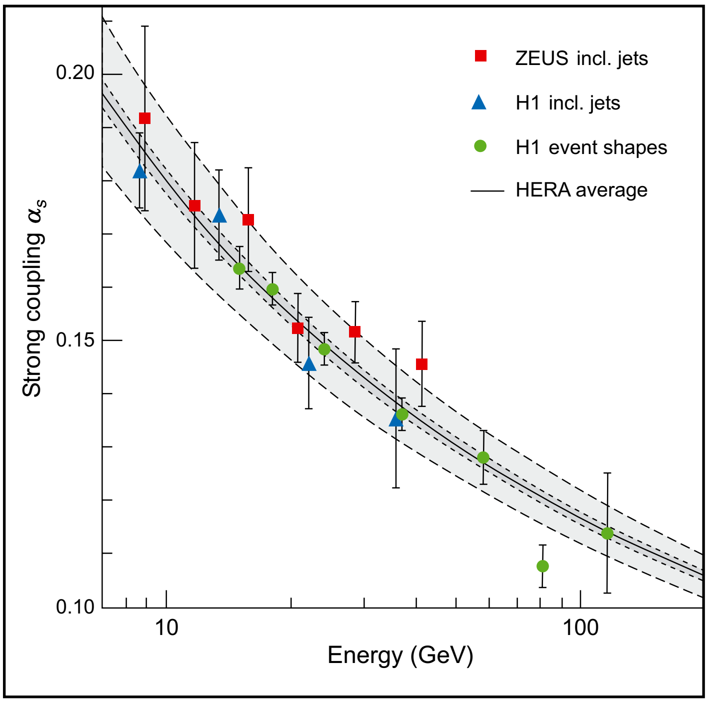
The observation that the parton density changes with increasing energy results from the fundamental properties of the strong interaction during extremely short time intervals – not from the source of the emissions. The sharp increase in the structure functions observed at HERA thus reflects a basic and universal attribute of nature – the "cloud" of virtual quarks and gluons contained in the heart of all matter. There is currently no theoretical understanding of this fundamental structure. Further research in this area could ultimately lead to a revolutionary paradigm shift in the description of the strong interaction.

MEASURING FORCES.

The fundamental forces of nature

The proton lived up to its role as a micro-lab for studying QCD in another area of research at HERA. 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. It is only when the quarks are particularly close together that the force between them is weak. This situation is known as “asymptotic freedom.” As the distance between the quarks increases, the force between them grows ever stronger. 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 behavior of the coupling constant over a broad range of energies in a single experiment. The HERA results thus impressively confirm the behavior 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.

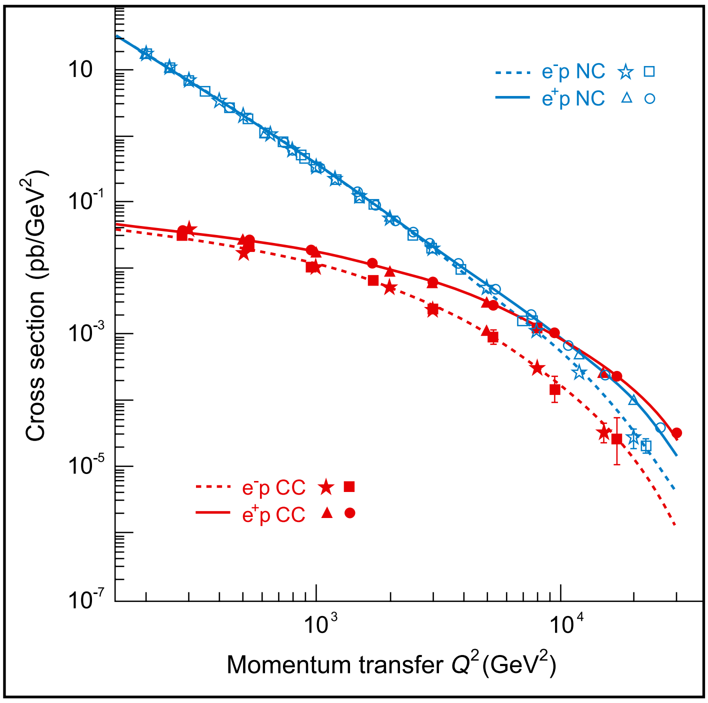


The dependence of the strong coupling constant α_S on the energy compared with the expectation of quantum chromodynamics. At large momentum transfers (short distances), the strong force becomes increasingly weak (asymptotic freedom).

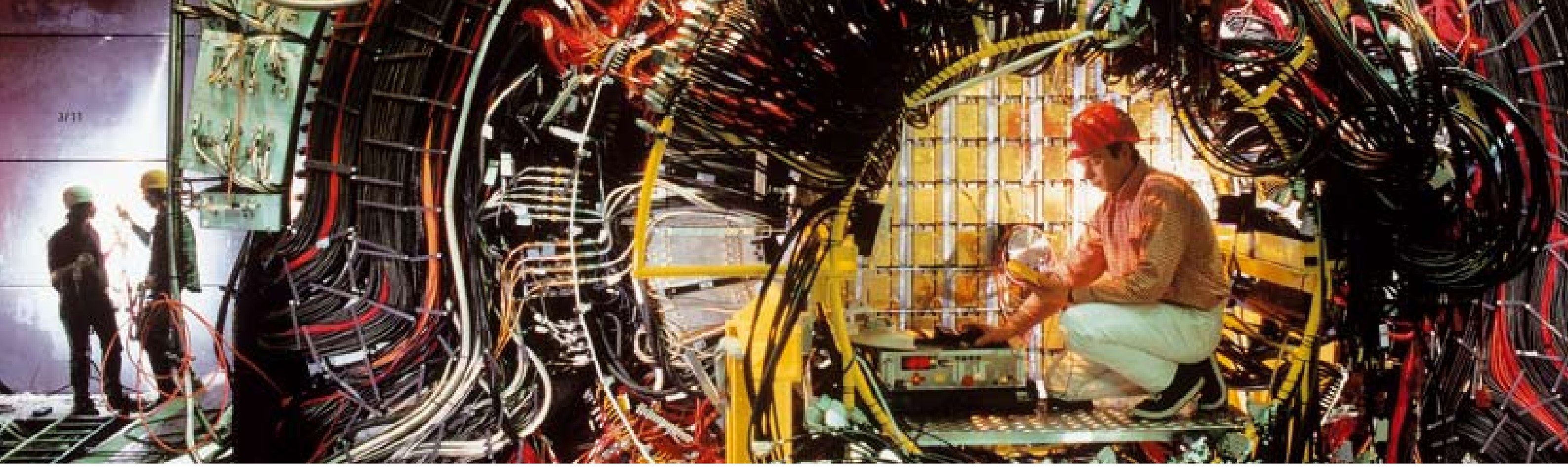
The electroweak force

Although HERA is used mostly for studies of the strong interaction, its high-energy electron-proton collisions also enable scientists to take a close look at other forces of nature. For example, the aim of studying the electroweak interaction in detail formed part of the application for HERA’s approval.

Among other things, H1 and ZEUS were able to measure the frequency with which neutral current reactions (electromagnetic and weak force) and charged current reactions (weak force) occur as a function of the minimum distance of the particles during collisions in the HERA detectors (see box p. 21). At low energies, i.e. large distances, the electromagnetic scattering processes occur significantly more often than the weak ones, because at these distances the electromagnetic force acts much more strongly than the weak force. At smaller distances and correspondingly higher energies, however, both reactions occur at about the same rate, i.e. both forces are equally strong. This behavior is an important property of the electroweak force, which the two forces unite to at very high energies. H1 and ZEUS therefore directly observe the effects of the electroweak unification, which has been theoretically predicted as the first step toward the grand unification of the fundamental forces of nature.



The reaction cross sections of the neutral current (blue, electromagnetic and weak interaction), and of the charged current (red, purely weak interaction), as a function of the momentum transfer Q^2 for electron-proton and positron-proton scattering. The reaction rates become comparable at high momentum transfers.

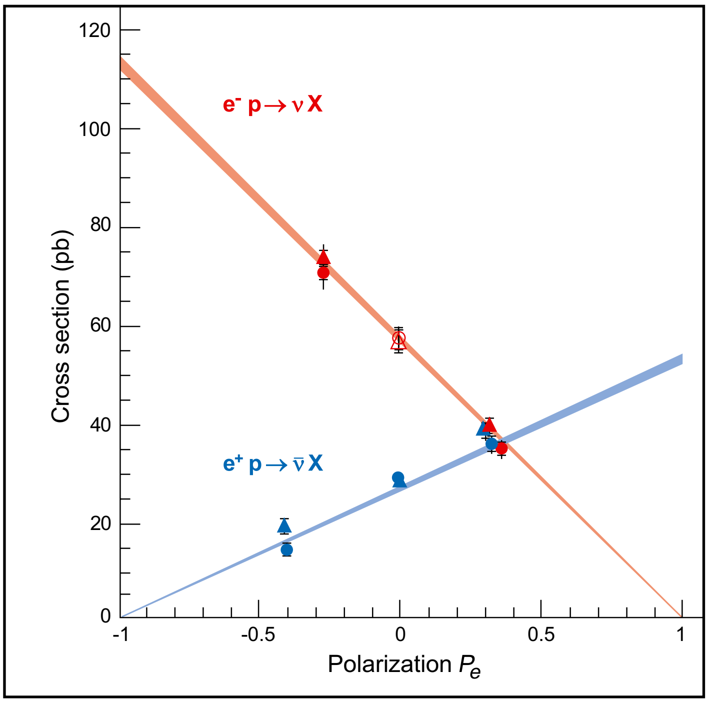


Right-handed neutrinos prohibited

The longitudinal polarization of the electrons in the second phase of HERA operations opened up new possibilities for the study of the electroweak force as well. H1 and ZEUS were, for example, able to measure the charged currents as a function of the various polarization states and thus prove that there is no such thing as a right-handed current in nature, even at the high energies produced by HERA. Because only left-handed neutrinos exist in nature (i.e. polarized in the direction opposite to which they are traveling), the transformation of a right-handed electron (polarized in the direction of flight) into a right-handed neutrino via the weak interaction should be impossible. That at least is what is predicted by the theory of the weak interaction – and the converse behavior had already been demonstrated in earlier neutrino scattering experiments in which a neutrino is transformed into an electron by means of the weak interaction.

Now, using the charged current reactions, H1 and ZEUS observed the complementary process – inverse neutrino scattering (see box p. 21, bottom figure; you see the neutrino scattering when you look at the graph from right to left, rather than from left to right). As the HERA measurements show, the cross section does indeed disappear for right-handed electrons (and, correspondingly, for left-handed positrons as well). The HERA experiments thus impressively confirmed this key prediction of the theory of the weak interaction, even at the high energies at HERA.

During the second phase of HERA operations, the physicists were also able to make initial determinations regarding the coupling of the Z-boson – the neutral exchange particle of the weak interaction – to the up and down quarks in the proton. This initial data supplements the measurements made at the LEP accelerator at CERN, and with additional statistics will serve as a further test of the Standard Model.



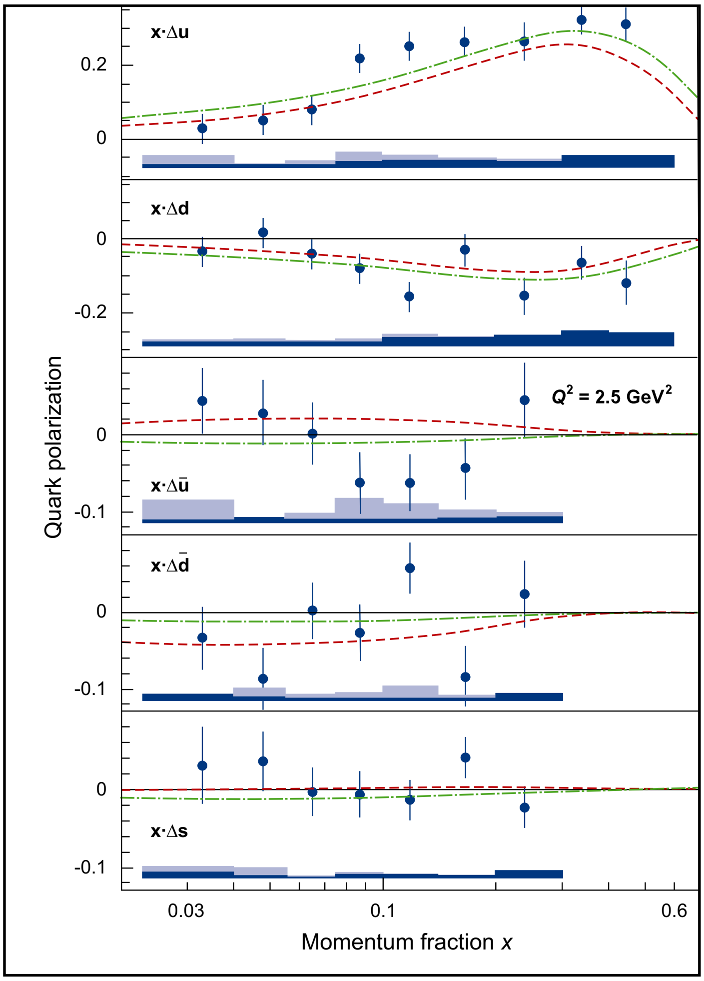
The cross sections for charged current scattering as a function of the polarization of the electrons and positrons. In the case of electrons (red), the reaction rate for negative, left-handed polarization is higher than for positive, right-handed polarization. The event rates then disappear when extrapolating to completely right-handed electrons, $P_e = +1$. The opposite is observed for positrons, with the cross section approaching zero for left-handed polarization.

SPINNING ROUND.

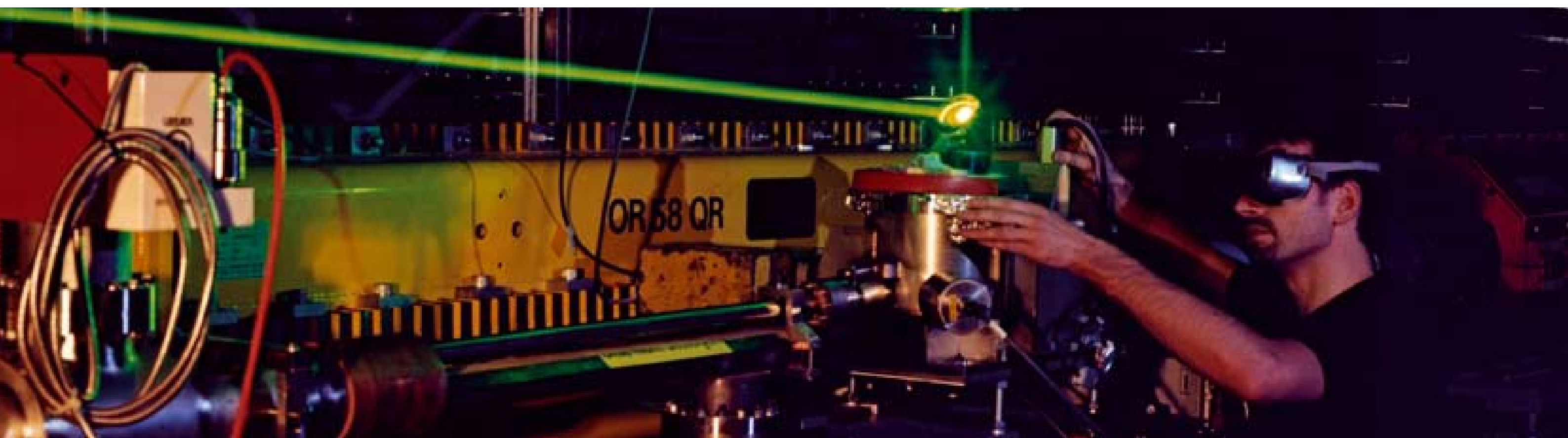
The nucleon spin

Another important contribution to the overall understanding of the proton is made by the third HERA experiment, HERMES, which studies the origin of nucleon spin, i.e. the spin of the protons and neutrons. Experiments carried out at the CERN and SLAC research centers in the mid-1980s had already determined that the three main components of the nucleon – the valence quarks – together account for only around one-third of the total spin. The HERMES physicists attempt to find out where the other two-thirds come from by sending the longitudinally polarized electrons or positrons from the HERA storage ring through a gas-filled cell. There, the particles collide with the gas atoms, which are also longitudinally polarized. Because the type and frequency of the collisions depend on the polarization of the nucleon components, the particle reactions observed enable the scientists to determine where the nucleon spin actually originates from.

During HERA's first operational phase, HERMES impressively completed its first assignment, which was to measure the individual contributions made to the nucleon spin by each of the various types of quark. Using measurements on longitudinally polarized gases, the HERMES physicists provided the world's first model-independent determination of the separate contributions made to the nucleon spin by the up, down, and strange quarks.



Helicity distributions of the up, down and strange quarks as a function of x at a common value of Q^2. The data reveal that while the spins of the up valence quarks point in the same direction as the overall nucleon spin, the down valence quarks carry a spin pointing in the opposite direction. The polarizations of the sea quarks are all consistent with zero.



Assembly work inside the HERMES detector: HERA's polarized electron beam first passes through the target cell located on the right outside the picture. Here, the electrons collide with the gas atoms, which are also polarized. The generated particles and the scattered electron fly through the HERMES detector from the right to the left, and are detected in its various components. Behind the reflecting films on the left and right side of the picture are gas-filled wire chambers used to reconstruct the tracks of the particles. The aluminum-coated films that seal the chambers hermetically are made from Mylar, a material that is also used for spacesuits or emergency blankets, for example.

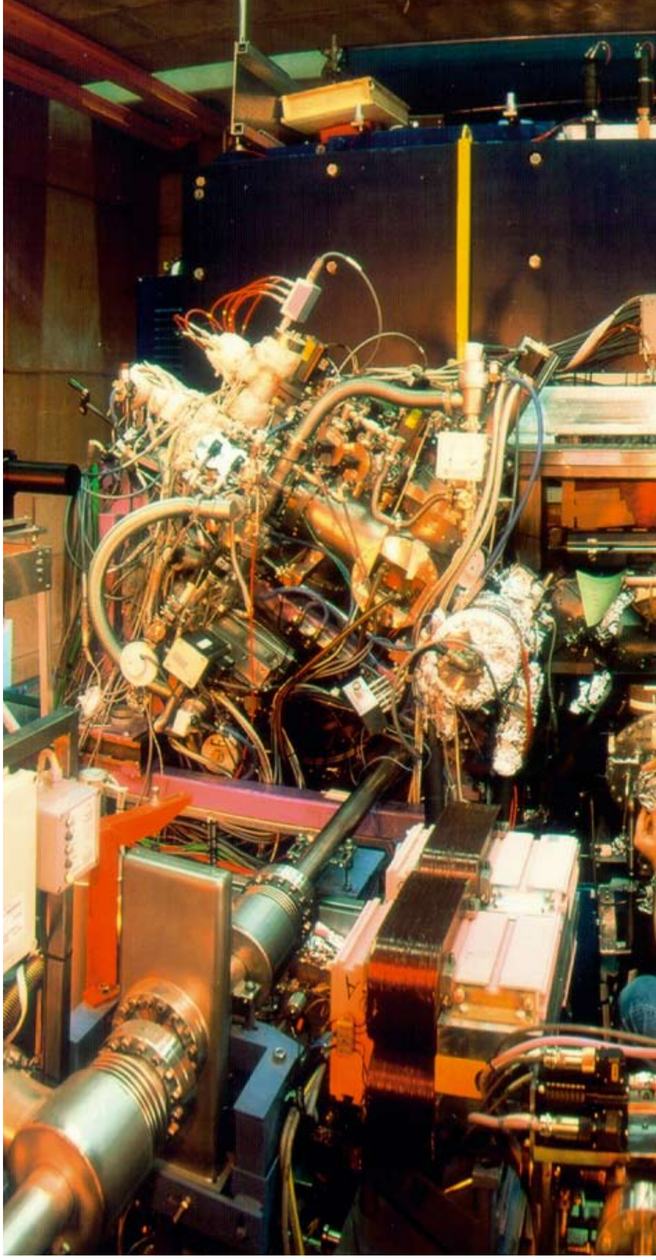
Laser polarimeter in the HERA tunnel: During HERA operation, the green laser beam is directed against the electron beam within the beam pipe in order to determine how well the electrons have been polarized. In this picture, the laser beam is outside the beam pipe so that adjustment work can be carried out.

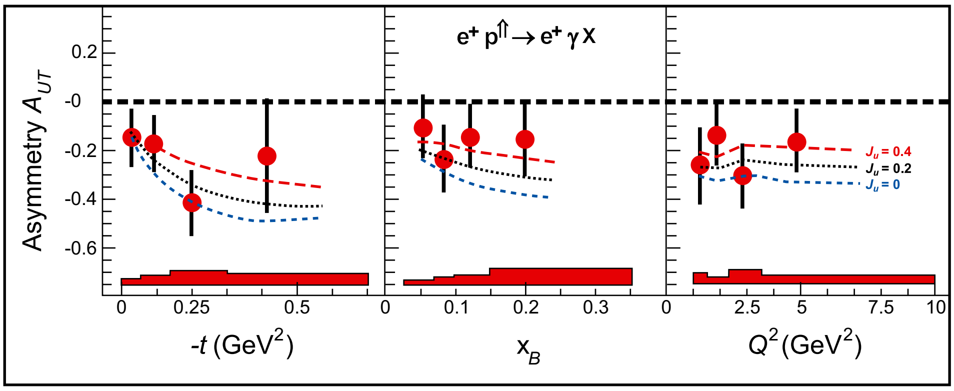
The results reveal that the largest contribution to the nucleon spin comes from the valence quarks. The up quarks make a positive contribution as their spin is preferably aligned with the spin of the nucleon, while the down quarks provide a contribution with opposite sign. The polarizations of the sea quarks are all consistent with zero – an especially important result. Under the assumption that all types of quark behave in the same way dynamically inside the nucleon, previous experiments had led to the conclusion that the strange quarks play a significant, canceling, 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.

The final parts of the spin puzzle

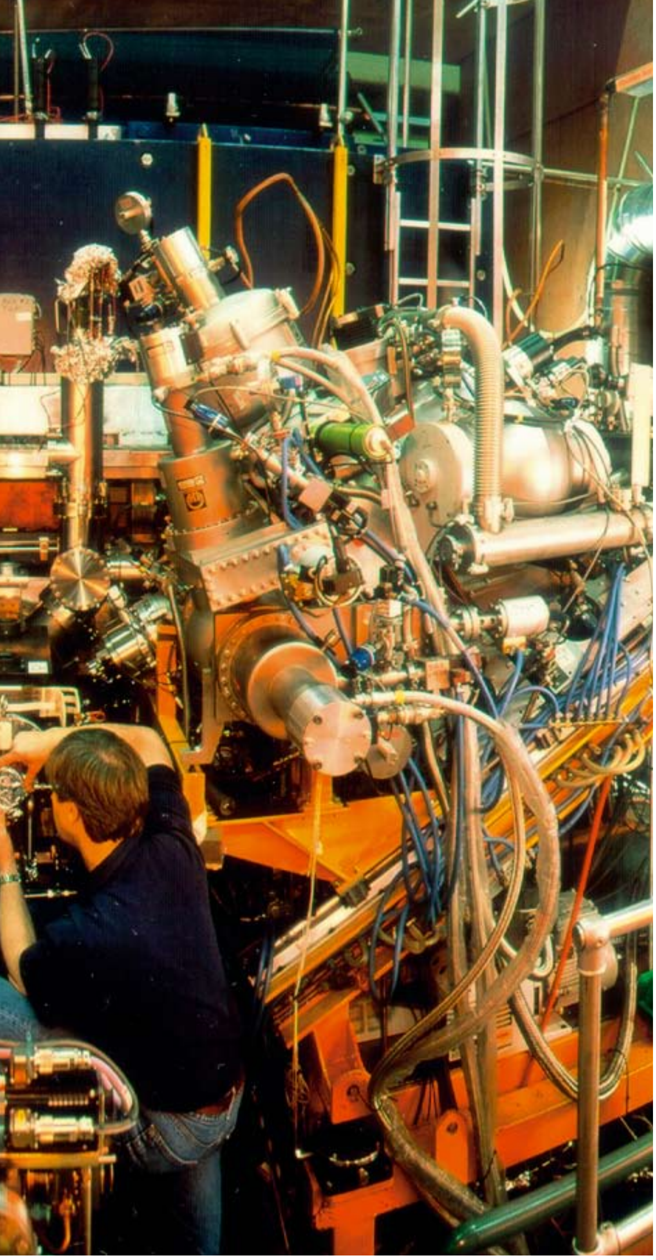
Following their studies of the quark spins, the physicists turned their attention to the gluon spin and the orbital angular momentum of the quarks and gluons, which could also be contributing to the nucleon spin. Here, the HERMES scientists succeeded in making one of the first measurements providing 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 based on the concept of generalized parton distributions (GPD), 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 enables the scientists to study these remaining aspects of the spin puzzle.

Detailed insight is provided here by so-called exclusive reactions in which the nucleon that collides with the electron doesn't fragment but instead remains in its ground state. HERMES makes it possible to take a large number of different measurements with various exclusive final states, with the resulting data providing information on the total orbital angular momentum of the quarks in the nucleon. With the help of deeply virtual Compton scattering (DVCS) – which was experimentally detected for the first time in 2001 by H1, ZEUS and HERMES, as well as by the CEBAF Large Angle Spectrometer at Jefferson Lab – on a transversely polarized target, the HERMES physicists were able to realize a first model-dependent extraction of the total orbital angular momentum of the up quarks. The HERMES team will refine their knowledge of DVCS even further through the utilization of measurements taken with a new recoil detector from 2006-2007. In doing so, they will make a key contribution to improving the models of generalized parton distributions (GPDs) in the hope of being able to identify the total orbital angular momentum of the up quarks in the near future.



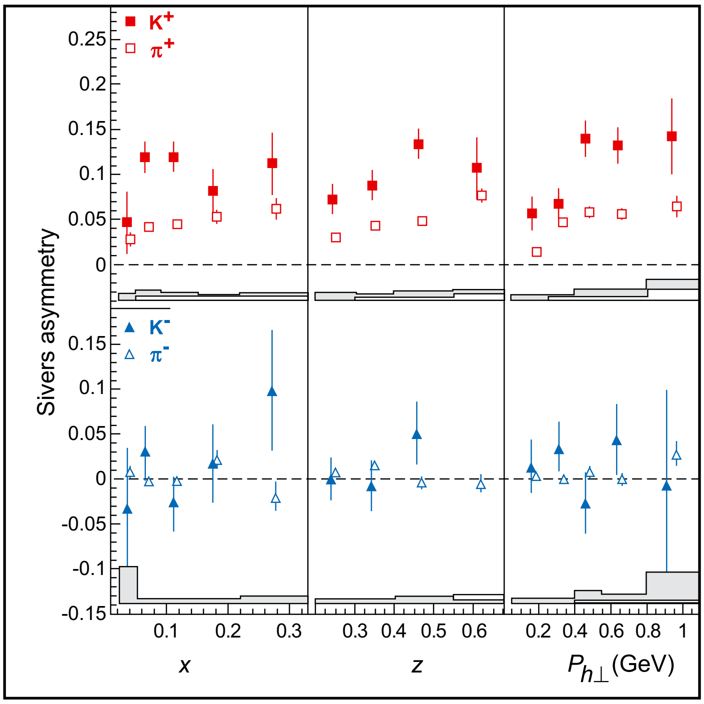


Transverse target-spin asymmetry associated with deeply virtual Compton scattering compared with predictions from a model using various total angular momenta J_u for the up quarks, while fixing the total angular momentum for the down quarks $J_d = 0$. This is the first, albeit model-dependent, determination of the total angular momentum of the up quarks.



Phenomenologically, the nucleon can be characterized in terms of parton distribution functions (PDFs, see p. 24) that describe how often the constituents of the nucleon will be found in a certain state. Within this framework, there are three fundamental quark distributions: the quark number density, which has been measured with very high precision by H1 and ZEUS; the helicity distribution, which was the main result of the HERMES run on longitudinally polarized hydrogen and deuterium gases; and the transversity distribution, which 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. Using the measurements taken on transversely polarized hydrogen, the HERMES physicists can now for the first time determine this transversity distribution. They also have access to the Sivers function, which describes the distribution of unpolarized quarks in a transversely polarized nucleon. As the Sivers function should vanish in the absence of quark orbital angular momentum, its measurement marks an additional important step in the study of orbital angular momentums in the nucleon. Analysis of the initial data shows that the Sivers function seems to be significantly positive, which indicates that the quarks in the nucleon do in fact possess a non-vanishing orbital angular momentum.

Although HERMES focuses on nucleon spin, the overall physics program 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.



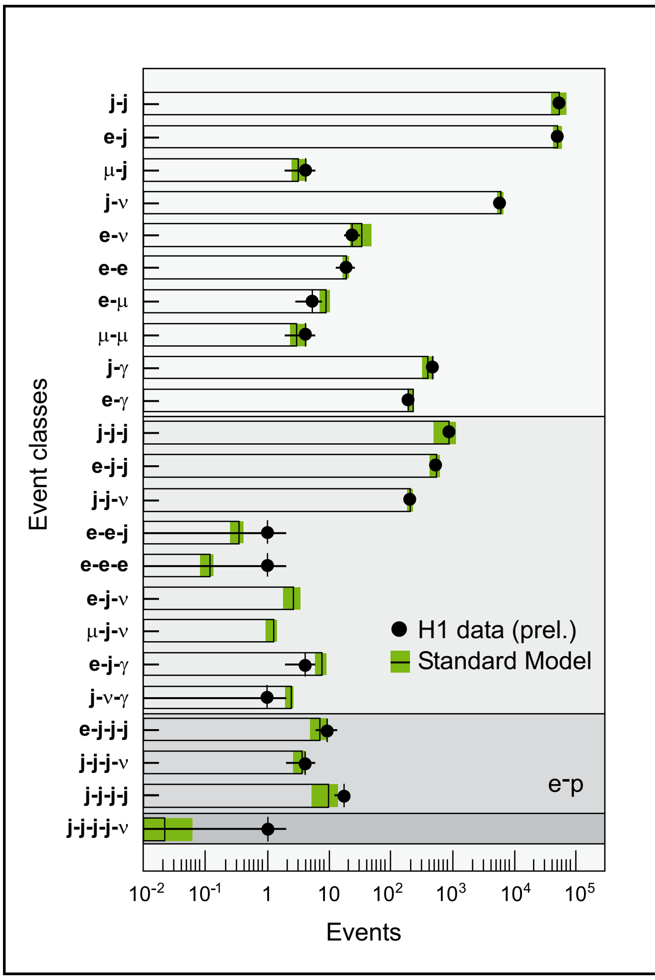
Sivers asymmetry for positive and negative kaons and pions as functions of x, the energy fraction z and the transverse momentum of the kaon resp. pion. The positive π^+ und K^+ Sivers signal provides a first hint that the quarks in the nucleon possess a non-vanishing orbital angular momentum.

EXPLORING THE BOUNDARIES.

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 are also more collision events here. As a result, the HERA physicists are 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. With regard to whether quarks may have a finite diameter or a substructure, the search for additional spatial dimensions, or the investigation of leptoquarks or R-parity violating SUSY particles – the HERA physicists, in some cases, are able to work more model-independently and to reach better limits than fellow scientists at other large accelerator facilities such as LEP in Geneva or Tevatron in Chicago.

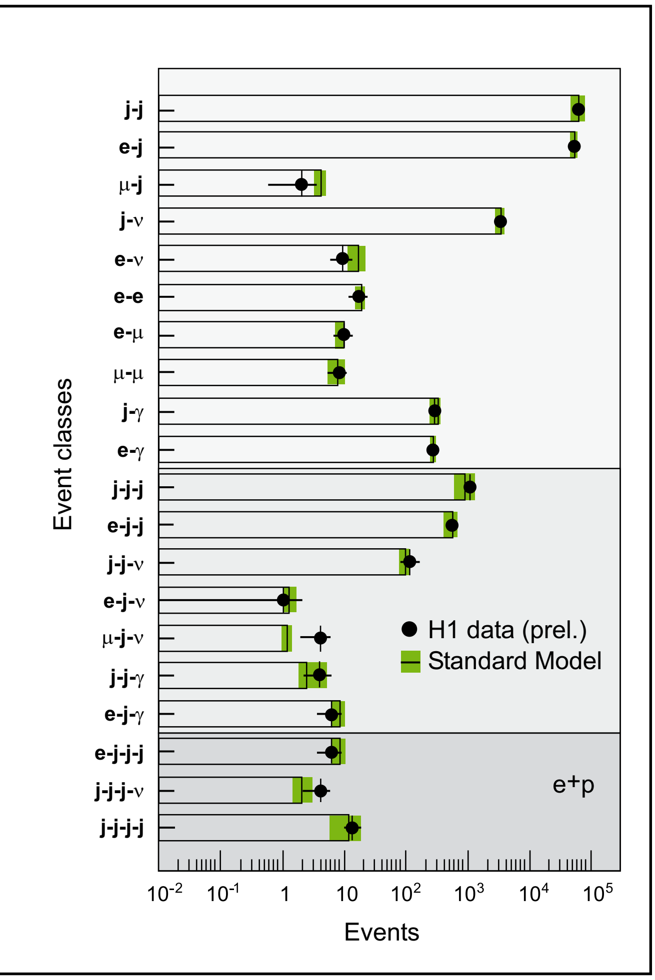


Model-independent analysis used in the search for deviations from the Standard Model at the highest momentum transfers. The diagrams show a host of different types of events, featuring combinations of jets, electrons, muons, photons and neutrinos. The observed event rates for electron-proton scattering (left) and positron-proton scattering (right) agree extremely well with the predictions of the Standard Model.

Hans-Ulrich Martyn

When Hans-Ulrich Martyn from the RWTH Technical University in Aachen came to Hamburg as a post-doc in 1974, it was to be for a few years only. Meanwhile, he has been at DESY for more than three decades – participating first in the DASP experiment at DORIS, then in TASSO at the PETRA accelerator. He then moved on to HERA, more particularly to the H1 experiment, at which he has been working from the very first preparation phase until today. In 2007, he will retire together with HERA. But of course, he will keep on following the development of particle physics with great suspense.

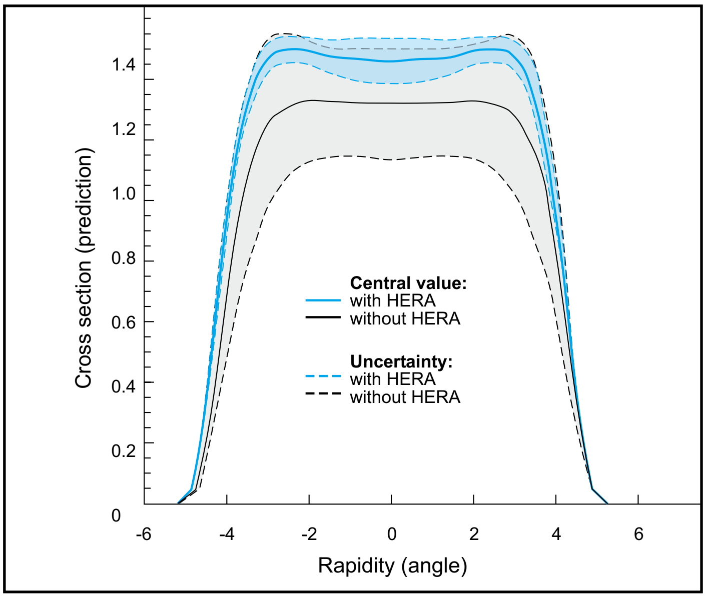
I would really like to find out just where the limits of the so far highly successful Standard Model lie. Are, for example, quarks really point-like, or do they have an inner structure, i.e. another layer of preons? If quarks and electrons are indeed members of a larger family, then leptoquarks should exist. Do quarks have supersymmetric partners? And, an absolutely amazing idea, are there other spatial dimensions in the atomic realm, whereby gravitation could exercise a direct influence on particle physics? Unfortunately, we haven't been able to find any indications at HERA that would support such revolutionary ideas, some of which could help to further our understanding of the unification of the forces at extremely high energy scales. Future experiments at the LHC at CERN and at the International Linear Collider ILC will show whether, and in what direction, the Standard Model must be extended. That's going to be incredibly exciting.



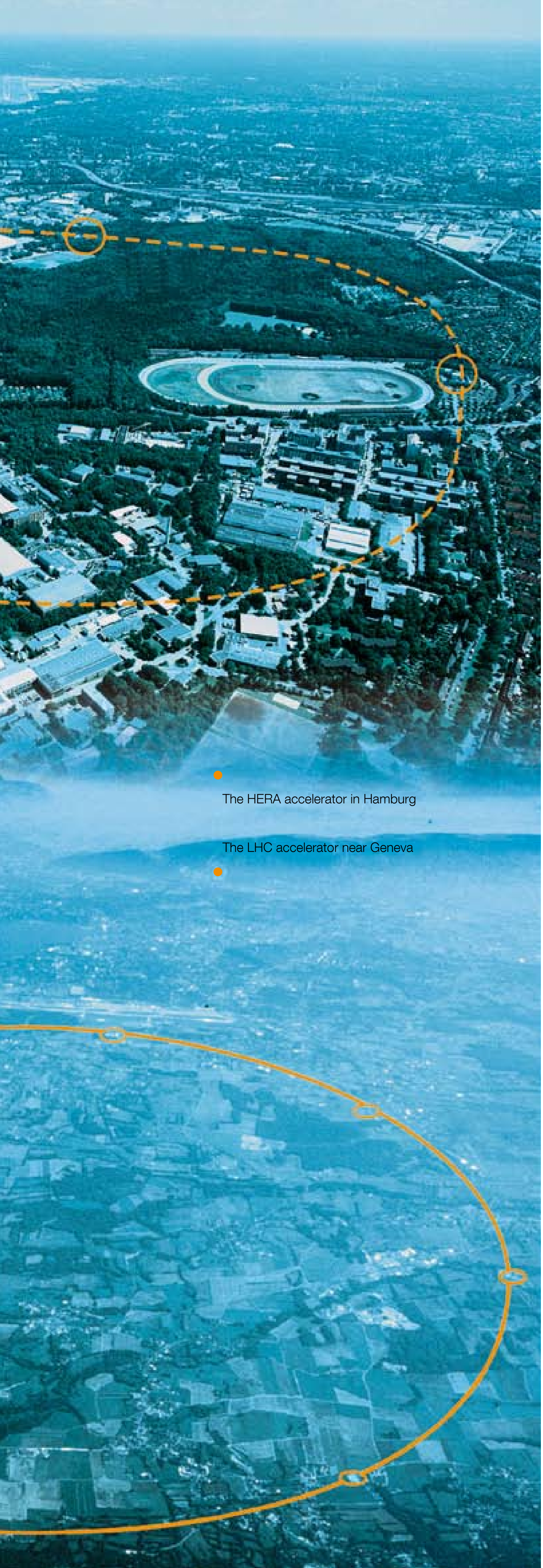
TWO PARTNERS.

HERA and the LHC

In 2007, the most powerful particle accelerator in the world will take up operations at CERN in Geneva: the Large Hadron Collider LHC, which will smash protons into one another at energies about 50 times higher than those of the particle collisions at HERA. The LHC will enable physicists to search for the hitherto undiscovered Higgs particle and possible supersymmetric states of matter. The results provided by HERA will be indispensable for their work: the proton-proton collisions that take place in the LHC are extremely complex, and therefore difficult to describe in theoretical terms, because they involve extended, composite particles rather than point-like ones. 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. Especially important, for example, are precise measurements of the parton distribution functions (PDFs, see p. 24), which describe the density of the various quarks and the gluons in the proton. Thanks to the very successful HERA operation in recent years and the outstanding performance of the detectors, the HERA experiments even gained access to the heavy charm and bottom quarks, which arise for an extremely short period of time in the proton as virtual particles. When it comes to producing the Higgs particle in particular, it is extremely important to have the most accurate idea possible of these density distributions. The more exactly the share of charm and bottom quarks in the proton is known, the more accurate the predictions of Higgs production at the LHC will be.



The cross section for the production of W^+ bosons at the LHC – without and with HERA. Without taking into account the parton distributions measured by HERA, the margin of error of the prediction is 17% (broken lines, black). Thanks to the HERA data, this error shrinks to about 3% (blue). Producing W and Z bosons is an important gauge process of the Standard Model, with which e.g. the luminosity (intensity of the collisions) of the LHC is determined.



The HERA accelerator in Hamburg

The LHC accelerator near Geneva

Many of these measurements, which are fundamentally important for the LHC, could only have been taken at HERA. To strengthen this connection, and to also ensure optimal preparation of the experiments at the LHC in the light of the HERA findings, DESY and CERN have been intensifying their cooperation in this area since 2004. This enabled them to support the transfer of knowledge between the researchers at HERA and at the LHC and to create an active, long-term connection between the two organizations, which takes account of the overlapping areas of interest in physics at HERA and the LHC. Many HERA scientists, as well as students and doctoral candidates, are already participating in the LHC experiments ATLAS and CMS. Thanks to the continual transfer of HERA research work into the research at the LHC, this aspect of particle physics at DESY will continue beyond the conclusion of the HERA data evaluation in the next decade.

Karl Hubert Mess

From 1981 to 1994, Karl Hubert Mess and his group were responsible for much of what kept HERA going. Now, Mess is facing what is in many respects a very similar challenge at the LHC at CERN, where he can apply the experience he gained at HERA.

The most important things are the memories of a great period filled with many challenges, possibilities and difficulties, and with great colleagues in an outstanding partnership. This combination stands out as unique in my entire career.

After much preliminary work, the high point was the phased process of commissioning HERA. And although this start-up was well-coordinated (not by me), it still had the whole group holding its breath.

The most important thing I learned, though – which was such a positive experience at HERA – is that you can move mountains with a few good people. This is true provided you fight to ensure that they have the freedom to move and develop, and that you support them when needed with ideas, critical questions and training – in other words, with good feedback. People are the most important part of a project. And this remains true for the exciting time that has just started for me at the LHC.

THINKING AHEAD.

HERA – Physics with a future

Although the data taking at the HERA experiments ended in the summer of 2007, the evaluation of the recorded data is continuing at full speed – and it will last far into the next decade. The prospects are exciting: the HERA physicists are now perfecting a comprehensive experimental description of the proton, with a precision and multifaceted quality that is unprecedented.

In recent years, HERA has enabled the physicists to uncover a wealth of different – and in part unexpected – aspects of the proton and the forces at work within it. With the analysis of the data collected up to the summer of 2007, they will be melding these individual aspects into a large, cohesive whole, a global image of strongly interacting matter viewed at small distance and short time scales. Given HERA's unique nature, this image will endure for a long time – defining for years, and possibly decades, the most up-to-date scientific findings regarding the dynamics of the strong interaction.

HERA's detailed study of electron-proton scattering provided a fundamental understanding of the basic building blocks of our world and the forces acting between them. With their results, the HERA physicists are passing the baton back to the theorists – who now must refine or change their model calculations in order to explain the results gained from HERA and to incorporate them into particle theory.

The HERA results have tremendously stimulated the work of the theorists right from the outset, particularly in the field of quantum chromodynamics, where a very intensive, fruitful collaboration between theory and experiments has arisen. The picture of the proton and the forces of nature gained from the HERA experiments thus represents the underlying basis not only for many future particle physics experiments but also for many current developments in the world of theoretical particle physics.

We would like to thank everyone who contributed to the making of this brochure for their untiring support, especially Allen Caldwell (Max Planck Institute for Physics, Munich), Eckhard Elsen (DESY) and Hans-Ulrich Martyn (RWTH Aachen).

IMPRINT.

Publisher
Deutsches Elektronen-Synchrotron DESY
Member of the Helmholtz Association
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Design
Jung von Matt/brand identity GmbH, Hamburg

Layout
Britta Liebaug

Graphics
DESY
H1-Kollaboration
HERMES-Kollaboration
ZEUS-Kollaboration

Photographs
CERN
DESY
Ilka Flegel, Jena
Peter Ginter, Lohmar
David Parker / Science Photo Library, London
Manfred Schulze-Alex, Hamburg
Heike Thum-Schmielau, Hamburg

Photograph on page 26 by courtesy of
AUTO BILD, Hamburg

Translation
TransForm GmbH, Cologne

Printing
Heigener Europrint GmbH, Hamburg

Copy deadline
June 2007

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