LOOKING DEEPER INTO THE PROTON

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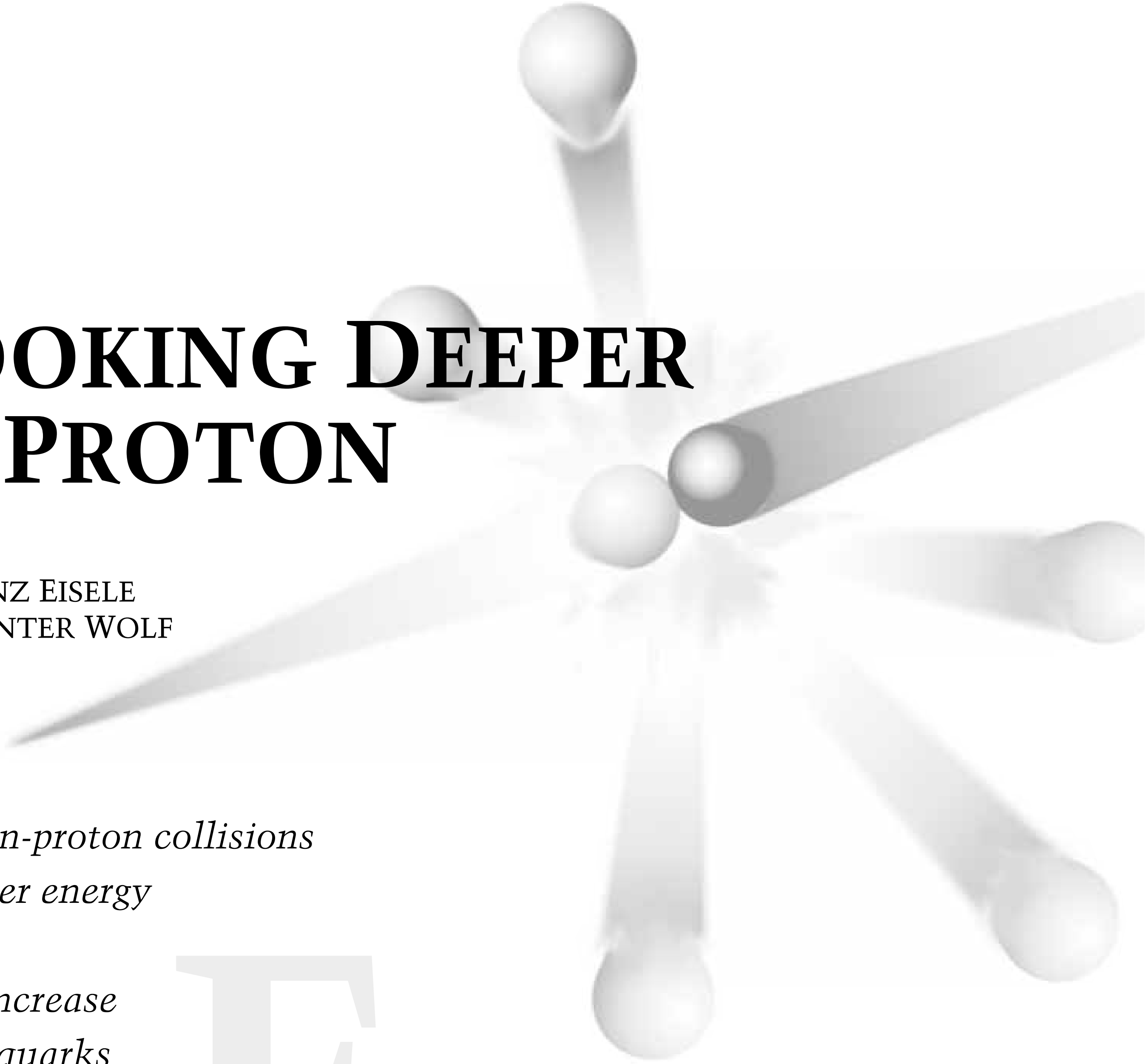


Electron-proton collisions at higher energy show a rapid increase of soft quarks and gluons in the proton.

For more than forty years high energy electron beams have been used as an ideal probe for measuring the internal structure of extended objects like nuclei and their building blocks, the proton and the neutron. At energies of several GeV one begins to resolve substructures in the proton.The highlight of these electron-scattering experiments was the discovery at SLAC in 1969 that the proton is actually made of pointlike constituents which later were identified as quarks and gluons.

The electron-proton collider HERA, which has been operating since the summer of 1992 at the German research center DESY in Hamburg, boosts the resolution power of electron-scattering experiments by more than an order of magnitude and allows a much deeper look inside the proton. It may even provide the possibility of seeing the structure of quarks and electrons if they themselves are not truly pointlike.

The basic concept for unraveling the structure of matter by scattering experiments is straightforward. A beam of energetic and point-like particles (= test particles) is directed against a target material, and the energies and angular distributions of the scattered beam particles are measured. An early example is the experiment of Rutherford and his coworkers Geiger and Marsden (1909–1913), who scattered alpha particles (helium nuclei) from metal foils. The observed angular distribution of the alphas led to the conclusion that atoms are almost all empty space but possess a small and massive core against which the alphas are occasionally scattered at large angles.

The object size Δ that can be resolved in the scattering process is determined by the kick or momentum Q that the test particle transfers to the target particle, $\Delta = 0.2/Q$, where Q is measured in GeV and Δ in fm (1 fm = 1 fermi or 1 femtometer = 10^{-13} cm). The maximum momentum transfer Q (and hence the resolution) increases with the energy of the test particle. In the Rutherford experiment the incident alpha particles were provided by radioactive decay and had kinetic energies in the MeV range, thus permitting the identification of objects as small as a few fm. The core or nucleus of the atom was found to have a radius smaller than 30 fm, or about 10,000 times smaller than the whole atom.

The structure of the individual nucleons (protons and neutrons) that make up the nucleus can best be explored with beams of leptons, such as electrons, muons and neutrinos which are produced at high energy accelerators. These particles are themselves pointlike—as far as we know—and this is one of the reasons why their interactions with other particles are well understood. Experiments performed in the late 1950s with elastic scattering of electrons around 1 GeV, for instance at Stanford, showed that nucleons are not pointlike but are instead extended objects with a radius of about 0.8 fm. Particle physics was revolutionized in the late 1960s when the SLAC-MIT group discovered Bjorken scaling which showed that nucleons are made of even smaller, apparently pointlike constituents, called partons. The evidence came from 20 GeV electrons striking a nucleon target and scattering inelastically at large angles. This was reminiscent of Rutherford's observation but now seen at the much smaller resolution scale of a tenth of the proton radius. The pointlike parton constituents were later found to match the properties of the quarks that had previously been postulated by Gell-Mann and Zweig.

The results from the SLAC-MIT experiment were explained by the quark-parton model of Feynman and, together with further lepton scattering experiments, led to the formulation of Quantum Chromodynamics (QCD), the theory that describes the strong interactions in terms of a new force acting on color charges in much the same way as the electrodynamic force acts on electric charges. Nucleons are made of quarks and gluons which carry color charge. Quarks possess, in addition, electromagnetic and weak charges. Gluons are responsible for binding quarks together in the nucleon in a way that is similar to photons binding electrons and the nucleus together to form an atom. The observable strongly interacting particles are color neutral; similarly, atoms are electrically neutral. Several generations of lepton-scattering experiments have since measured the momentum distributions of quarks and gluons inside the proton and neutron, and they have made invaluable contributions to our understanding of the basic weak, electromagnetic and strong interactions.

As an example, in contrast to the electromagnetic interactions, the weak interactions that are responsible for the radioactivity from nuclear beta decay are mediated by the exchange of any of three massive, charged or neutral vector bosons $W^{\pm}$ and Z^0, with 85 and 100 times the mass of a proton respectively. Their study as well as the search for new currents and the question of whether quarks and leptons are composite particles called for much higher Q^2 values. Prior to HERA, the lepton beam in these experiments was directed onto a stationary (fixed) target containing neutrons and/or protons. A maximum energy of 600 GeV was reached at Fermilab for muon and neutrino beams, thus providing lepton-nucleon center of mass energies of 30 GeV and momentum transfers of 20 GeV, which is equivalent to a resolution of $\Delta = 10^{-2}$ fm. To gain an order of magnitude in resolution with the same technique would require increasing the lepton energy by two orders of magnitude to 50,000 GeV, for example by lining up a thousand SLAC-type linear accelerators, each 3 km long, one behind the other. This does not seem to be a practical solution.

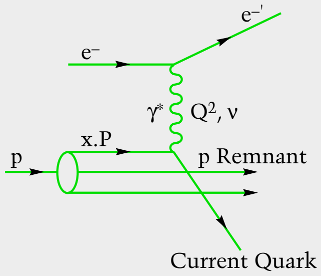
THE HERA MACHINE

At HERA the equivalent electron beam energy of 50,000 GeV is achieved by colliding 30 GeV electrons head-on with 820 GeV protons, which results in a center of mass energy of 300 GeV. (E_e, E_p are the energies of the electron and proton beams.) The two beams are accelerated and stored in two independent rings of 6.3 km circumference mounted on top of each other. Magnetic guide fields keep the beams on orbit. For the electron beam, standard room-temperature electromagnets are adequate. For the proton beam, superconducting magnets had to be built which operate at a temperature of 4.3 K and provide a field of 4.7 Tesla.

The rate of collisions between electrons and protons is given by the product of the cross section σ for electron-proton scattering and the luminosity L of the collider, $n = \sigma \times L$. The luminosity depends on the particle densities in the two beams. In fixed-target experiments proton densities as high as 10^{23} per cm^2 can readily be achieved. Not so in a collider: the proton density in HERA is nine orders of magnitude smaller. In order to compensate, at least partially, for the lower density, protons and electrons are stored in up to 210 bunches each, which counter-rotate at nearly the velocity of light in the two rings and cross each other every 96 nanoseconds at two points. The design luminosity of $L = 1.5 \times 10^{31}$ $\text{cm}^{-2}\text{s}^{-1}$ leads to 15 events per second for a cross section of 10^{-30}cm^2 ($=1\mu$b). The peak luminosity has risen steadily since the start of experimentation in June 1992 to 5×10^{30} $\text{cm}^{-2}\text{s}^{-1}$ in late 1994. The integrated luminosity delivered per experiment (see figure) illustrates the progress made in understanding the machine. In 1994 the total luminosity reached 6 pb^{-1} ($= 6{\times}10^{36}$ $\text{cm}^{-2}\text{s}^{-1}$) which yields 6 million events for a cross section of 1 μb. These data are now under analysis. By 1996 an annual luminosity of 30–50 pb^{-1} is expected. The physics results that will be discussed below have been

Inelastic Electron-Proton Scattering

In a simple picture of inelastic electron-proton scattering the electron emits a virtual photon (γ^*) which transfers a kick Q and an energy ν to the proton in the proton rest system (see figure below).



The exchanged photon, which can be thought of as a neutral current flowing from the electron to the proton, is virtual and has a mass squared ,

$$m_\gamma^2 = -Q^2.$$

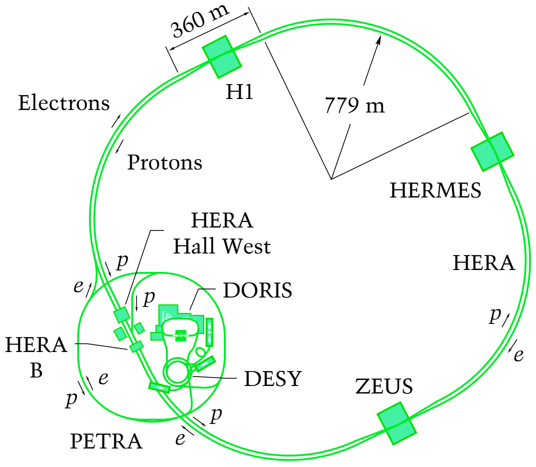
If Q is large, so that Δ is small compared to the radius of the proton,

$$Q >> 1 \text{ GeV},$$

the photon does not interact with the proton as a whole but rather with one of its quarks. (Since the photon couples only to electromagnetic charges, it does not interact directly with gluons, which are electrically neutral.) In the simplest case, the basic process is the elastic scattering of an electron on a quark. The quark carries a fraction x of the proton momentum which is related to Q^2 and ν by

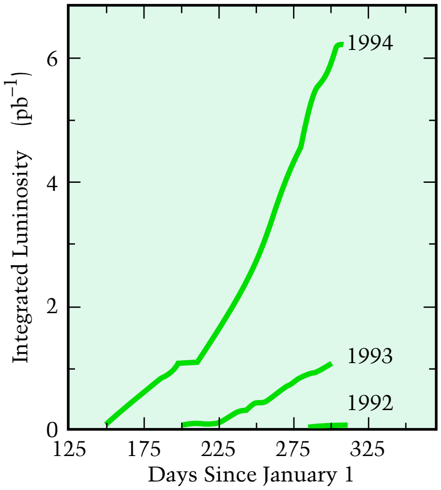
$$x = Q^2/(2\, m_p \nu),$$

where m_p is the proton mass. The struck quark knocked out from the proton as well as the proton remnant left behind carry color charge and cannot directly be observed. Both fragment into jets of strongly interacting particles (hadrons) such as nucleons, pions and kaons. One assumes that at the end of the fragmentation process the color charges from the struck quark and from the proton remnant neutralize each other.



Layout of the HERA collider together with the preaccelerators DESY and PETRA, showing also the location of the experiments.

Development of the integrated luminosity versus time for the data taking in 1992-1994.



obtained from analysis of the 1993 data, which correspond to a total luminosity of 0.6 pb^{-1}.

An ambitious goal at HERA was the provision of polarized beams of electrons and positrons with spins parallel and antiparallel to the direction of flight. This has been achieved for the first time in a storage ring with polarizations of 60 percent for the electron beam.

EXPERIMENTS AT HERA

Two of the four interaction points are occupied by the general-purpose detectors H1 and ZEUS, which have been taking data since the start of HERA in 1992. At the third point the HERMES detector is under construction for studying the scattering of polarized electrons on polarized protons and light nuclei from a gas jet. The fourth interaction region is earmarked for HERA-B, which will use the halo of the proton beam from HERA to produce B-mesons and to search for CP violation in the B system.

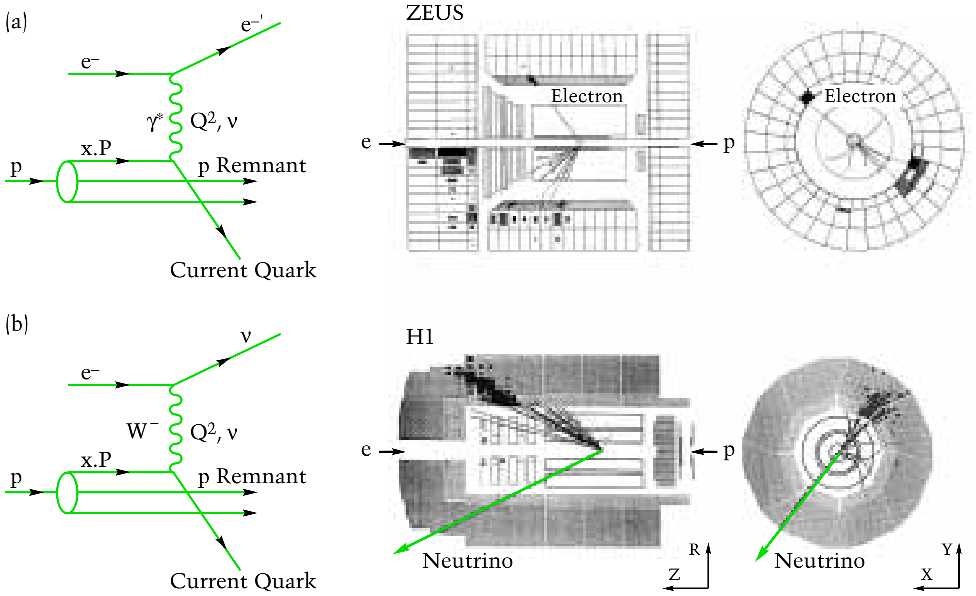
The H1 and ZEUS detectors are designed for optimum precision in measuring inelastic electron-proton scattering. A typical neutral-current event produced via the exchange of a photon or Z exchange is displayed in the figure (facing page). One observes an energetic and isolated electron whose transverse momentum relative to the beam axis is balanced by a set of strongly interacting particles, called hadrons, most likely stemming from the struck quark. The energy deposited near the proton direction stems presumably from the proton remnant. The two fundamental variables Q^2 and x which characterize the scattering process can be determined from the energy and angle of either the scattered electron or of the hadron system.

In the case of a charged-current event produced by W^+ or W^- exchange, the outgoing lepton is a neutrino, $e^-p \rightarrow \nu X$, which leaves no trace in the detector. Such events must be recognized by the missing transverse momentum carried away by the neutrino. The example shown in the figure on the facing page has a transverse momentum imbalance which indicates that the neutrino escaped as shown with an energy of about 200 GeV. For charged-current events, Q^2 and x can only be determined from the hadron system. The identification of these events requires a detector that covers the full solid angle without gaps and holes, so that particles like photons, K mesons and neutrons cannot escape undetected.

In view of the emphasis on the energy and angle measurements of electrons and hadrons, it is no surprise that the H1 and ZEUS detectors are determined by their choice of calorimeter. A calorimeter measures the energy and direction of particles by total absorption and the localization of the energy deposition. Both experiments use a sampling calorimeter, where layers of absorber and detector alternate. Hadrons, photons and electrons that hit the calorimeter produce showers of secondary particles in the absorber plates. The number of secondaries is counted in the detector layers and is a measure of the energy of the incident particle. ZEUS uses depleted uranium plates as absorber, with scintillator for readout, which provides a compensating calorimeter with the best possible energy resolution for hadrons. "Compensation" means that electromagnetic particles (electrons, photons) and hadrons of the same energy yield the same signal. The slight radioactivity of the uranium provides a stable calibration. With the exception of the forward and rear beam holes, the calorimeter covers hermetically the full solid angle. H1 chose liquid argon for readout, and lead and steel plates as absorbers. Liquid-argon readout offers a stable and simple calibration and allows a fine transverse and longitudinal segmentation of the readout. The calorimeter is noncompensating, but by analyzing the shower profiles equal signals for electrons and hadrons can be obtained.

In addition to the calorimeter, both detectors are equipped with wire chambers around the collision point for accurate tracking of charged particles. A superconducting solenoid provides a high magnetic field for measuring particle momenta from their observed track curvature. The high resolution calorimeter is surrounded by the iron yoke, which is instrumented with wire chambers for the detection of leaking showers and for the identification of penetrating muons. In addition, the first 100 meters of the collider rings upstream and downstream of the central detector are used as spectrometers. They are instrumented with calorimeter and tracking devices for the detection of protons and neutrons produced in the proton direction, and of photons and electrons produced in the electron direction. The latter serve for measuring the luminosity and for tagging of photoproduction.

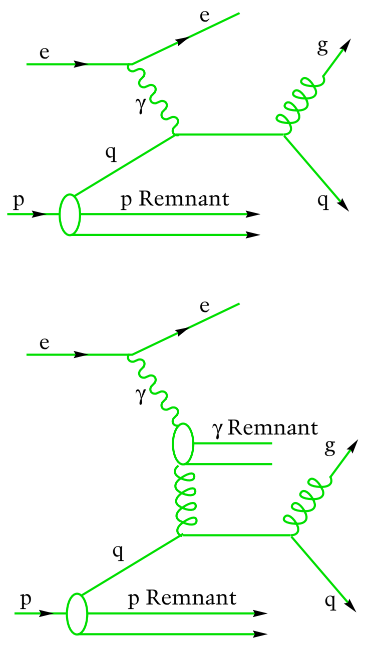
The high beam-crossing rate and the large number of electronic channels in both experiments required the development of new concepts for acquisition of the data. The signals from the 200,000 to 300,000 channels, amounting to several Terabytes (10^{12} bytes) of information per second, are stored every 96 nsec in analog or digital pipelines that can hold the results from 25 to 50 beam crossings. In parallel, signals obtained by summing over many channels are stored in trigger pipelines and analyzed in giant parallel processors to select the interesting events, which are finally recorded on tape.



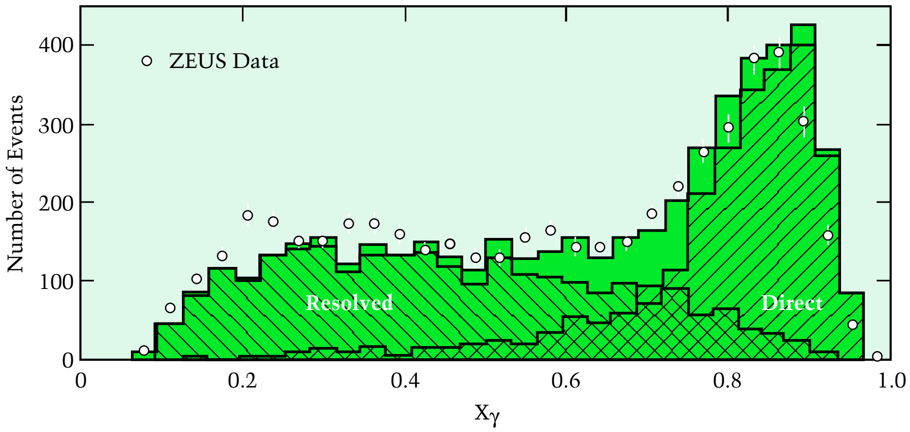
Events from electron-proton scattering observed in the H1 and ZEUS detectors in views parallel (center) and perpendicular (right) to the beam axis. Tracks of charged particles are reconstructed from hits registered in the inner tracking chambers. The energy deposition from particles is measured by the calorimeter; energy desposits in a readout cell are displayed by rectangles. Top row: a neutral current event, ep → eX, as measured in the ZEUS detector with Q^2 = 5300 GeV^2. The transverse energy of the electron is balanced by a hadron jet at large angle from the current quark. In addition, there is a substantial energy deposition near the proton beam direction stemming from the proton remnant. Bottom row: a charged current event, ep → νX, as observed with the H1 detector at Q^2 = 20,000 GeV^2. There is a jet emitted to one side of the detector whose transverse momentum is not balanced by other detected particles, indicating the emission of an undetected neutrino to the opposite side (solid green line).

THE JANUS HEAD OF THE PHOTON

"Die ganzen 50 Jahre bewußter Gruebelei haben mich der Frage was sind Lichtquanten nicht naeher gebracht." "The whole 50 years haven't brought me closer to the question of what is the nature of light quanta," wrote A. Einstein in 1951, in reference to the experimental observation that photons can behave both as waves and as particles. HERA is a copious source of photons with mass-squared values so close to zero that they can be regarded as real photons. The photon energy measured in the



Photoproduction at HERA by the emission of an almost real photon ($Q^2 \cong 0$). Top: A direct photon process where the photon interacts directly with a quark from the proton, producing a quark and a gluon which turn into two jets emitted at large angles. In addition, there is a jet resulting from the proton remnant which has the direction of the incoming proton. The total energy of the photon participates in the hard interaction, $x_\gamma = 1$. Bottom: A resolved photon process where the photon resolves into quarks and gluons. One of the gluons interacts with a quark from the proton, leading to two large angle jets plus the proton remnant jet in the proton direction and the photon remnant jet in the photon direction. Only a fraction of the photon energy participates in the hard scattering, $x_\gamma = 1$.



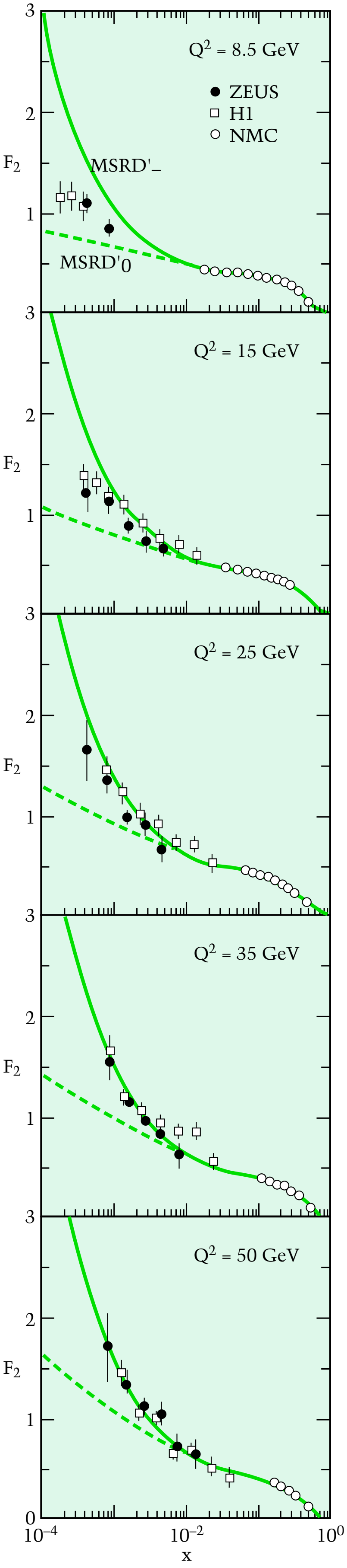
The fractional energy x_γ of the photon participating in hard scattering of photoproduction leading to two large-angle jets. Two distinct components are seen: the direct-photon contribution peaking at large values of x_γ, and the resolved-photon contribution with smaller values of x_γ.

proton's rest system can be as high as 50,000 GeV. The photon interacts with the electrically charged quarks in the proton. This is called a direct photon interaction. However, Heisenberg's uncertainty principle allows the photon for a short time also to fluctuate into a quark-antiquark pair. Although the time is short, it is long enough for a photon with HERA energies to travel a distance which is many hundred proton radii long. The quarks in turn emit gluons so that the photon looks like a cloud of quarks and gluons which then interacts with the quarks and gluons of the proton. This is dubbed a *resolved* photon interaction. The large photon energies available at HERA allow one to distinguish between the two modes of interaction by selecting events from hard scattering with two energetic and large angle jets. From the energies and directions of the two jets one can determine whether the *total* energy of the photon ($x_\gamma = 1$) participated in the collision with a constituent of the proton as for direct interactions; or alternatively whether only a fraction of the energy ($x_\gamma < 1$) participated, as for resolved interactions. The frequency distribution of the energy fraction (see figure) shows clearly the presence of both processes through a direct peak near $x_\gamma = 1$ and a second resolved component at smaller x_γ values. This is the first measurement where the interaction of the direct and the resolved photon with a proton has been demonstrated. The observation of resolved photon processes can now be used to measure the partonic structure of the photon, so that HERA becomes also a microscope which explores the interior of the photon.

For the event sample shown the contributions from the direct and resolved photon are of comparable magnitude. This is so because events from hard scattering were selected. Overall, soft-scattering events are much more abundant, and in such events by far the dominant contribution comes from resolved processes where the photon behaves like a bag of quarks and gluons. It might well be said that Einstein had already forseen the split personality of the photon when he said, *"Jeder Lump meint er weiß, was ein Photon ist, aber er irrt sich."* ("Every idiot thinks he knows what a photon is, but he is mistaken.")

THE INFLATION OF SOFT QUARKS AND GLUONS IN THE PROTON

A topic that was not on the top of the agenda when HERA was first proposed, but which has received increasing attention in the last two



The proton structure function F_2 (x, Q^2) as a function of x for fixed Q^2 as measured by the HERA experiments at small x, and by the fixed-target experiment NMC at large x. A strong rise is seen as x tends to zero. The two curves show the expectations prior to HERA for the case that the gluon density at low Q^2 is constant with x (dashed curves) or rapidly rising as x → 0 (solid curves). Both curves describe the fixed-target data.

years and has led to the first surprise from HERA, comes from the measurement of very soft partons. The proton contains at least two *up* quarks and one *down* quark, called the valence quarks, and gluons which provide the binding force between them. Gluon annihilation into quark-antiquark pairs and radiation of gluons from quarks both increase the number of partons in the proton, so that on average each of these partons carries only a small fraction x of the total proton momentum. Individual partons become visible if the momentum kick *Q* they receive is above 2 GeV. The high energies provided by HERA permit observation at this *Q* value of partons that carry as little as $x = 10^{-4}$ of the total proton momentum, whereas for fixed-target experiments x must be larger than 10^{-2}.

From the measurements made during the 25 years prior to HERA, one had a rather precise knowledge of the parton density for $x > 10^{-2}$, but it was impossible to firmly predict the behavior of the density at much smaller x values. The surprising result from the HERA measurement is best seen in the accompanying figure, which shows the measured x dependence of F_2 for five different values of Q^2. The structure function and hence the density of quarks, which seems to flatten off as x decreases in the range of fixed-target experiments (see the data points from the NMC experiment at $x > 10^{-2}$) suddenly shows a dramatic rise in the HERA region of x below 10^{-2}. An analysis of the change of F_2 with Q has shown that the density of gluons in the proton increases also as x becomes smaller.

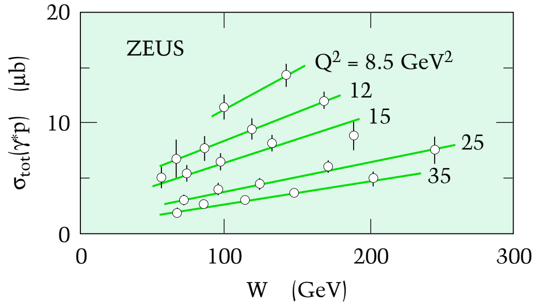
The measurement of F_2 can be converted into a measurement of the total cross section for the scattering of virtual photons on protons, $\sigma_{tot}(\gamma{*}p)$, which gives a more intuitive picture of what happens. The total center of mass energy W of the photon-proton system for small x is related to x and Q^2 by the relation $W^2 = Q^2/x$. Unlike any known total cross section for real particle scattering at high energies, $\sigma_{tot}(\gamma{*}p)$ rises approximately linearly with the total center of mass energy W for fixed Q^2, as shown in the figure on the next page. Another way of saying this is that the virtual photon sees a proton that becomes more

Density of Quarks in the Proton

The density of quarks, $q(x,Q^2)$, in the proton can be obtained from the structure function of the proton,

$$F_2(x,Q^2) = \Sigma_q e_q^2\, x \times q(x,Q^2),$$

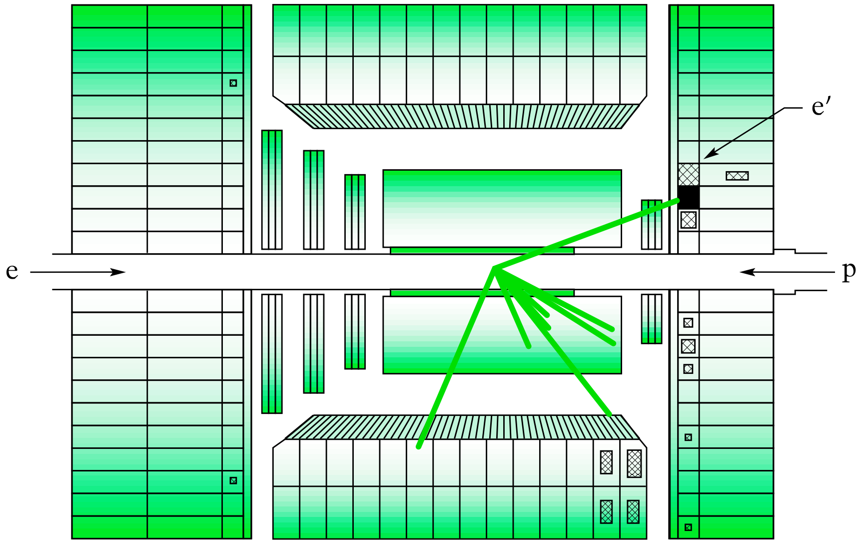
which is directly measured in deep inelastic electron-proton scattering. Here, e_q is the electric charge of the quark q; for instance, e_q = (2/3) for *up* quarks and (–1/3) for *down* quarks The measured quark distributions depend on the resolution and therefore on Q. As Q is increased, the probing electron resolves more and more of the substructure in the proton, with the main effect being that an increasing number of soft quarks and gluons should be found.



The total cross section for virtual photon-proton scattering, $\sigma_{tot}(\gamma^*p)$, for fixed Q^2, seen to rise approximately linearly with the center of mass energy W.

and more opaque (or "black") as *W* increases, as a result of the growing number of low-*x* partons.

This was not entirely unexpected. Some of the QCD predictions for the soft parton region included a strong rise of the parton densities for *x* approaching zero, using the so-called Lipatov evolution equation. All evolution schemes which have been derived so far for small *x* invoke different approximations, and their validity is not clear. While the question of which evolution equation may be valid at small *x* is hotly discussed among experts, there is another interesting and even more fundamental question: *will HERA see the condensation of partons at small x?* The strong increase of the quark and gluon densities observed at HERA provokes the question of whether these parton densities can continue to rise at the same rate forever. The answer is clearly no, since otherwise the total photon-proton cross section would eventually violate unitarity. What will presumably happen is that the parton densities become so high that the partons interact and recombine before they are hit, leading to a saturation of the parton densities. According to Gribov, Levin and Ryskin there is a good chance that the transition from free quarks or a quark "gas" to a quark "liquid" is within the kinematic reach of the experiments at HERA. The probability is even higher when the parton densities do not uniformly populate the proton but rather concentrate in a few hot spots, for instance around the valence quarks.



Diffractive event produced by inelastic electron-proton scattering at $Q^2 = 58$ GeV. The diffractive nature is seen from the absence of energy deposits near the proton direction.

DIFFRACTION OF VIRTUAL PHOTONS

Diffraction is a well known phenomenon in optics. A striking example is the observation that a light beam which is intercepted by a small disc shows maximum intensity directly behind the center of the disc where no direct light rays can go. It has been known for quite some time that a similar diffraction behavior is observed when energetic photons scatter elastically on a proton or produce a vector meson with the same quantum numbers as the photon. These diffractive processes, which are also prominent in hadron-hadron interactions, are phenomenologically described by the exchange of a colorless, neutral object called the Pomeron. So far the nature of the Pomeron is not understood, and a quantitative description of diffractive processes in the framework of QCD is not possible.

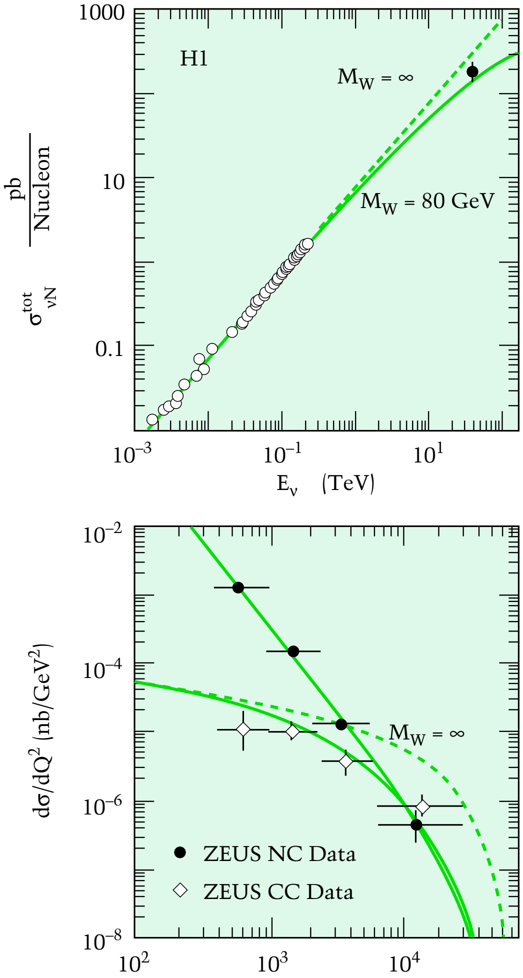
The observation of a new class of diffractive events by the HERA experiments may be the key for understanding diffraction scattering. These so-called "large rapidity gap" events are observed to contribute a sizeable fraction of the total cross section also at large Q^2. Their signature is the production of a massive hadronic system without visible energy flow in the direction of the proton remnant. An example of such an event is displayed in the figure on the previous page (bottom left). It is remarkable for the absence of energy deposition in the forward direction. Since these diffractive events show the same Q^2 dependence as the total event rate, one concludes that their production occurs on constituents in the proton whose size is much smaller than the radius of the proton. However, because of the absence of particle production in the forward direction these constituents cannot be quarks or gluons but must be color neutral and therefore a new type of constituent. It is intriguing to identify them with the Pomeron. These unusual events offer the possibility to study at HERA the nature of diffractive processes as a function of resolving power and energy transfer.

WEAK INTERACTIONS BECOME STRONG AT HIGH ENERGIES

While the charged vector bosons were first observed at CERN in 1983, the effect of the W mass in weak interactions has never been directly seen. The two HERA experiments were able to identify some fifty charged-current events in the 1993 data, where instead of an electron a neutrino was emitted. The value of Q for the majority of these events is comparable to the W mass. The observed event rate can indeed only be understood if a particle with a mass near the W mass is exchanged. Moreover, the comparison with events that have a scattered electron in the final state shows directly and for the first time that the weak interaction becomes as strong as the electromagnetic interaction when Q becomes comparable to the mass of the W, whereas it is about 10^{11} times smaller at the low energies involved in nuclear beta decay. This is a fundamental prediction of the electroweak theory.

OUTLOOK

The strong increase of soft parton densities and the search for saturation effects combined with the chance to test QCD in a new regime will remain a hot subject of HERA physics. The HERA experiments had a first look into the physics at high Q^2. This is an area which will come into full bloom when the design luminosity is reached. It will allow one to probe quarks and electrons for substructure, will provide stringent tests of QCD and will show new pieces of the neutral and charged currents—if there are any. Every step in luminosity will increase also the sensitivity to new particles with masses up to 250–300 GeV hardly accessible at other existing accelerators.



Top: Measurement of the charged-current cross section for $ep \to \nu X$ *by H1 translated into the cross section for the inverse process* $\nu p \to eX$ *at a neutrino energy of 50 TeV and compared to the results from the low energy fixed-target experiments. The straight line (dashed) shows the expectation if the W mass is infinite; the solid line was calculated for a W mass of 80.2 GeV. The finite W mass reduces the cross section at HERA by more than a factor of two, in agreement with the measurement. Bottom: The cross sections for neutral-current* ($ep \to eX$) *and charged-current scattering* ($ep \to \nu X$) *measured by ZEUS become comparable as* Q^2 *approaches the mass squared of the W* ($Q^2 = 6400$ GeV^2)*.*