Nikolaj Pavel

Deeply Probing Quarks and Gluons

EXPERIMENTAL PARTICLE PHYSICS

The ZEUS Experiment is one of the two large international experiments at the electron proton collider HERA at DESY, in which the structure of the proton is investigated with the highest precision so far reached. The proton turns out to have a very complicated dynamical structure due to processes driven by the strong interaction between its constituents, the quarks, which involves the gluons as mediator of this force. The precise measurement of the quark and gluon distributions is essential to deeply understand the nature of the strong interaction, which is mainly responsible for the formation of ordinary matter.

Are Quarks Reality?

Our present understanding of the structure of ordinary matter in the universe can be summarized as shown in Fig. 1, where a zoom into matter is illustrated symbolically. At the smallest scale one finds the quarks, which are the constituents of the nucleons (proton and neutron) and many other particles called hadrons which formerly were regarded as elementary. In the early 60's the number of such »elementary« particles which were discovered in cosmic ray and accelerator based experiments, had grown such, that one was looking for a more fundamental structure of this ›zoo of particles‹. Gellman and Zweig suggested in 1964 a model, in which all known particles of this ›zoo‹ could be built of – at that time – 3 constituents which he named with the fantasy word »quarks»*. In the beginning it was not clear whether these quarks were only part of an abstract theoretical model, but a few years later experimental evidence for pointlike objects inside the proton was found (see Infobox). With the electron-proton (*e-p*) collider HERA at DESY/Hamburg** (see Fig. 3) one can test the size and quantum numbers of these constituents. In *e-p*-scattering experiments at such extremly high energies, the underlying theory for the interaction between the quarks, the theory of Quantum Chromodynamik (QCD), can be thoroughly investigated. The ZEUS-Experiment is one of the two large multi-purpose detectors (see Fig. 4) in which the high energy *e-p*-collision events at HERA together with the particles, which are produced in such collisions, are measured with high precision.

** taken from James Joyce's last novel «Finnigans Wake«: Three Quarks for Muster Mark!*

*** HERA = Hadron-Elektron-Ringanlage; DESY = Deutsches Elektronen-Synchrotron*

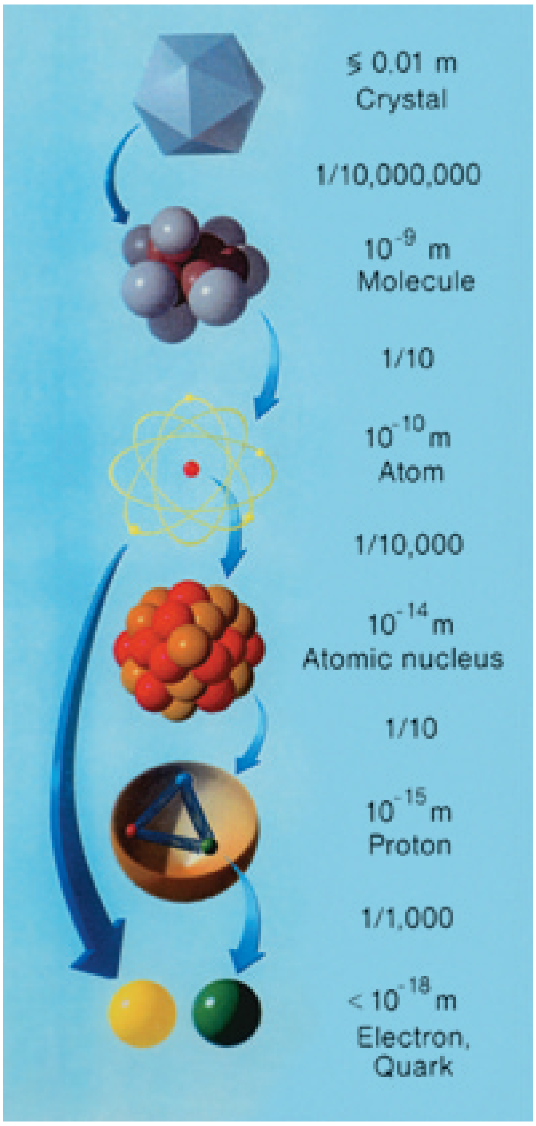


Fig. 1
Schematic zoom into the structure of matter (Source: DESY-PR)

ZEUS-Experiment

Das ZEUS-Experiment ist eines der beiden großen internationalen Experimente am Elektron-Protonen-Beschleuniger HERA von DESY, in welchem die Struktur des Protons mit der gegenwärtig höchstmöglichen Präzision untersucht wird. Das Proton ist durch eine komplizierte dynamische Struktur gekennzeichnet. Deren Prozesse werden durch die starke Wechselwirkung seiner Bestandteile, den »Quarks«, gesteuert, an denen die Gluonen als Austauschteilchen beteiligt sind. Die präzise Messung der Quark- und Gluonen-Verteilung ist essentiell für das Verständnis der starken Wechselwirkung, die hauptsächlich verantwortlich ist für die Struktur der Materie.

The Imprisoned Quark – Quark Confinement

An important and unique characteristic of quarks is that they do not exist as quasi-free particles on a macroscopic scale as all the members of the ›particle zoo‹ mentioned above. The »strong interaction«, one of the 4 fundamental forces in the universe, is acting between quarks. In contrast to the electromagnetic force, which decreases with the distance between electrically charged objects, the force between quarks is constant. This has the consequence that there is an ever increasing field energy between quarks, if one tries to pull them apart from each other, as it is done in high energy deep inelastic *e-p* scattering processes. This increasing field energy materializes into new quark-antiquark (q-$\overline{q}$) pairs from which within some 10^{-25}sec lots of new hadrons are formed, i.e. particles of ordinary matter consisting of 3 quarks (like proton, neutron) or q-$\overline{q}$ like a e.g. pion. At high energies the direction of the particle jets (bundles of hadrons formed) still reflects the kinematics of the underlying elementary particle reaction on the level of quarks and leptons (here electron). This can be seen in Fig. 5, where a violent deep inelastic *e-p* event recorded with the ZEUS experiment is shown. With the results of the two *e-p*-collision experiments at HERA (H1, ZEUS) the highest energies for this process so far have been reached and allow us to zoom into the proton down to a scale of 10^{-18}cm.

Fig. 3
Aerial view of DESY with the HERA accelerator (underground) indicated by the dashed line. The location of the two e-p *collision experiments H1 and ZEUS (also under ground) is indicated as well as the location of the HERA-B Experiment, where proton-nucleus scattering is investigated (see [7]). (Source: DESY-PR)*

The strong interaction, i.e. the force between quarks, can be described by a quantum field theory, which is constructed like the quantum electro-dynamic (QED), which successfully describes the electromagnetic force. The role which is played in QED by the electric charge, is taken in QCD by another physics property called colour charge (therefore the name quantum chromodynamic for the theory for the strong interaction). However, there is one striking difference: the gluons, which are the exchange particle for the strong interaction – like the photons are the exchange particle in QED for the electromagnetic force – carry colour charge themselves and hence can interact with themselves. This fact, which is ultimately related to the underlying symmetry in the quantum field theory of QCD, results in this specific behaviour of quarks and the strong interaction between them. Quarks can exist as free particles only at extremly high energies which corresponds to very short time (and space) scales. In this case the perturbative ansatz for the QCD is quite successful. However at the scale of protons (and other hadrons) and the hadron binding energy scales, perturbative methods fail, because higher order terms which become very quickly too complicated to be calculated, cannot be neglected. New ideas, e.g. from lattice calculations [5] and string theory [6] are needed and offer a new approach to the understanding of the QCD phenomena at the macroscopic scale which are directly observable.

Infobox

Probing the inner structure of protons is done by scattering high energy electrons (*e*) off protons (*p*). The higher the energy is, the higher the momentum transfer between electron and proton (Q^2) can be, and this allows smaller structures to be resolved. Since electrons and protons interact predominantly with each other through the electromagnetic force and hence by the exchange of a photon, higher values of Q^2 correspond to smaller wavelengths of this photon and so to a better power of spatial resolution. From the energy and angle distribution of the scattered electrons, the structure function (F_2) is extracted which contains the information on the extension of the target (more precisely the spatial charge distribution). For pointlike objects F_2 should be independent of Q^2 and vary only with a dimensionless variable. Indeed the proton structure function was found to be almost flat in Q^2, as soon as the proton breaks up in a so called deep inelastic scattering (DIS) process (Fig.2) [1]. This behaviour is called »scaling« of the structure function F_2. The dimensionless scaling variable x can be interpreted in DIS as the fraction of the proton momentum carried by the pointlike objects, i.e. the quarks. In this framework F_2 can be interpreted as the sum of the fractional momentum distribution of the quarks in the proton, weighted with square of the electric charge of the quarks.

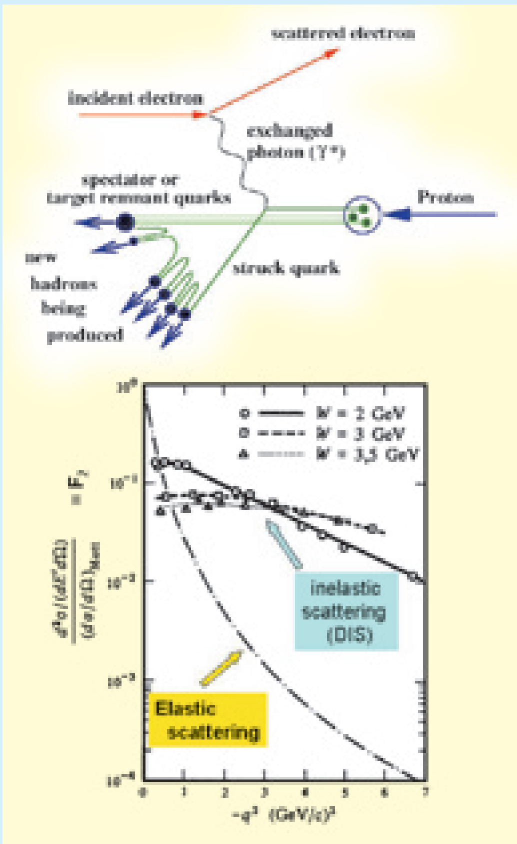


Fig. 2
Upper part: *Illustration of inelastic* e-p *scattering (DIS), where a photon with high amount of momentum and energy is exchanged, expressed by the variable* Q^2*. The proton is destroyed in such collisions and many new final state particles are observed instead.*
Lower part: *Structure function extracted from the energy and angle distribution of the scattered electron in case of DIS as function of the momentum transfer (*Q^2*) at fixed value of* x *(dimensionless variable, see text) (from [2]). Note the striking difference of the* Q^2*-dependence for DIS (proton broken up) and elastic scattering (proton remains integer).*

Fig. 4
View into the ZEUS detector which is opened for maintenance. The ›heart‹ of this detector is the high precision Uranium-Scintillator Calorimeter (black device in the centre).
(Source: DESY-PR)

The ›Overcrowded‹ Proton – Parton Dynamics in the Proton

The valence quarks which in the naive Quark-Parton-Model define the quantum numbers of the proton, interact with each other through the strong interaction i.e. by exchange of gluons. These gluons can make vacuum polarization forming q-$\overline{q}$ pairs for very short times, which are compatible with the Heisenberg uncertainty relation, like photons can produce e^--e^+-pairs. In addition, the gluons can interact amongst themselves creating pairs of gluons as illustrated in Fig. 6. When probing the proton at high energies i.e. making a snapshot of it at the scale of smaller than 10^{-25}seconds, one sees more and more of these extra quarks (called sea quarks) and gluons, the higher the momentum of the photon exchanged (Q^2) is. As a consequence, one observes a violation of the scaling behaviour described in the Infobox. Due to the dynamic QCD processes inside the proton, the distribution of the fractional proton momentum of quarks is modified such that quarks are ›shuffled‹ from the high x-region to the low x-region. This can be seen when plotting the structure function F_2 (which is essentially the sum of all quark distribution functions in the proton) as a function of Q^2 at various fixed values of x (see Fig. 7). Extrapolating this behaviour to even lower values of x the problem arises that the proton gets ›overcrowded‹. The interaction cross section which is in this ansatz proportional to the number of partons (= quarks and gluons in the proton) would violate the unitary boundary and acquire unphysical values. This becomes evident in Fig. 8, where one can see that F_2, i.e. the number of quarks per unit in x steeply increases, if one takes an ultra-fast snapshot. Which kind of process prevents this violation is still actively debated. It could be that parton wave functions start to overlap and lead to a recombination and thus to a reduction of the number of partons. Also in this case, pertubative QCD is not sufficient to describe such effects, but phenomenology or, in future, lattice calculations are needed. For the experimentalist it is crucial to measure the steepness of the increase of F_2, since the various models can be distinguished by that information.

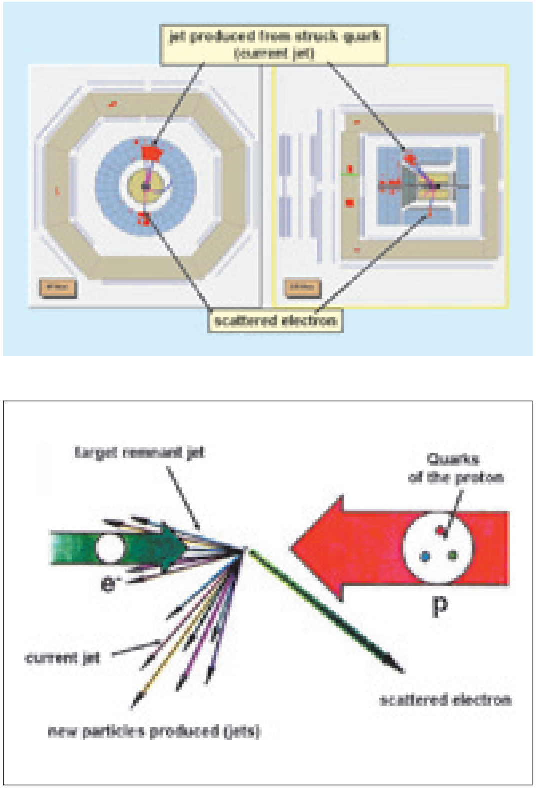


Fig. 5
Upper part: *Event display of a deep inelastic (DIS) event in the ZEUS-experiment. The »current« jet is a bundle of hadrons formed from the struck quark in the colour ?eld between the struck quark and the spectator quarks, the two remaining quarks of the proton, which move in the direction of the incident proton (see illustration below). Most of the hadrons from the »target remnant« jet disappear in the insensitive area around the beam pipe of the detector.*
Lower part: *Schematic illustration of an inelastic* e-p *collision.*
(Source: DESY-PR)

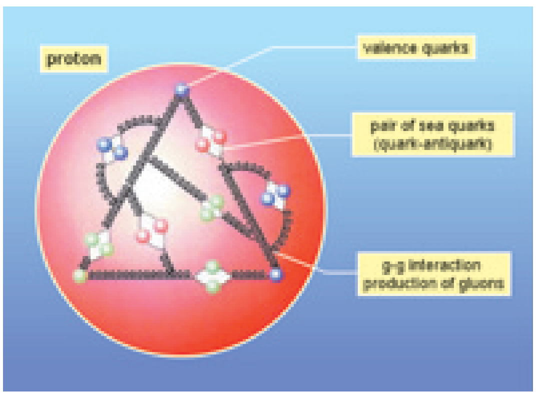


Fig. 6
Proton structure as seen with highest resolution in time and space. Apart from the 3 valence quarks there are plenty of sea quarks and gluons, which are created dynamically by QCD processes on a extremely short time/space scale. At the high energies reached at HERA, they can be resolved and measured.
(Source: DESY-PR)

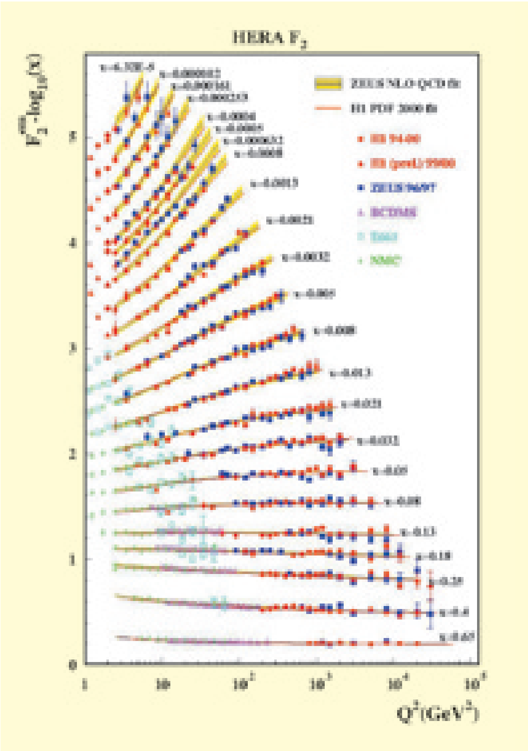


Fig. 7
The proton structure function F_2 measured in a huge range of momentum transfer Q^2 and scaling variable x. Measurements of HERA experiments are combined with those of earlier experiments at lower energies. One sees the characteristic scaling violation pattern (Q^2-dependence) which can be explained by the dynamic QCD processes illustrated in Fig. 6. (from [3]) The Q^2 dependence is strongest for small x values and values of x close to one.

Outlook into the Future

Apart from the proton structure and related QCD effects, there are many more physics topics addressed in the *e-p* collision experiments at HERA, which can only be mentioned here, such as:

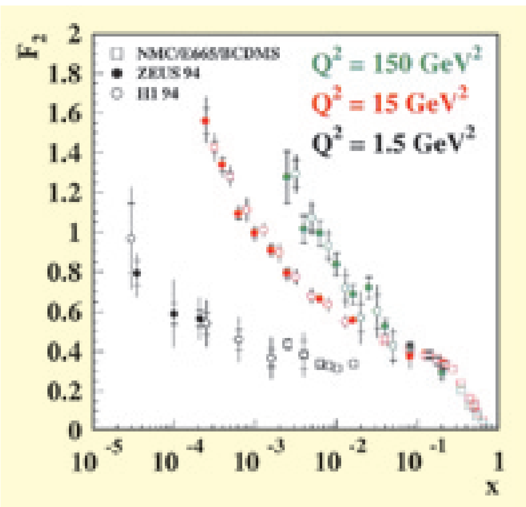
- The process of the formation of hadrons after the electron-quark scattering (called »fragmentation«). This process is also investigated in the HERA-B experiment where the question of the time scale of this process is addressed [7], using the nucleus as a kind of detector at the scale of 10^{-15}m [8].
- The structure of the photon, which addresses the important question of how the quantum state of the vaccum in QCD can be described.
- The occurrence of heavy quarks and production of hadrons with heavy quark content, investigation of the production of hadrons made of 5 quarks (penta quarks)
- Search for signs of physics effects beyond the Standard Model, which describes almost all effects in elementary particle physics so far, and the search for supersymmetric (SUSY) particles.

These goals are approached with an increased luminosity after the upgrade of the HERA accelerator and with upgraded detector components. The ZEUS detector has been supplemented with a micro vertex detector allowing the measurement of vertices from short live time hadrons, e.g. those containing the heavy b-quark, and an improved tracking for fast charged particles in the direction of the incident *p*-beam.

References

[1] *Bloom, E.D. et al.:* Phys. Rev. Lett. 23 (1969) 930.
[2] *Breidenbach, M. et al.*: Phys. Rev. Lett. 23 (1969) 935.
[3] *ZEUS Collab. / Chekanov, S. et al.:* Phys. Rev. D67 (2003).
[4] *ZEUS Collab. / Breitweg, J. et al.:* Europ Phys. Journal C7 (1999) 609.
[5] *Müller-Preussker, Michael / Wolff, Ulli:* »The Strong Force: Simulations of Quarks and Gluons«, this Humboldt-Spektrum (3–4/2004).
[6] *Erdmenger, Johanna:* »Quantenfield Theory and String Theory«, this Humboldt-Spektrum (3–4/2004).
[7] *zur Nedden, Martin:* »Probing the Formation Process of Matter with Charm and Beauty Quarks«, this Humboldt-Spektrum (3–4/2004).
[8] *Nikolaj A. Pavel:* Nucl. Phys. A532 (1991) 465.

Fig. 8
The proton structure function F_2 at various values of Q^2 as a function of x, the proton momentum fraction of a quark. At high resolution (high values of Q^2, one observes a steep increase of F_2 towards low x values indicating a steeply increasing numbers of quarks which are generated dynamically by QCD processes (see Fig. 6)) (from [4]).



Prof. Dr. Nikolaj Pavel
Born 1958, studied Physics in Wuppertal, graduation in 1983, PhD in 1989. Worked at CERN (Geneva) as summer student (1983), as graduate student (1984–88), assistant professor at University Hamburg, working at e-p collision experiment ZEUS (DESY) (1990–95), Marie-Curie Fellow and Guest Lecturer at Imperial College/London (1996/97), associated professor at the University Siegen, leading the Institute for Detector Physics (temporary chair), working on particle detector applications in biomedical physics and astroparticle physics (1998–2002) , since 2003 full professor for experimental elementary particle physics at the Humboldt-Universität zu Berlin. Experiments at DESY, SLAC and in La Palma.

Contact
Humboldt-Universität zu Berlin
Faculty of Mathematics and Natural Sciences I
Department of Physics
Newtonstr. 15
D–12489 Berlin-Adlershof
Phone: +49-30-2093–7817
Fax: +49-30-2093–7642
E-Mail: pavel@physik.hu-berlin.de