HERA:

A SUPER-MICROSCOPE FOR THE PROTON AT THE ENERGY FRONTIER

* **Cristinel Diaconu** [1] and **Emmanuel Sauvan** [2],
* [1] CPPM, Aix-Marseille University, CNRS/IN2P3, Marseille, France and Deutsches Elektronen Synchrotron, Hamburg, Germany
* [2] CPPM, Aix-Marseille University, CNRS/IN2P3, Marseille, France
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Some 40 years ago the inner structure of the proton was revealed by the first 'deep-inelastic scattering' experiments at SLAC near Stanford. Energies were so large that the proton was decomposed, yielding evidence of point-like particles inside the proton, the so-called "partons". Now the electron-proton collider HERA in Hamburg is yielding new and precise information on proton structure.

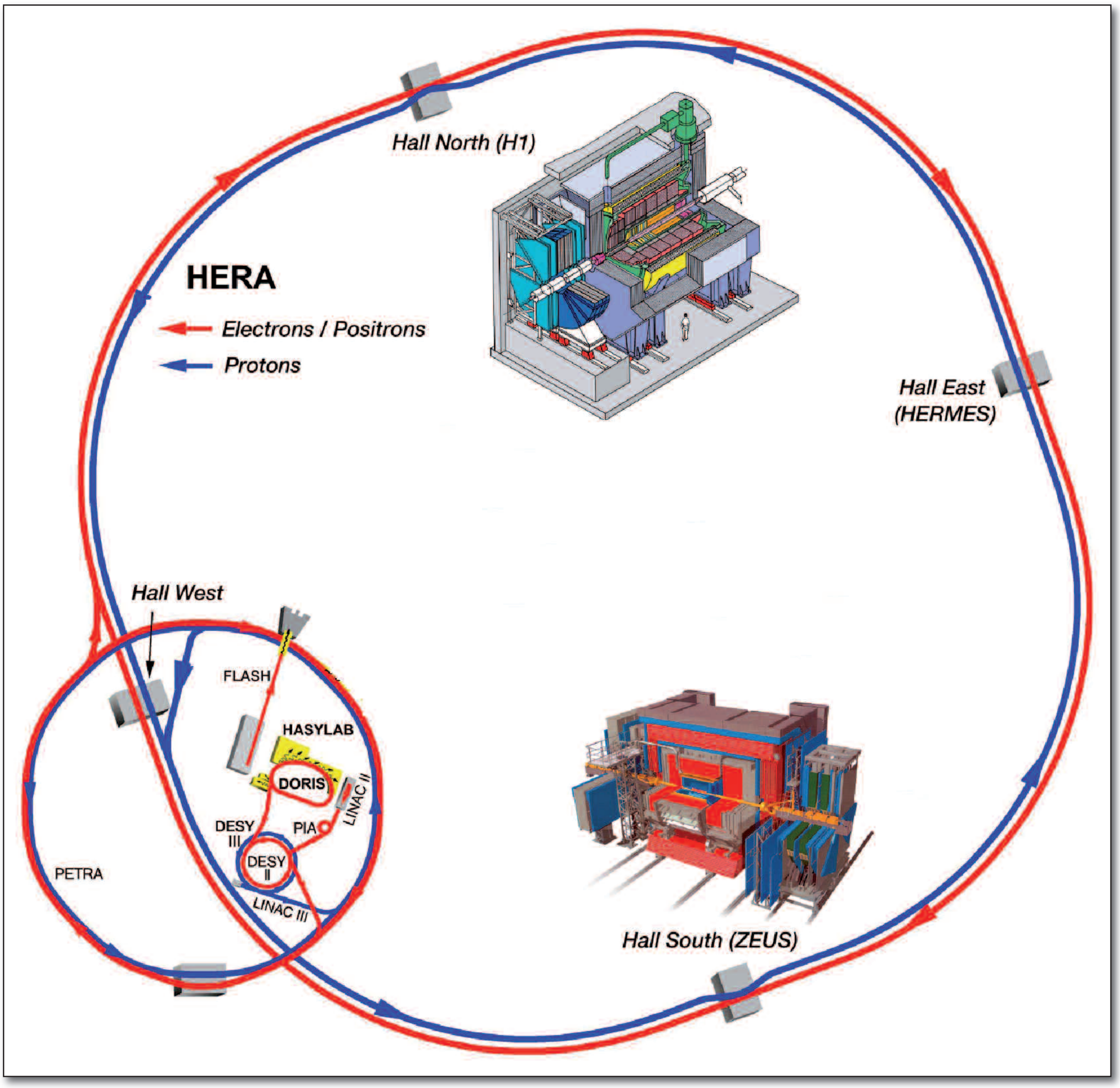
◀ P23: Inside the tunnel of the electron-proton collider HERA.

We know today that the partons are fundamental particles called quarks, interacting via vector bosons called gluons. They form the proton and the neutron, that are both baryons ('heavy particles', derived from the Greek *barus*, or heavy). Baryonic matter, that dominates the mass of the visible Universe, is therefore mostly composed of quarks and gluons. These carry an essential quantum number named "colour" and are the main characters of the theory of strong interactions: Quantum Chromo-Dynamics (QCD). This picture emerged in the seventies and eighties from many deep-inelastic scattering (DIS) experiments [1] that consolidated and refined the first discoveries.

A decisive step in the understanding of the proton structure was the arrival of the unique electron-proton collider HERA (Hadron Electron Ring Accelerator) at DESY (Deutsches Elektronen-SYnchrotron), in Hamburg, Germany. The centre-of-mass energy available at HERA of up to 320 GeV results from collisions of 27.5 GeV electrons or positrons with 920 GeV protons. The collider experimental program was developed with two multi-purpose, hermetic detectors, H1 [2] and ZEUS [3], designed to measure particles produced in each electron-proton interaction and operated by two collaborations of more than 300 physicists, from 90 institutes and 30 countries. The detectors contained internal trackers able to measure charged particle momenta, and calorimeters completing the measurement of the energy flow. A scheme of the HERA collider, together with the location of the H1 and ZEUS detectors is shown in Figure 1. The collisions started in 1992 and the data-taking ended June 30, 2007. The final precision analyses using the collected data are currently in progress. A few recent results, demonstrating the scientific reach of the HERA programme, are presented here.

Proton structure measurements

The collision of an electron with a proton is generally mediated by a photon, emitted from the incident electron. The distance δ probed into the proton by this photon is of the order of its wavelength which, following the Heisenberg's uncertainty principle, is inversely proportional to the amount of momentum transfer Q between the

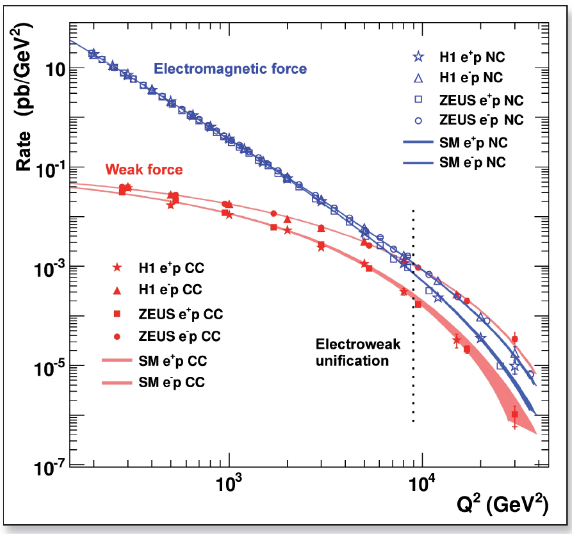


► FIG. 1: A schematic view of the HERA accelerator ring, including the injectors and the two collider mode detectors H1 and ZEUS. The accelerator ring as a circumference of 6.3 km and is situated at 30 m under Hamburg city. The detectors have a typical size of 10 m and are shown in a longitudinal section displaying the multiple detection technologies installed around the interaction point.

electron and the proton δ[fm] = 0.2 / Q [MeV]. This relation suggests that the spatial precision δ is improved by increasing the momentum transfer, which can be achieved by increasing the collisions energies. This explains why high energy colliders act as powerful microscopes. Since the energy available at HERA is 320 GeV it is easy to see that the probed distances are of order 10^{-18} m. This means resolving details of a size that is 1000 times smaller than the size of the proton, measured already in the fifties to be around 10^{-15} m. At such small distances, the photon can directly interact with the constituents quarks of the proton. The reaction reveals how the quarks compose the proton, via measurement of the fraction x of the proton's momentum carried by the struck quark. The accessed domain extends to very low values of x, in a region never explored before. Moreover, the large amount of momentum transferred allows also the exchange of the so-called weak bosons, carriers of another type of force, the weak force. While photons are massless, the weak bosons are rather heavy, with masses of the order of 100 GeV, such that they can occur as mediators of the electron-proton interaction only if the momentum transfer approaches their mass.

Unlike photons, which are sensitive to the electromagnetic charge only, the weak bosons couple differently to the various types of quarks. They induce processes with different strengths when positrons or electrons are used to probe the proton. If the exchanged boson is neutral, the process is said to proceed via the neutral current (NC) interaction and the scattered electron or positron is measured in the final state. In contrast, the charged current (CC) process, due to the exchange of the charged weak boson $W^{\pm}$, converts the initial positron or electron into a neutrino. The CC events exhibit an imbalance in the detected final state, since the produced neutrinos do not interact with the apparatus and escape undetected. The measurement of the rate of the neutral and charged current processes at HERA, expressed as a function of the transferred momentum squared Q^2, is shown in Figure 2. At low values of Q^2 the rate of CC interactions is much smaller than for NC, reflecting the nature of the pure weak interactions. However, at values of Q^2 close to the squared mass of the weak bosons, the rates become comparable, demonstrating the similar nature of the electromagnetic and weak interactions at high energies and pointing to the unification of forces, predicted by the theory.

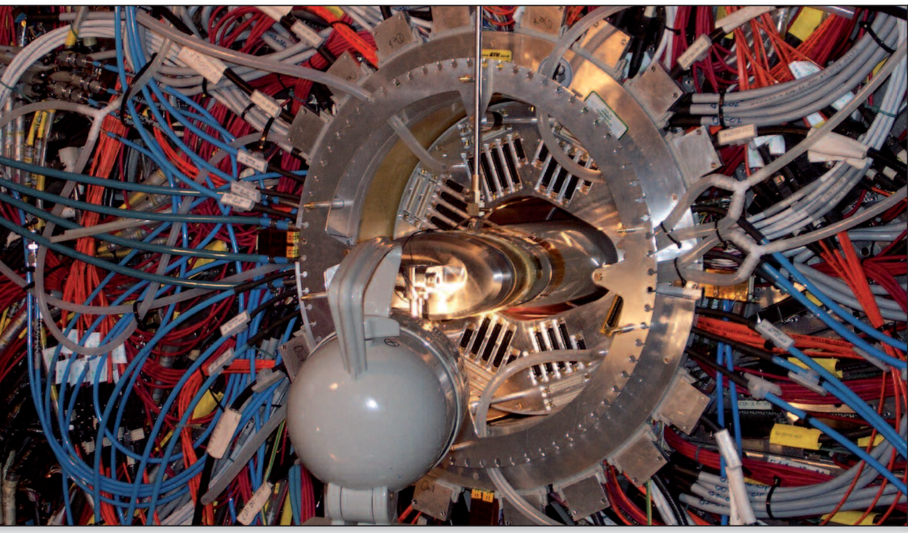
The kinematic domain probed at HERA extends also to very low x values, around 10^{-5}, where the partons carry only a tiny fraction of the proton momentum. This regime was probed for the first time at HERA and revealed a surprising picture: more and more partons are found in the proton as x decreases. QCD explains this intriguing cloud of partons as quarks produced by gluons, which are abundant in the low x regime and fluctuate to quark-antiquarks pairs. These quarks interact with the incoming electron within a laps of time that is also inversely proportional to the momentum transfer Q. Therefore the amount of partons at low x also increases with Q: the higher Q, the shorter the time of interaction, increasing thereby the chances to reveal the gluon-to-quarks fluctuations. This behaviour is observed in Figure 3. The variation with Q^2 of the rate of the NC interactions is increasingly violent for lower x and the precise data obtained at HERA is well described by the theory.

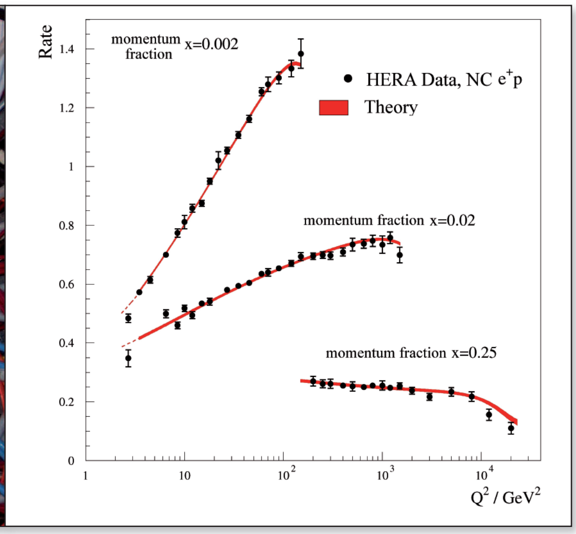


◄ **FIG. 2:** Rates, in picobarn (1pb=10^{-36} cm^2) per GeV2, of neutral (NC) and charged (CC) boson exchange processes as a function of the transferred momentum squared Q^2 performed by the H1 and ZEUS experiments at HERA, using electron- and positron-proton collision data. The measurements are in excellent agreement with the theory (Standard Model SM), which is shown as a shaded band.

There is however one component of the DIS process that cannot be predicted and is still a puzzle in contemporary physics, namely the dynamics of the quarks and gluons inside the proton; in short: the proton structure. This lack of predictability is the consequence of a peculiar property of the strong force: the asymptotic freedom. Whereas the other forces tend to decrease when the distance between the interacting particles increases, for the strong force the behaviour is reversed: two quarks are rather free while close in space and their interaction becomes stronger as they get separated. This property is described perfectly by QCD and also explains why quarks cannot exist in a free state and are always confined in color-neutral particles (hadrons). However, the unfortunate consequence of such a behaviour is that, given the size of the proton, the typical distance between the quarks is such that the coupling constant is large. Therefore, the usual calculation methods based on perturbative developments, successfully used in the case of a small coupling at high energies, are not applicable.

A way to simplify the problem is provided by a factorisation theorem, which separates the calculable part and allows for robust predictions. The physical observables (rates of physical processes) can be described as a convolution between the parton distribution functions (PDFs), describing the distributions of quarks and gluons in the proton, and some coefficients that are calculable in QCD. Even if the exact shape of the PDF's cannot be predicted, their evolution with Q^2 is calculable. It is therefore sufficient to consider a set of

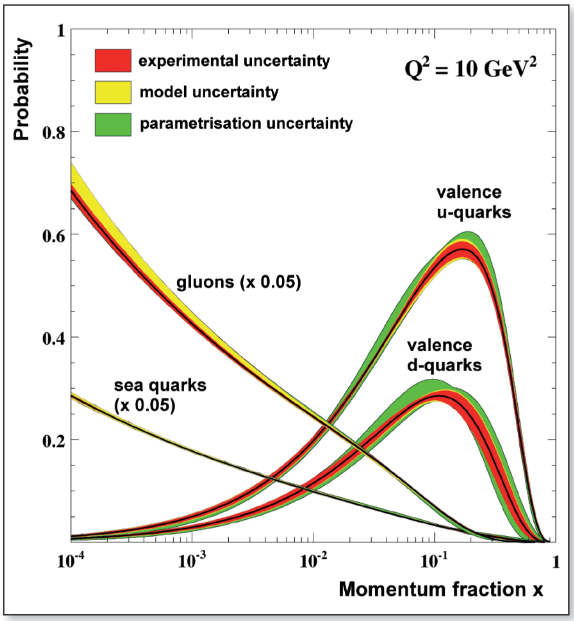




▲ Light on the heart of the H1 detector at HERA

► **FIG. 3:** Examples of rates of neutral boson exchange (NC) measured as a function of the transfered momentum Q squared at a given x. The evolution as a function of Q^2 is described by the theory and is a clear sign of the gluon contributions to the proton structure.

unknowns PDFs for the quark $q(x,Q_0^2)$ and gluon $g(x,Q_0^2)$, parameterized as a function of x at a given value of $Q^2 = Q_0^2$. Since the theory predicts both the insertion of these functions into the observable rates and also their evolution from Q_0^2 to any Q^2, all measurements over the large range in x and Q^2 available at HERA can be used to constrain the unknown PDFs. A recent determination of these functions describing the proton structure is shown in Figure 4, as obtained from a global fit of more that 600 measurements, resulting



▲ **FIG. 4:** Distribution of quarks and gluons in the proton as a function of the carried proton momentum fraction x. The "valence" quark distributions peak is around $x = 1/3$, as expected for the three constituents quarks building the proton. The distribution of the gluon as well as that of quarks occurring from gluon fluctuations ("sea") dominate the proton content at low x (these distributions are shown after division by a factor 20). The obtained precision is impressive, in particular at low x, below ~0.01, where no data was available before HERA.

from combining H1 and ZEUS data. The HERA data uniquely constrain the proton structure at low x, where the gluon largely dominates the partonic content. HERA DIS measurements provide therefore fundamental and unique knowledge for the understanding of the proton structure. Beyond the intrinsic value of the research in this domain, the measurements are particularly important for experiments involving protons, in particular for the Large Hadron Collider (LHC), the powerful proton-proton collider to start operations this year at CERN at an energy of 14 TeV (Terra Electron-Volts), seven times larger than the present similar collider running at Fermilab, Chicago in the United States.

Strong interaction probes

During the DIS experiments the scattered quark produces a jet of particles in the detector, due to the hadronisation process, which leads to the production of a statistically variable number of particles grouped in a jet. The scattered quark may also radiate high-energy gluons, which in turn can also produce a jet of particles. DIS events with more than one jet are therefore a clear signature of gluon radiation. Since this phenomenon involves the coupling between the quarks and gluons, the strength of the strong interactions (the so-called strong coupling α_s) can be measured from the rate of multi-jet events produced at HERA. In addition, HERA provides a way to test the strong interaction at various scales. Due to the correspondence between the transferred momentum Q and the distance probed, the measurement domain in Q allows the investigation, within a single experiment, of the strong coupling variation as a function of the typical distance between the particles interacting strongly. A recent measurement of the strong coupling as a function of the interaction scale is shown in Figure 5. The data displays the so-called "running" of the strong coupling over about two orders of magnitude in Q, as predicted by QCD. The coupling is indeed observed to be larger at low Q (*i.e.*, large distances) while it decreases at high Q, where particles interact over smaller distances. This is the property of asymptotic freedom, which is spectacularly confirmed by this complex and precise measurement.

On the energy edge

The present understanding of the particle physics is summarised in a theory called the Standard Model. This theory emerged in the last decades as a result of spectacular advances in experiment and theory. It includes quarks and leptons (particles similar to the electron) and their interactions via electromagnetic, weak and strong forces. Perhaps the most puzzling experimental observation successfully accommodated in the Standard Model is the organisation in three families of the known quarks and leptons, as well as their mass hierarchy. This apparent and unexplained ordering may be the result of a substructure, in the same way as Mendeleev's periodic table of the elements is explained by the content in protons and nucleons of the atomic nuclei. The electron-proton collisions at the highest momentum transfer are ideal to reveal new substructures inside the proton, probing this time the partons or even the incoming electrons. No significant discrepancy between the data and the Standard Model has been observed, in spite of extensive searches in a large number of channels (Figure 6). The results confirm that the known elementary particles are indeed point-like, with a size in any case smaller than the experimental resolution of 10^{-18} m. However, HERA allows also to substantially broaden the range of validity of the Standard Model and to restrict the possible phase space for new phenomena, new particles or new interactions.

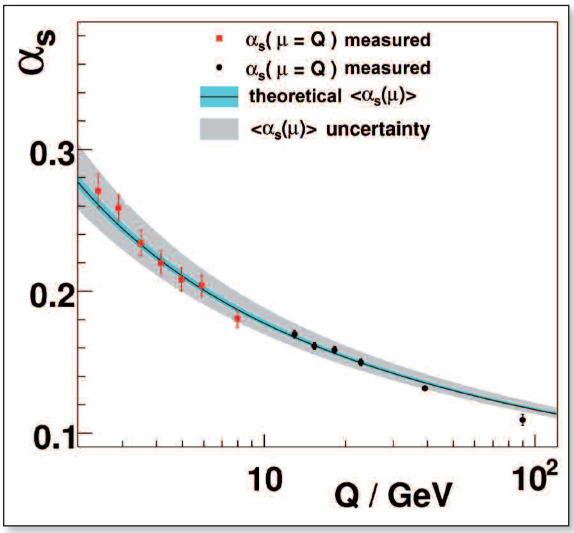
Outlook

Understanding of the structure of matter is a fundamental scientific goal. Tremendous progress has been made due to the experimental program at the HERA collider, which continues to deliver scientific results of high precision, probing the proton structure and investigating the energy frontier in a unique configuration. ■

About the Authors

Cristinel Diaconu is Directeur de Recherche at the Centre de Physique des Particules de Marseille (CPPM), CNRS, France. He studied at Bucharest University and obtained his PhD in 1996 at Marseille University. He is at present spokesperson of the H1 Collaboration operating one of the two detectors at HERA collider.

Emmanuel Sauvan is Chargé de Recherche at the Centre de Physique des Particules de Marseille (CPPM), CNRS, France. He received his Ph.D. in 2000 for work on the structure of exotic neutron rich nuclei. Presently, he is co-responsible of the H1 working group searching for new phenomena and leads the H1 group of the CPPM.



◀ **FIG. 5:** The dependence of the strong coupling constant α_s on the energy scale represented by *Q* compared with the expectation of quantum chromodynamics. At large momentum transfers (short distances), the strong force becomes increasingly weak, clearly displaying the property of asymptotic freedom.

References

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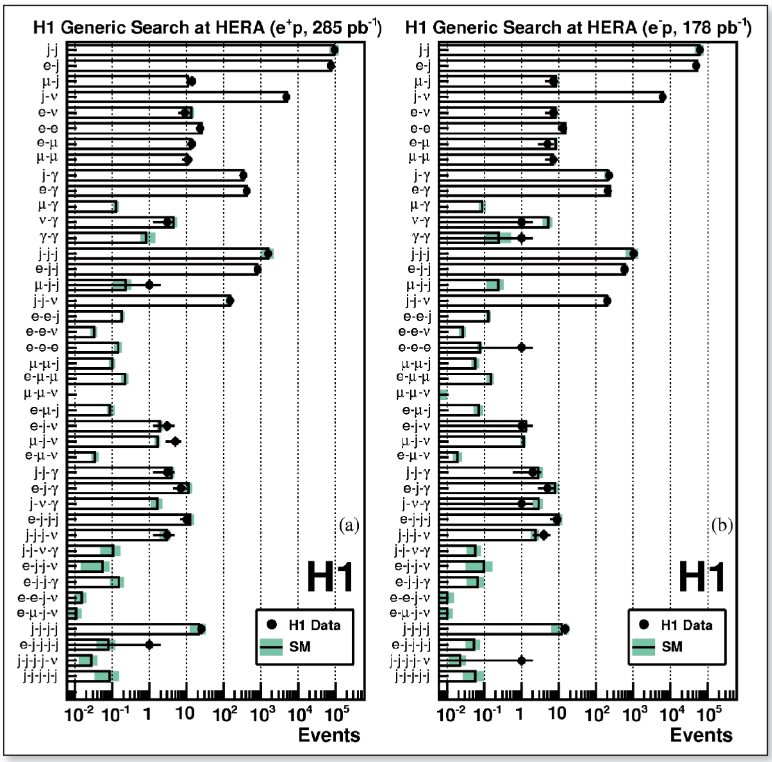
[3] ZEUS experiment and its scientific results are described at: www-zeus.desy.de



▲ **FIG. 6:** Total event yield observed for each type of events in a general, model-independent search for new phenomena at HERA. Various event classes are defined as combinations of jets (j), electrons (e), muons (μ), photons (γ) and neutrinos (ν). The observed event rates, represented as full dots, for positron-proton scattering (left) and electron-proton scattering (right) agree well with the predictions of the Standard Model SM (histogram) leaving no room for new physics effects at HERA.