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HERA – From an Idea to Results

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Abstract

For many decades, deep inelastic scattering has been a key tool in the quest for the understanding of the innermost structure of matter. HERA (Hadron-Elektron-Ringanlage, or Hadron-Electron Ring Accelerator), located at DESY in Hamburg, was the first storage ring in which leptons collided with protons. Using a collider increased the centre-of-mass energy by a factor of ten over previous fixed-target experiments, thus making HERA the most powerful electron microscope in the world. Data taking at HERA began in 1992 and ended in the summer of 2007. The international collaboration on the construction of the accelerator represented a new way of jointly building large research infrastructure. Two collider experiments, H1 and ZEUS, have provided a detailed and very precise picture of the proton and the forces acting within it. Many searches for new physics were performed at the electron-proton energy frontier. Two fixed target experiments, HERMES and HERA-B which used only the electron and proton beams of HERA, respectively, studied the spin structure of the nucleon and the production of strangeness, charm, and bottom in high-energy proton collisions.

Introduction

Around 1910, E. Rutherford and his co-workers were the first to analyse the inner structure of atoms by scattering alpha-particles off a gold foil. About 60 years later, accelerator-based deep-inelastic scattering using electrons as projectiles led at the Stanford Linear Accelerator to the discovery of partons as hard, point-like constituents of the proton (Breidenbach (1969)). This discovery established lepton-proton scattering as a very powerful technique. In order to reach yet higher resolution, two paths were pursued: Using very high energy muons or neutrinos and using the collider technique, by also accelerating the protons and by colliding them with high energy leptons. The second solution was studied especially in Europe in a number of workshops and reports, leading in May 1980 to a recommendation by the European Committee for Future Accelerators, ECFA. ECFA recommended strongly the construction of an electron/positron-proton collider at DESY and welcomed the possibility of its being used by the European community. This recommendation was unanimously approved by the Plenary ECFA assembly.

In February 1981 the project was positively evaluated by a review panel of the German science ministry, in July of the same year the detailed proposal was published, followed in 1984 by the official 'go-ahead' from the German funding agencies, after significant contributions from international partners had been secured (see below).

Building an Accelerator in International Collaboration

The construction of HERA is an impressive example for international collaboration in particle physics. The HERA collider was the first major accelerator project at a national laboratory which was internationally funded. Previously, the construction of accelerators was funded to 100 % by the host countries, while experiments were frequently funded and built by international collaborations. The desire to use HERA was, however, so large, that many international partners declared their willingness to contribute through components and manpower to the construction. In total, more than 45 institutes from 12 countries contributed to the construction (about 22 % of the HERA construction cost of 700 Mio. € was carried by the international partners). This way of building new research infrastructures became later known as the 'HERA-Model'.

Two elements were essential for this model to work: The personal engagement of individuals and the willingness of the German government to invest in a major facility using this model. A few individuals deserve mentioning. At DESY the driving forces behind the project were V. Soergel (Chairman of the Board of Directors), G.A. Voss (project leader for the electron ring, civil construction and infrastructure), and B. Wiik (for many years one of the leading proponents for electron-proton colliders and project leader for the proton ring). Among the international partners Italy played as special role as the largest contributor (half of the superconducting magnets were provided as in-kind contribution from Italy). The driving force behind Italy's engagement was A. Zichichi (then president of INFN), who had realised that a major engagement in the superconducting magnet construction would provide an essential boost of know-how to the Italian industry in the area of superconducting magnets to the Italian industry (Fig. 1).

The HERA Double Ring Collider

The HERA ring (Voss and Wiik (1994)) has a circumference of 6.3 km. Inside the HERA tunnel, leptons (electrons or positrons) and protons were stored in two independent storage rings. Leptons and protons were pre-accelerated in a chain of accelerators before being injected into the HERA ring, where they were accelerated to their nominal energies (most of the time 820 and 920 GeV for protons and 27.5 GeV for electrons or positrons). The lepton ring was equipped with warm magnets, while the proton ring used superconducting magnets to provide the high magnetic field needed for proton energies close to 1 TeV.

A few milestones on the way to completion were: Civil construction (1984-87), mass production of the superconducting magnets (1988-90), installation of the electron ring and in August 1988 the first stored electron beam, completion of the installation of the proton ring (September 1990), commissioning of the proton ring (April 1991). On 19 October 1991 first collisions of electrons end protons were observed.

During the HERA construction and operation substantial challenges had to be met. A few examples are the design of the superconducting magnets; the collision of different particle species (never done so far); handling a large number of colliding bunches; and the short, 96-ns bunch-repetition time, which was also a major challenge for the experiments.

The HERA Harvest

The luminosity operation and data taking of the collider experiments started in 1992 and ended in June 2007. Until 1997, HERA accelerated protons to 820 GeV and leptons to 27.5 GeV. In 1998, the beam energy for protons was increased to 920 GeV, corresponding to a centre-of-mass energy of 318 GeV and a spatial resolution of 10^{-18} m. After a significant luminosity upgrade program (2000-2001) a fourfold luminosity increase was achieved. During the last few months of operation in 2007, the proton-beam energy was lowered to 460 GeV and 575 GeV in order to measure one particular structure function. HERA operation ended in June 2007 after 15 years of data collection, having delivered its design luminosity. The total integrated collider luminosity delivered by HERA amounted to 320 pb-1 (for electrons), and 460 pb-1 (for positrons).

One special feature of HERA was the fact that the lepton beam became naturally transversely polarized through the emission of synchrotron radiation (Sokholov & Ternov (1964)). The characteristic build-up time of polarization in HERA was approximately 40 min. Spin rotators on both sides of the experiments (Buon & Steffen (1986)) changed the transverse polarization of the beam into a longitudinal one. The polarisation reached 65% when only one experiment used the polarised beam and decreased due to a larger beam-beam interaction to 40% when three experiments used the polarisation.

Experiments at HERA

HERA had four interaction regions used by the experiments H1, ZEUS, HERMES, and HERA-B. Of the four experiments, H1 and ZEUS used the colliding lepton and proton beams, whereas HERMES used only the leptons and HERA-B only the protons.

The H1 and ZEUS detectors were large magnetic spectrometers with nearly hermetic coverage. They were designed following similar physics considerations but with different technical solutions, both for the calorimetric and the tracking measurements. They are described in detail in (Abt (1997) and Holm (1993)).

The main component of the H1 detector was a finely segmented liquid argon calorimeter surrounded by a superconducting coil, together with an instrumented iron structure acting as both a shower tail catcher and a muon detector. Tracks in the forward direction were measured in the forward tracking detector. Fig. 2 shows a schematic view of the H1 detector with the tracks and energy deposition of an electron and a hadronic shower superimposed.

The main component of the ZEUS detector was a uranium–scintillator calorimeter. Charged particles were tracked in the central tracking detector, which operated in a magnetic field provided by a thin superconducting solenoid that was positioned inside the calorimeter. Drift chambers provided additional tracking in the forward and rear directions.

The collider experiments H1 and ZEUS had to cope with a number of considerable challenges: bunch crossings every 96 ns, currents of up to 100 mA in the proton beam, and very asymmetric energies of the colliding particles.

The HERMES experiment was designed to study the spin structure of the nucleon with collisions of longitudinally polarized electrons or positrons on the (polarised) gas jet target. A detailed description of the HERMES experiment can be found in (Ackerstaff (1998)). The HERMES detector was a forward spectrometer with a large number of tracking chambers and several particle-identification detectors. The spectrometer was constructed as two identical halves, mounted above and below the beam pipes.

HERA-B had been designed to measure all charged particles and photons produced in the central rapidity region by collisions of protons from the HERA proton ring with the nuclei of target wires positioned in the halo of the beam. It consisted of a vertex detector, followed by a magnetic spectrometer. These components were supplemented by an electromagnetic calorimeter, a ring-imaging Cherenkov detector, and a muon identifier. More details on the detector and trigger system can be found in (Abt et al. (2006)).

Physics Results from the Collider Experiments

In HERA, a point-like probe (electron or positron) collided with a complex target (proton). The principal processes of interest in these collisions are the neutral-current (NC) and charged-current (CC) interactions of the electron or positron with the proton through the exchange of a neutral or charged virtual boson. These processes are characterized by either the scattered electron/positron or a neutrino in the final state.

The following variables are used to describe the kinematics: the virtuality of the exchanged boson, $-q^2 = Q^2$, where q is the four-momentum of the boson and the so-called Bjorken scaling variable, $x = Q^2/(2\, p \cdot q)$, where p is the four-momentum of the proton and x the fraction of the proton momentum carried by the struck quark.

The main emphases of the collider experiments were the measure the proton structure with unprecedented precision, the study the strong force in a clean laboratory, the study the electroweak force, the exploration of the physics beyond the Standard Model which could manifest itself for example as some form of *lepton-quark* fusion and become visible through the observation of lepto-quarks.

In the following, only a few highlights among the results are being presented. A comprehensive review of collider physics results from HERA-I can be found in (Klein & Yoshida (2008)). A more recent review can be found in (Diaconu et al. (2010)).

Strong Interaction

A measure of the density of quarks and gluons in the proton is provided by the so-called *structure functions* (F_2, F_3, F_L). The precise knowledge of the structure functions of the proton provides important information about the features of the strong interaction (QCD) and is of vital importance for understanding the results from proton-proton collisions as measured at the Tevatron and the Large Hadron Collider LHC. The structure functions depend only on the variables x and Q^2.

The HERA measurements of the inclusive deep-inelastic scattering (DIS) cross sections provide information on the structure of the proton in the ranges $10^{-6} < x < 0.5$ and $0.04\ \mathrm{GeV}^2 < Q^2 < 10^5\ \mathrm{GeV}^2$. At small Q^2, F_2 rises moderately toward low x. The rise of F_2 with Q^2 becomes more and more pronounced as Q^2 increases. This rise is an effect of the gluon splitting into a quark-antiquark pair $g \rightarrow$ *quark pair*. With growing Q^2, the time resolution of the probing photon improves, leading to an increasing number of interacting partons from the gluons short time fluctuations into quarks. The “steep rise in F_2” with decreasing x, due to density increase of soft partons (gluon splitting), is one of the most significant discoveries of HERA (Fig. 3). This rise is also qualitatively predicted by perturbative QCD. The H1 and ZEUS Collaborations achieved a significant reduction of their systematic uncertainties by combining their independent cross-section measurements, leading to a significant part of the reduction in the uncertainties through a cross-calibration of the two detectors and reaching a level of total uncertainty reaches of about 1%. In this way the complementary design of the two experiments paid off through an increased accuracy (Fig. 4) (Aaron et al. (2010)).

The leptons do not only probe the valence quark density, but provide also a measurement of the density of heavy quarks which contribute significantly to the total cross section: charm (20%) and beauty (5%). The cross sections of heavy quark production are described by perturbative QCD and allow testing if heavy quarks result only from gluon splitting or if an intrinsic, non-perturbative gluon density in the proton exists. The measurements indicate that there is no evidence for a non-perturbative gluon component.

The structure of the proton and QCD can be measured not only through the DIS cross-section, but also in more detail through the analysis of the hadronic final states. Extensive tests of jet and particle production have shown an excellent agreement of the data with QCD.

Jets with large transverse energy result when the struck quark radiates energetic gluons. The production rate of these jets is sensitive to the strong coupling constant, α_s. Jet cross sections were measured as functions of Q^2 and *transverse energy*. The dependence of the cross sections on these variables allows measuring α_s at various energies in a single experiment. The observed decrease of α_s with increasing scale demonstrates strikingly the asymptotic freedom of QCD (Schoerner-Sadenius (2011) (Fig. 5).

Electroweak Interaction, Searches and Other Topics

The large centre-of-mass energy of HERA gave access to a measurement of the weak and electromagnetic effects in a region where the NC and CC cross sections, i.e. the electromagnetic and weak forces, are of comparable strength. In Figure 6 the NC and CC *electron- and positron-p* scattering cross sections are shown as a function of Q^2 (Chekanov et al. (2008 & 2009)). At small values of Q^2, the NC process dominates because only electromagnetic effects contribute. When Q^2 is comparable to the mass squared of the Z^0 and W -bosons, the two cross sections are of similar magnitude. In addition, the CC cross section is much larger in e^-p than in e^+p scattering. In e^-p scattering, the exchanged W^- couples mostly to the *u*-valence quarks, which are approximately twice as abundant in the proton as the *d*-valence quarks. A similar but smaller effect can be observed in the NC cross section, where the difference between the e^+p and e^-p cross sections is due to interference between photon and Z^0 exchange. From this difference one obtains the parity violating structure function xF_3, which provides information about the valence quark distributions. It is impressive to see that the measured cross sections agree with the predictions of the Standard Model over 6 orders of magnitude and that the electromagnetic and weak forces become of similar strength at high energies, directly showing the unification of forces.

The availability of longitudinally polarised beams in H1 and ZEUS gave access to a measurement of the polarisation dependence of the CC cross section. This cross section depends linearly on the polarisation and will vanish for right-handed electrons or left-handed positrons. The three measurements of the CC cross sections made with un-polarised beams and with negatively and positively polarized beams lie on a straight line when plotted as a function of the beam polarization. In agreement with the Standard Model, no right handed CC events were observed. However, this measurement was less precise than from other methods.

HERA was also sensitive to many kinds of new physics – for example the production of lepto-quarks, R-violating supersymmetry, etc., allowing searches for physics beyond the Standard Model with sensitivities which for many channels were comparable to or higher than at LEP and the Tevatron. In the course of data taking some signals of unexpected physics were observed by both H1 and ZEUS. These were indications for lepto-quarks and an apparent excess of high p_T leptons. However, the signals came and went, and were statistical fluctuations which disappeared with more accumulated data (see for ex ample Ciesielski (2009)).

The ratio of the measurements of the neutral-current cross section for e^+p and e^-p scattering has been used to determine an upper limit on the quark radius. If quarks were not point-like, the predicted Standard Model cross section at largest Q^2 would follow a form factor depending on the effective quark radius. In the measurements no deviation from the Standard Model prediction has been found, from which an upper limit for the quark radius of approximately 0.63×10^{-18} m has been determined, illustrating the power of HERA as an electron microscope (Ciesielski (2009)).

Physics Results from HERMES: What is the Origin of the Proton Spin?

The HERMES experiment was proposed after the unexpected observation by the EMC Collaboration (Ashman (1988)) that only a small fraction of the nucleon's spin could be attributed to the spins of the quarks. The primary scientific goal of HERMES was therefore the detailed investigation of the spin structure of the nucleon. Using the polarised electrons/positrons together with a polarised target, combined with a tagging of the final state quark species (as the flavour content of the final state hadrons is connected to the flavour of the struck quark), HERMES determined with high precision the contribution of different quark types to the spin of the proton to be approximately 1/3, while the rest must be attributed to gluons and orbital angular momenta. In addition, HERMES extracted a rather small value of the average gluon polarization $\Delta g/g = 0.05 \pm 0.15$ in the range $0.1 < x < 0.4$ (Airapetian (2010)). Thus, the measurements by HERMES have confirmed with high precision the contribution of quark spins to the spin of the nucleon. Yet, the full explanation of the nucleon spin still remains unclear.

The physics reach of the experiment extended well beyond the original scientific goal, and HERMES explored many details of hadron structure, hadron production, hadronic interactions, and especially hard exclusive reactions with electromagnetic probes at centre-of-mass energies of approx. 7 GeV. Many of the results published to date are discussed in (Rith (2002) and Burkardt (2010)).

Physics Results from HERA-B

The HERA-B Collaboration proposed to measure *CP* violation in decays of *B* mesons. In order to achieve the needed integrated luminosity, a collision rate of protons from HERA with the target nuclei of 40 MHz was required, which in turn required the use of radiation-hard technologies and a multilevel di-lepton trigger and data-acquisition systems. The development of the trackers needed to cope with the intense particle fluxes at HERA proved more difficult than anticipated, and in 2000 it became apparent that HERA-B could not compete with the *e*+*e*− experiments. Nonetheless, the radiation issues had been overcome, and the experiment was nearing completion. The collaboration then decided to exploit the detector for a range of production studies with an emphasis on heavy-flavour production. The two principal results were the determination of the total cross section for *b* quark production (Abt (2007)) and the measurement of charmonium production and its dependency on the atomic number of the target nucleus.

Summary

During fifteen years of very successfully operation, the electron/positron collider HERA has reached its luminosity goals and has provided a wealth of results which exceeded the expectations in terms of precision and which significantly deepened our understanding of the strong and electroweak forces, while at the same time exploring uncharted territory beyond the Standard Model. HERA became a unique probe for physics at small *x* and provided detailed insight into the structure of the proton. Many results are essential for the interpretation of the LHC measurements and for all other experiments in which precise knowledge of the proton structure is important. Many of the HERA results will enter the text books and remain valid for a long time, present a challenge to theorists, particularly in the field of QCD, in order to explain the measurements.

At the same time HERA became a role model for how to build large research infrastructure in a joint national and international effort.

Acknowledgements

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References

The following references represent only a small sample of the full list of HERA publications. For more references the reader is referred to Diaconu at al. (2010) and the references therein.

Aaron FD et al. (H1 and ZEUS Collab.) *JHEP01 109 (2010)* and references therein

Abt I et al. (H1 Collab.) *Nucl. Instrum. Methods A* 386:310 (1997)

Abt I et al. (HERA-B Collab.) *Phys. Rev. D* 73:052005 (2006)

Abt I et al. (HERA-B Collab.) *Phys. Lett.* B650:103 (2007)

Ackerstaff K et al. (HERMES Collab.) *Nucl. Instrum. Methods A* 417:230 (1998)

Airapetian A et al. (HERMES Collab.). arXiv:1002.3921 [hep-ex] (2010)

Ashman J et al. (EMC Collab.) *Phys. Lett.* B 206:364 (1988)

Breidenbach M et al. *Phys. Rev. Lett.* 23:935 (1969)

Buon J, Steffen K *Nucl. Instrum. Methods A* 245:248 (1986)

Burkardt M et al. *Rep. Prog. Phys.* 73:016201 (2010)

Chekanov S et al. (ZEUS Collab.) *Eur. Phys. J. C* 61:223 (2008) and Chekanov S, et al. (ZEUS Collab.) *Eur. Phys. J. C* 62:625 (2009)

Ciesielski R (for H1 and ZEUS Collab.) *PoS (EPS-HEP 2009):269 (2009)*

Diaconu C, Haas T, Medinnis M, Rith K, and Wagner A. *Annu. Rev. Nucl. Part. Sci.* 60:101 (2010)

Holm U ed. (ZEUS Collab.) Status rep. http://www-zeus.desy.de/bluebook/bluebook.html (1993)

Klein M, Yoshida R. *Prog. Nucl. Part. Phys.* 61:334 (2008)

Rith K. *Prog. Nucl. Part. Phys.* 49:245 (2002)

Schoerner-Sadenius, T. arXiv:1111.7290 [hep-ex] (2011)

Sokholov AA, Ternov M. *Sov. Phys. Dokl.* 8:1203 (1964)

Voss GA, Wiik BH. *Annu. Rev. Nucl. Part. Sci.* 44:413 (1994)

Pictures _ HERA – from an Idea to Results (A. Wagner)

Figure 1: V. Soergel (left), A. Zichichi and the former It alian Pri me Minister G. Andreotti, discussing the Italian engagement in HERA.

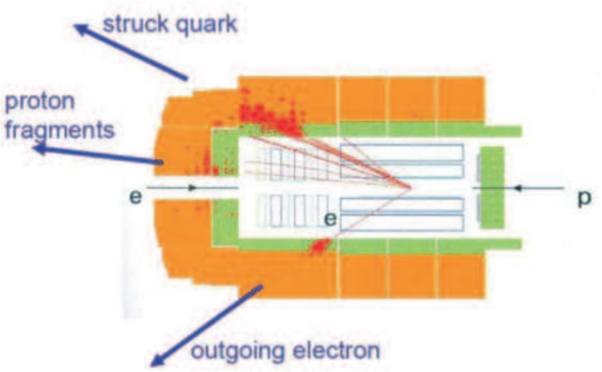

Figure 2: Schem atic view of the H1 experiment and, superimposed, a neutral current event. The scattered electron, the particle shower resulting from the str uck quark and traces of the proton fragments are clearly visible

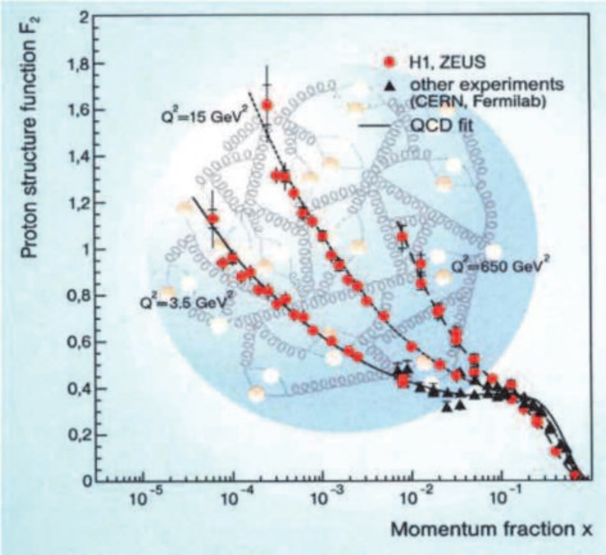

Figure 3: The proton structure function F_2 (a measure of the number of quarks and gluons in the proton) as function of the momentum fraction x, for various values of Q^2 (a measure for the special resolution). The strong rise of the parton density at low x is clearly visible, increasing with Q^2.

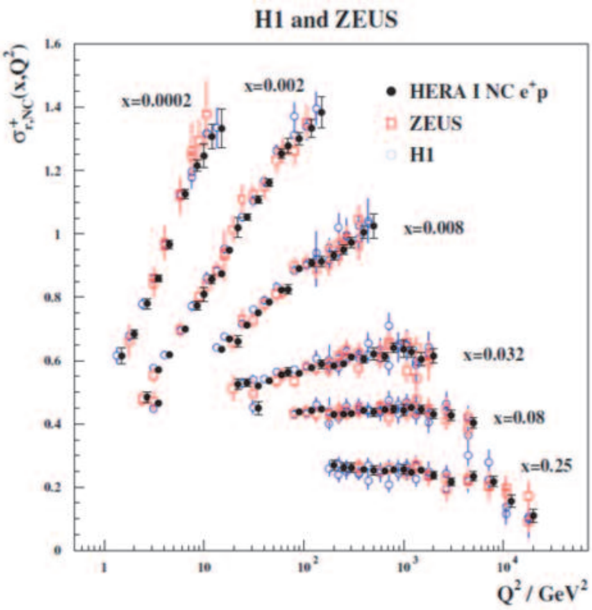

Figure 4: HERA combined NC e^+p reduced cross section as a function of Q^2 for six x-bins compared to the separate H1 and ZEUS data input to the averaging procedure. The individual measurements are displaced horizontally for better visibility.

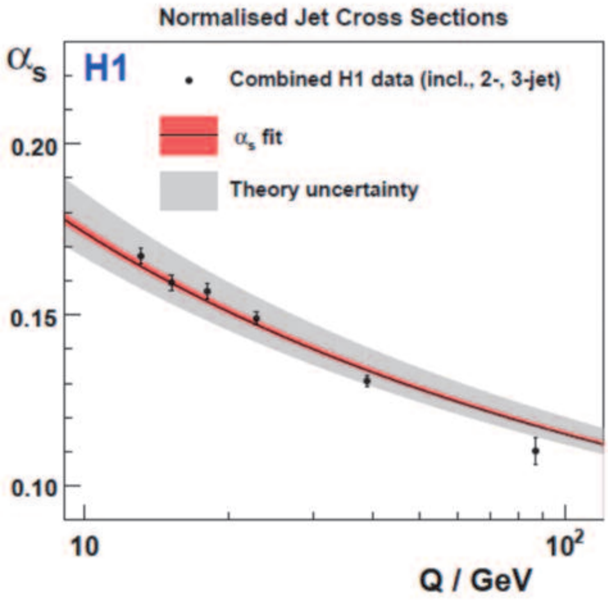

Figure 5: The value of the strong coupling constant α_s as function of energy, obtained by H1 by a simultaneous fit of all normalized jet cross sections.

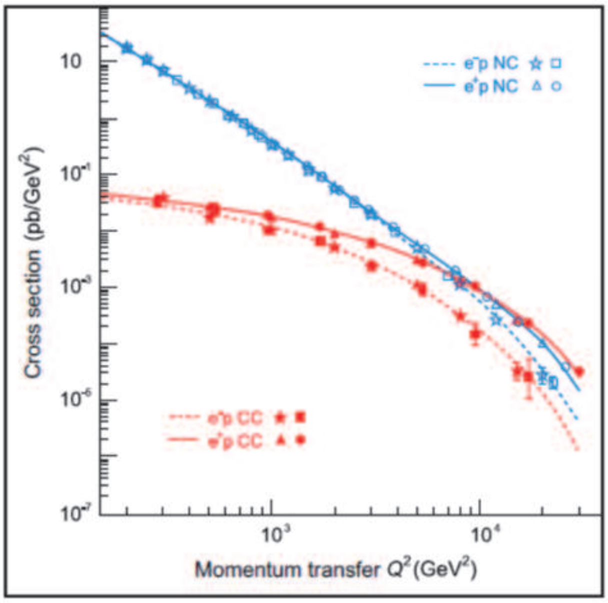

Figure 6: The cross section for deep inelastic electron- and positron-proton scattering neutral current (NC) and charged current (CC) events as function of the momentum transfer Q^2. The lines indicate the expectations from the Standard Model.