THE PHYSICS OF DEEP INELASTIC SCATTERING AT HERA

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In this paper an introduction to the physics of deep inelastic scattering is given together with an account of recent results obtained in electron– or positron–proton collisions at the HERA collider. The physics of the deep inelastic scattering is placed in the historical perspective of the quest for the ultimate structure of the matter. The proton structure measurements and tests of the theory of the strong interactions and of the electroweak sector of the Standard Model are presented. The rôle of HERA as a collider at the energy frontier and its legacy to the physics programme at the Large Hadron Collider are discussed.

1. INTRODUCTION TO DEEP INELASTIC SCATTERING

1.1. AN HISTORICAL PERSPECTIVE ON THE MATTER STRUCTURE

The quest for the structure of the matter is central to the history of science. In the early days, philosophers expressed the wish to reduce the world to a number of elementary building blocks. The “greek” model attempted to explain the world through four elements (water, air, earth and fire), from which the objects of the whole world were built. The model, extended by Aristotle to include a fifth element (the quiescence, or the vacuum) foresaw also interaction among the basic elements leading to transformations and creation of all forms of matter and phenomena. A different approach, more abstract, was adopted by Platon, who used as basic elements a set of geometric bodies, from which the whole world could be composed. Although none of these ancient models were able to confront to some relevant observation, their merit is rather to state the question and to try some systematic answer [1]. The first serious measurements of the matter composition were made with the advent of chemistry. The elements, found by Lavoisier and Davy, dismantled Aristotle model since the air was shown to contain a more elementary component, the oxygen. This was the first proof of “compositeness”. About 50 elements were discovered during the first half of the 19th century. In order to systemise this wealth, Mendellev

them in a table and discovered the periodicity. The first version of the table had empty slots, so new elements were predicted. They were discovered a few years later with properties in an remarkable agreement with the prediction. The elements were suposed to be composed of “atoms”.

In the beginning of the XX century, atoms were known to radiate and to absorb radiation which indicated that they were not elementary but composed particles. The way to identify and measure the composition of the atoms was pioneered in 1911 by Geiger, Marsden and Rutherford (GMR), who opened a new era in the study of the matter structure: the scattering experiments. GMR observed that some of the α particles colliding with a gold foil were backscattered. This is unexpected if gold atoms were a continous charge distribution within a finite volume. In Rutherford’s words: “it was as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you”. This could only have happened if the α particle had hit a concentrated field, like a point-like massive charge centre identified as the atomic nucleus.

The resolution with which the “target” can be investigated by a point-like incoming particle determined by the uncertainty principle: the higher the transfer momentum (denoted by \( Q \)), the smaller the details that can be “flashed” and imprinted in the angular distribution of the scattered (point-like) particle. The resolution can be expressed as:

\[
\delta = \frac{0.2 \cdot 10^{-15} \text{m}}{Q[\text{GeV}]}.
\]

For a momentum transfer of around 1 GeV the probed distances are comparable with the size of the proton.

The search for further substructure levels continued with the scattering of leptons on light nuclei \((H, D)\) in order to investigate the structure of protons and neutrons, the main components of the nuclear matter. Besides the electron and the nucleons, many other particles were discovered in the first half of the XXth century. Their production and decay properties gave rise to a new type of “chemistry”, in which the particle reactions revealed two new forces: the weak force and the strong force. In particular, besides the proton and the neutron, many similar particles produced by strong interactions were discovered. There was the time for a new “table” and a new concept of compositness. The hadrons were predicted to be composed of quarks, a new type of particles with fractional electric charge, interacting via the carriers of the strong force, the so-called gluons.

Quarks and gluons were discovered using electrons of higher and higher energies, which were ultimately able resolve the nucleon’s structure in the so called deep inelastic scattering (DIS). In this paper, an introduction to the physics of DIS is given using as examples the first experimental results that established the basic model of the nucleon structure [2]. A qualitative change
occurred with the HERA project, an electron–proton collider at very high energy. The physics and a selection of HERA results will also be described.

1.2. THE OBSERVABLES OF LEPTON-HADRON SCATTERING

The framework in which lepton–hadron scattering is described is shown in Fig. 1. The scattering can occur via the exchange of $\gamma$ or $Z$ bosons (neutral currents NC) or via $W$ bosons (charged currents CC). In the latter case, a neutrino is expected in the final state for an incoming charged lepton (and vice versa).

![Fig. 1 – Lepton-hadron scattering: an exchange of a boson in the $t$-channel.](image)

The incoming electron (with a four-momentum $k$) scatters off the proton ($P$) to a final state electron with four-momentum $k'$ via a virtual photon $\gamma^*$ or a weak boson with a virtuality $Q^2$ exchanged in the $t$-channel. In inelastic scattering, one can assume that only a part of the proton ("parton") enters the reaction. The Bjorken variable $x$ is associated with the fraction of the momentum of the proton carried by the struck parton. The total centre-of-mass energy is given by $\sqrt{s}$ and the energy of the $\gamma^* p$ system is given by $W$, which is equivalent to the total mass of the hadronic system in the final state $M_X$. In the case of elastic scattering $M_X = M_p$ and from the $M_X$ expression it follows that $Q^2 = 2Pq$ and $x = 1$ (the whole proton interacts). Only two variables are independent, since the reaction is completely defined by the scattering angle and by the electron-parton centre-of-mass energy. The variable $\nu$ has a simple meaning in the proton rest frame, as the energy lost by the electron during the scattering $\nu = E_e - E'_e$, while $y$ represents the fractional energy loss $y = \frac{E_e - E'_e}{E_e}$. $Q^2$ can be expressed as a function of the electron energy and scattering angle, $Q^2 = 4E_e E'_e \cos^2 \frac{\Theta}{2}$. From these relations, it is obvious that the DIS kinematics
can be calculated from the measurement of the scattered electron only. The measurement of the hadrons in the final state, if available, can be exploited as an extra constraint in NC scattering. It is the only way to reconstruct the CC kinematics, since the outgoing neutrino is not measured.

1.3. ELASTIC LEPTON-HADRON SCATTERING

The parameterisation of the elastic differential cross section as a function of $Q^2$ depends on the electric ($G_E$) and magnetic ($G_M$) form factors of the proton and can be written as:

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left[ G_E^2 + \tau G_M^2 \left(1 - \frac{M^2}{Q^2}\right) + \frac{y^2}{2} G_M^2 \right]$$

It is useful to remember that the scattering amplitude $A_p$ of a particle on a charge with a finite charge distribution $\rho(\vec{r})$ can be factorized as $A_p = A_0 F(q)$, where $A_0$ is the amplitude of the scattering off a point-like charge and $F(q)$ is a form-factor that depends on the momentum transfer $q$. It can be demonstrated that the form–factor is the Fourier Transform (FT) of the charge distribution. Therefore, the scattering cross-section can be related to the charge distribution inside the target.

An important step forward in the understanding of the structure of matter has been made by Hofstadter et al. [3] in an elastic $ep$ (and later $ed$) experiment using electrons with energies of up to 246 MeV to investigate the charge distribution inside the proton. The result is shown in Fig. 2 (left). The measured cross section at large scattering angles is below the prediction for scattering off a

![Fig. 2](image-url)  
**Fig. 2** – Left: The measurement of the cross section as a function of diffusion angle (Hofstader). Center: First result on deep inelastic cross section measurement. Right: The illustration of the Callan-Gross relation (from [5]).
point-like charge. Using the form–factor argument presented above, the typical size of the proton charge distribution is found to be around $10^{-15}$ m. This observation implied that the proton is not pointlike. Its structure can be investigated using electrons with higher energy such that inelastic reactions are induced.

1.4. DEEP INELASTIC SCATTERING AND THE NAIVE PARTON MODEL

In addition to $Q^2$, one more variable ($x$) is needed to describe inelastic $ep$ scattering at a given beam energy, since only a part of the “target” is involved. In the double differential cross section, the elastic form factors are replaced by the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$.

$$\frac{d\sigma}{dQ^2 dx} = \frac{4\pi\alpha^2}{Q^4} \left[ (1 + (1 - y)^2) F_2 + \frac{1 - y}{x} (F_2 - 2x F_1) \right]$$  \hspace{1cm} (2)

The structure functions represent a generalisation of the form factors, however, the simple interpretation as the FT of the charge distribution is not possible, due to the extra variable $x$. Nevertheless, the structure functions provide however direct information on the proton components. This can be demonstrated within the so-called “parton model”. The assumption is that the proton, proven to have a finite size of around $10^{-15}$ m, is composed of point-like spin 1/2 particles, the “partons”. The formalism is expressed in the “infinite momentum” frame, in which the motion of the parton within the proton is much slower than the time of interaction. The lepton–proton interaction is described as a coherent scattering of the lepton on a sum of independent (“frozen”) partons. If we consider the lepton–parton cross section

$$\frac{d\sigma}{dQ^2} = \frac{2\pi\alpha^2}{Q^4} e_q^2 \left[ 1 + (1 - y)^2 \right],$$  \hspace{1cm} (3)

and assuming the proton is a sum of partons of charge $e_q$ and momentum fraction distribution $q(x)$, the lepton-proton cross section can be written as:

$$\frac{d\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4} \left[ 1 + (1 - y)^2 \right] \sum_q e_q^2 q(x).$$  \hspace{1cm} (4)

Comparing with the equation 2 results in the following relation:

$$F_2 = x \sum_q e_q^2 q(x)$$  \hspace{1cm} (5)

In this formula one can see explicitly that to first approximation the structure function $F_2$ does not depend on $Q^2$. This property, called “Bjorken scaling”, occur since a point-like parton is seen in the same way by all wavelengths. In
addition, a direct relationship is deduced between \( F_2 \) and \( F_1 \), called Callan-Gross relation [4]: 
\[ F_2 = 2xF_1 \]
This relation is typical for spin 1/2 constituents (scalar constituents would lead to \( F_1 = 0 \) for example).

The high energy linac built at SLAC in the sixties using the new klystron technology allowed collisions of electrons of up to 20 GeV energy with protons from a liquid hydrogen target. The scattered electrons were measured in a two arm spectrometer at variable scattering angles and the cross section was measured in a range of \( Q^2 \) and \( x \), reconstructed as explained in section 2. The measured structure function [6] \( F_2 \) was found to be rather flat in \( Q^2 \) in contradiction with the elastic scattering case, but in agreement with Bjorken scaling and the naive quark parton model (Fig. 2 (center)). Subsequently, the Callan–Gross relation \( F_2 = 2xF_1 \), valid for spin 1/2 constituents, was confirmed, as shown in Fig. 2 (right). The measurements of the nucleon structure continued with lepton beams of various types and energies. These fixed target experiments are listed in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Reaction Process</th>
<th>Beam Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC-MIT</td>
<td>1968</td>
<td>( ep, ed ) NC</td>
<td>4.5–20 GeV</td>
</tr>
<tr>
<td>CDHS,CHARM</td>
<td>&lt; 1984</td>
<td>( \nu eFe ) CC</td>
<td>&lt; 260 GeV</td>
</tr>
<tr>
<td>FMMF</td>
<td>&lt; 1988</td>
<td>( \nu N ) CC</td>
<td>&lt; 500 GeV</td>
</tr>
<tr>
<td>CCFR</td>
<td>1979–1988</td>
<td>( \nu Fe ) CC</td>
<td>&lt; 600 GeV</td>
</tr>
<tr>
<td>BCDMS</td>
<td>1981–1985</td>
<td>( \mu \mu ) NC</td>
<td>100–280 GeV</td>
</tr>
<tr>
<td>EMC</td>
<td>&lt; 1983</td>
<td>( \mu e ) NC</td>
<td>&lt; 325 GeV</td>
</tr>
<tr>
<td>NMC</td>
<td>1986–1989</td>
<td>( \mu \mu ) NC</td>
<td>90–280 GeV</td>
</tr>
<tr>
<td>E665</td>
<td>1987–1992</td>
<td>( \mu e ) NC</td>
<td>90–470 GeV</td>
</tr>
<tr>
<td>SLAC-MIT</td>
<td>1996–1997</td>
<td>( \nu eFe ) CC/NC</td>
<td>&lt; 600 GeV</td>
</tr>
</tbody>
</table>

Although extremely simple, the parton model leads to powerful predictions, in good agreement with the first experimental observations. Nevertheless, the model was to be improved using the quantum field theory of strong interactions that emerged in the 1970’s.

1.5. THE STANDARD MODEL AND THE IMPROVED QUARK–PARTON MODEL

At the beginning of the XX century, the proton, the photon and the electron were the only known “elementary” particles. By 1960 already, more than 60 particles were known, identified in photo-emulsion plates exposed to cosmic rays or by the newly available high energy accelerated particle beams. Most of
these particles were classified as hadrons, \( i.e. \) particles sensitive to the strong (nuclear) force. This multiplicity required some “order” and pointed towards a substructure, which was explained via the “quark” model. In this model, the known hadrons are combinations of spin 1/2 components, the “quarks”. The first proposed quarks were “up” \( u \), “down” \( d \) and “strange” \( s \) as used in the 1960’s for a classification based on the symmetry group \( SU(3)_{\text{flavour}} \). Later more quarks were discovered: “charm” \( c \) (1974), “beauty” \( b \) (1977) and “top” \( t \) (1994). The electric quark charge is fractionary: +2/3 for \( u, c, t \) and −1/3 for \( d, s, b \) in units of \( e \).

The proton is a \((uud)\) combination while the neutron is attributed a \((udd)\) content.

The Standard Model symmetry gauge group corresponding to the electromagnetic, weak and strong interactions is \( U(1)_{\text{em}} \times SU(2)_{\text{weak}} \times SU(3)_{\text{strong}} \).

### Table 2

Fermionic content of the Standard Model and the respective quantum numbers.

<table>
<thead>
<tr>
<th>Family</th>
<th>Quantum numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>( e_L )</td>
<td>( e_L )</td>
</tr>
<tr>
<td>( \nu_L )</td>
<td>( \mu_L )</td>
</tr>
<tr>
<td>( u_L )</td>
<td>( c_L )</td>
</tr>
<tr>
<td>( d_L )</td>
<td>( s_L )</td>
</tr>
<tr>
<td>( u_R )</td>
<td>( c_R )</td>
</tr>
<tr>
<td>( d_R )</td>
<td>( s_R )</td>
</tr>
</tbody>
</table>

To date, quarks have not been detected as free particles, and this experimental observation has been encapsulated into a theorem related to a new quantum number, “colour”. The observable particles are always colour-less (“white”) states, since “colour”-ed objects (like the quarks) cannot exist freely. The theory of the strong interactions is in fact a gauge field theory of the colour quantum number, Quantum Chromodynamics (QCD) [7].
Quarks are bound inside the hadrons and interact via *gluons*, the mediating bosons of the strong force. Proton and neutrons can therefore be considered as a collection of quarks of two types: valence quarks, the components determining the nucleon identity (from $SU(3)_{\text{flavour}}$) and "sea" quarks and antiquarks related to the QCD vacuum, *i.e.* gluon fluctuations $g \rightarrow q\bar{q}$.

In the naive quark–parton model, the structure functions can be written in terms of quark distributions, expanding formula 5:

$$F_2^{p,n} = \frac{4}{9} x \left( u^{p,n} + \bar{u}^{p,n} \right) + \frac{1}{9} x \left( d^{p,n} + \bar{d}^{p,n} \right).$$

By isospin invariance one can identify $u(x) = u^p(x) = d^n(x) = d^p(x) = u^n(x)$ (and similarly for anti-quarks). The scattering of leptons off deuterons (nuclei with one neutron and one proton) lead to structure functions that can be expressed as $F_2^d = F_2^p + F_2^n$.

If the scattered lepton is a neutrino, only quarks of a given flavour are tested. The neutrinos interact via charged $W^\pm$ bosons and thereby cannot "see" the quarks for which the charge conservation would be violated. For instance the reaction $\nu_u d \rightarrow \mu^- + u$ is possible, while the $u$ quark interact only with antineutrinos $\bar{\nu}_\mu u \rightarrow \mu^+ + d$. Applying the same procedure as for the electron–

![Image](image.png)

**Fig. 3** – The comparison [8] of the $F_2$ structure function measured in muon-deuteron scattering with the structure function measured in neutrino-deuteron scattering $F_2^\nu$ scaled by the expected factor $5/18$. 
nucleon scattering, the structure function corresponding to neutrino scattering has an expression depending on the nucleon type (proton or nucleon):

\[
F_2^{np} = 2x\left(d(x) + \bar{u}(x)\right) \quad F_2^{nn} = 2x\left(u(x) + \bar{d}(x)\right)
\]

The ratio between the structure functions measured from the scattering of electrons and neutrinos off deuterons is expected to be:

\[
\frac{F_2}{F_2^e} = \frac{x\left(\frac{4}{9}u^p(x) + \frac{1}{9}d^p(x) + \frac{4}{9}u^n(x) + \frac{1}{9}d^n(x)\right)}{2x(d(x) + u(x))} = \frac{5}{18}
\]

The measurement of this ratio, presented in Fig. 3, confirm the prediction. This constitutes a sound evidence for the quark–parton model.

1.6. PROTON STRUCTURE AND QCD

Since \(F_2\) can be measured for both the proton and the neutron, the integral over \(x\) can be determined experimentally. The integral contains the contribution of individual quarks to the proton momentum (\(f_u, f_d\)):

\[
\int_0^1 F_2^p = \frac{4}{9} \int_0^1 x(u + \bar{u})dx + \frac{1}{9} \int_0^1 x(d + \bar{d})dx = \frac{4}{9} f_u + \frac{1}{9} f_d = 0.18^{(exp.)}
\]

\[
\int_0^1 F_2^n = \frac{4}{9} \int_0^1 x(u + \bar{u})dx + \frac{1}{9} \int_0^1 x(d + \bar{d})dx = \frac{1}{9} f_u + \frac{4}{9} f_d = 0.12^{(exp.)}
\]

Fig. 4 – The gluon induced subprocesses for parton density evolution and the associated kernels in the DGLAP equations.

If the system is solved, one can calculate \(f_u + f_d = 0.5\) which means that only one half of the proton momentum is carried by quarks and antiquarks. The missing half had been attributed to the gluons. This is a puzzle but also a challenge for QCD, since a very large fraction of the mass of the visible (baryonic) universe seems to be built by the carriers of the strong force. In
addition, the parton model contains another puzzle: quarks are confined (i.e. tightly bound) inside the proton, but at the same time they behave quasi–free during a DIS interaction. In QCD, gluon emission is proportional to the strong coupling constant $\alpha_s$, which is predicted to increase with increasing distance (decreasing $Q^2$):

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \beta(\alpha_s(\mu^2)) \log(Q^2/\mu^2)}$$  \hspace{1cm} (6)

where $\mu$ is an arbitrary scale at which the reference coupling is defined, while $Q^2$ is here the scale at which the strong interaction takes place and $\beta$ is a negative coefficient [9]. This property, also called “asymptotic freedom”, explains both why quarks are confined and the approximate correctness of the parton model, since at small distances, inside the proton, quarks interact softly and are indeed quasi free during the interaction.

QCD can be viewed as a generalisation of the simple parton model. The assumption is that quark and gluons distributions probed in DIS scattering are subject to QCD reactions. Possible sub-processes are shown in Fig. 6 and their influence on the quark and gluon distributions functions are calculable in QCD via the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations [10]. These equations describe the coupled evolution of the quark and gluon densities as a function of the virtuality $t = Q^2$:

$$t \frac{\partial}{\partial t} \left[ \begin{array}{c} q_j(x,t) \\ g(x,t) \end{array} \right] = \frac{\alpha_s(t)}{2\pi} \sum_{q_i,q_j} \int_0^1 \frac{d\xi}{\xi} \left[ \begin{array}{c} P_{qq}(\frac{\xi}{\xi}, \alpha_s(t)) q_j(\xi,t) \\ P_{qg}(\frac{\xi}{\xi}, \alpha_s(t)) q_j(\xi,t) \\ P_{gq}(\frac{\xi}{\xi}, \alpha_s(t)) g(\xi,t) \\ P_{gg}(\frac{\xi}{\xi}, \alpha_s(t)) g(\xi,t) \end{array} \right]$$  \hspace{1cm} (7)

These equations describe the “build-up” of observable quark and gluon densities from the possible deceleration of partons with higher $x$ via (for instance) gluon radiation or splitting, described by the kernel function $P_{qq,qg,gg}$. These internal appearances and recombinations lead to parton distributions (and therefore structure functions) that depend not only on $x$ but also on $Q^2$, violating the Bjorken scale invariance of the naive quark–parton model. The scaling violations are therefore an effect of the local strong interaction at very short distances. The determination of the scaling violations from cross section measurements over large domains of $x$ and $Q^2$ therefore test the QCD validity. These measurements also allow the strong coupling constant and the gluon distribution inside the proton to be extracted.
2. THE HERA PROJECT

2.1. THE COLLIDER

The idea for a large electron-proton collider to mark a new step in the studies for proton structure was promoted in the seventies [11]. The HERA collider project started in 1985 and produced the first electron–proton collisions in 1992. A scheme of the accelerator complex is shown in Fig. 5. It is composed of two accelerators designed to store and collide counter rotating electrons (e–), or positrons (e+), with an energy of 27.5 GeV and protons with an energy of 920 GeV. The centre–of–mass energy is 320 GeV, equivalent to a hypothetical fixed target experiment with a lepton beam energy of \( E = 50 \) TeV. The kinematic \((x, Q^2)\) plane accessible at HERA is shown in Fig. 5 (right) with a \( Q^2 \) domain up to about 50000 GeV\(^2\) and \( x \) down to 10\(^{-5}\). HERA complements the other high energy colliders Tevatron (Fermilab, Chicago, \( p\bar{p}, \sqrt{s} = 1960 \) GeV) and LEP (CERN, Geneva, \( e^+e^- \), until 2000, \( \sqrt{s} \) up to 209 GeV). The next accelerator, the Large Hadron Collider (LHC), will start operations in 2008 and is expected to collide two proton beams at a centre-of-mass energy of 14 TeV.

2.2. THE DETECTORS

The HERA ring serves two collider detectors H1 and ZEUS (shown in Fig. 5). They are built as hermetic (4\(\pi\)) multi-purpose detectors equipped with inner trackers able to measure charged particle momenta and calorimeters completing the measurement of the energy flow in events from electron–proton collisions. Two further experiments use \( e^\pm \) or \( p \) beams for fixed target studies: HERMES is dedicated to the study of polarised \( e^\pm p(N) \) collisions and (until 2003) HERA-B was built to study beauty production in hadronic collisions. Since 2003, the \( e^\pm \) beam is longitudinally polarised with an average polarisation in collision mode of \( P_{e^\pm} = 30–40\% \). HERA collisions will continue until July 2007. An integrated luminosity of 300 pb\(^{-1}\) (200 pb\(^{-1}\)) is about to be collected in \( e^\pm p \) \((e^\pm p)\) by each of the two collider mode experiments, H1 and ZEUS. The integrated luminosity as a function of time at HERA is shown in Fig. 7.

3. PROTON STRUCTURE MEASUREMENTS AT HERA

3.1. THE NEUTRAL CURRENT AND CHARGED CURRENT CROSS SECTIONS

The H1 and ZEUS experiments can measure both neutral current (NC) and charged current (CC) processes. The NC events contain a prominent electron and
a jet of particles measured in the calorimeter, while in CC events only the jet is visible since the outgoing neutrino is not detected. Examples of such events are shown in Fig. 8.

Since a large domain in $x$ and $Q^2$ is accessed, the NC cross section becomes sensitive to weak effects, beyond the simple electromagnetic form parameterised in equation 2. The $Z^0$ boson exchange can be incorporated into the so-called generalised structure functions. The cross section is parameterised as following:

$$\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} (Y_+\tilde{F}_2 + Y_-x\tilde{F}_3 - y^2\tilde{F}_L),$$

(8)

The helicity dependence of the electroweak interactions is given by the terms $Y_{\pm} = 1 \pm (1 - y^2)$. The generalised structure functions $\tilde{F}_2$ and $x\tilde{F}_3$ can be further decomposed as [12]

$$\tilde{F}_2 = F_2 - \nu_e \frac{\kappa Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + \left( \nu^2_e + a_e^2 \right) \left( \frac{\kappa Q^2}{Q^2 + M_Z^2} \right)^2 F_2^Z,$$

$$x\tilde{F}_3 = -a_e \frac{\kappa Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + \left( 2\nu_e a_e \right) \left( \frac{\kappa Q^2}{Q^2 + M_Z^2} \right)^2 xF_3^Z,$$

with $\kappa^{-1} = \frac{4M_W^2}{M_Z^2} \left( 1 - \frac{M_W^2}{M_Z^2} \right)$ in the on-mass-shell scheme. The quantities $\nu_e$ and $a_e$ are the vector and axial-vector weak couplings of the electron or positron to the $Z^0$ [8]. The electromagnetic structure function $F_2$ originates from photon exchange only and dominates in most of the accessible phase space. The functions $F_2^Z$ and $xF_3^Z$ are the contributions to $\tilde{F}_2$ and $x\tilde{F}_3$ from $Z^0$ exchange and the functions $F_2^{\gamma Z}$ and $xF_3^{\gamma Z}$ are the contributions from $\gamma Z$ interference. These contributions are significant only at high $Q^2$. For longitudinally unpolarised lepton beams the $\tilde{F}_2$ contribution is the same for $e^-$ and for $e^+$ scattering, while the $x\tilde{F}_3$ contribution changes sign as can be seen in eq. 8. The longitudinal structure function $\tilde{F}_L$ may be decomposed in a manner similar to $\tilde{F}_2$. Its contribution is significant only at high $y$.

In the quark parton model the structure functions $F_2$, $F_2^{\gamma Z}$ and $F_2^Z$ are related to the sum of the quark and anti-quark momentum distributions, $xq(x, Q^2)$ and $x\bar{q}(x, Q^2)$:
The physics of deep inelastic scattering at HERA

\[ [F_2, F_2^{Z^0}, F_2^Z] = x \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2](q + \bar{q}) \]  \hspace{1cm} (9)

and the structure functions \( xF_2^{Z^0} \) and \( xF_2^Z \) to the difference, which determines the valence quark distributions, \( xq_v(x, Q^2) \),

\[ [xF_2^{Z^0}, xF_2^Z] = 2x \sum_q [e_q a_q, v_q a_q](q - \bar{q}) = 2x \sum_{q=u,d} [e_q a_q, v_q a_q] q_v \hspace{1cm} (10) \]

In equations 9 and 10, \( v_q \) and \( a_q \) are the vector and axial-vector weak coupling constants of the quarks to the \( Z^0 \), respectively.

The charged current (CC) interactions, \( e^+p \to (\nu, X) \), are mediated by the exchange of a \( W \) boson in the \( t \) channel. The cross section is parameterised as:

\[
\frac{d^2\sigma_{CC}(e^+p)}{dx dQ^2} = \frac{G_F^2}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \tilde{\sigma}_{CC}(x, Q^2),
\]

with \( \tilde{\sigma}_{CC}(x, Q^2) = \frac{1}{2} \left[ Y_x W_2^+(x, Q^2) + Y_x W_3^+(x, Q^2) - y^2 W_3^+(x, Q^2) \right] \)

\( \tilde{\sigma} \) is the reduced cross section, \( G_F \) is the Fermi constant, \( M_W \) is the mass of the \( W \) boson, and \( W_2, xW_3 \) and \( W_L \), CC structure functions. In the quark parton model (QPM), the structure functions \( W_2^\pm \) and \( xW_3^\pm \) may be interpreted as lepton charge dependent sums and differences of quark and anti-quark distributions:

\[ W_2^+ = x(\bar{U} + D), \hspace{1cm} xW_3^+ = x(D - \bar{U}), \hspace{1cm} W_2^- = x(U + \bar{D}), \hspace{1cm} xW_3^- = x(U - \bar{D}) \]

whereas \( W_3^\pm = 0 \). The terms \( xU, xD, x\bar{U} \) and \( x\bar{D} \) are defined as the sum of up-type, of down-type, and of their anti-quark-type distributions, \( i.e. \) below the \( b \) quark mass threshold: \( xU = x(u + c), \hspace{1cm} xD = x(d + s), \hspace{1cm} x\bar{U} = x(\bar{u} + \bar{c}), \hspace{1cm} x\bar{D} = x(\bar{d} + \bar{s}) \).

The differential NC and CC cross sections as a function of \( Q^2 \) are shown in Fig. 9 (left) for \( e^+p \) collisions. At low \( Q^2 \) the NC cross section, driven by the electromagnetic interaction, is two orders of magnitude larger than the CC cross section which correspond to a pure weak interaction. At large \( Q^2 \) the two cross sections are similar. The largest \( Q^2 \) measurement corresponds to a resolution of \( \delta = 10^{-18} \) m, \( i.e. \) 1/1000 the proton size. The agreement between the measurement and the prediction based on QCD improved parton model suggests no evidence for quark substructure.

The double differential reduced cross section \( \tilde{\sigma}_{CC}(x, Q^2) \) is shown in Fig. 9 (right). The CC processes are sensitive to individual quark flavours, which
is especially visible at large $Q^2$: the $e^+p$ collisions probe the $d(x)$ quark distribution, while $e^-p$ are more sensitive to the $u(x)$. This is a very useful feature of the CC processes compared to the NC, where the flavour separation is weaker.

3.2. STRUCTURE FUNCTIONS MEASUREMENTS: $F_2$, $F_L$ AND $xF_3$

The NC cross section is dominated over a large domain by the $F_2$ contributions, defined in equation 8. The measurement of the NC cross section at HERA can therefore be translated into an $F_2$ measurement, which is shown in Fig. 10 together with the previous measurements performed at fixed target experiments. One can observe the Bjorken scaling in the region at high $x = 0.1$–$0.2$, but obvious scaling violation at lower $x$. This may be understood in terms of DGLAP equations as a contribution driven by the gluon

$$\frac{\partial F_2(x, Q^2)}{\partial \ln(Q^2)} \approx (10 \alpha_s(Q^2)/27\pi) x g(x, Q^2).$$

From the measurements at fixed $Q^2$ one can observe a steep increase of $F_2$ towards low $x$, as shown in Fig. 11 (left). The region at low $x$ is populated by quarks which have undergone a hard or multiple gluon radiation and carry a low fraction of the proton momentum at the time of the interaction. The observation of such large fluctuations to very high parton density is driven by the uncertainty principle, which requires that the interaction time be very short (i.e. high $Q^2$). In this regime, it is expected that the structure function grows at low $x$ and shrinks at large $x$, as is confirmed by the experimental observation. The rise of the structure functions at low $x$ is one of the most spectacular observations at HERA. It is predicted in the double leading log limit of QCD [13]. It can be intuitively understood in terms of gluon driven parton production at low $x$, as depicted in Fig. 11 (right).

The longitudinal structure function $F_L$ is usually a small correction, only visible at large $y$. The $F_L$ measurement from the cross section has to proceed in such a way that $F_2$ contribution is separated. Indirect methods assume some parameterisation of $F_2$ to extract $F_L$. Using this method, an $F_L$ determination can be performed and is shown in Fig. 10 at fixed $W$ (the $\gamma^*p$ centre-of-mass energy). In the naive QPM the longitudinal structure function $F_L = F_2 - 2xF_1 = 0$ and therefore $F_L$ contains by definition the deviations from the Callan-Gross relation. It can be shown that $F_L$ is directly related to the gluon density in the proton [14, 15]

$$x g(x) = 1.8 \left[ \frac{3\pi}{2\alpha_s} F_L(x, 0.4x) - F_2(0.8x) \right] = \frac{8.3}{\alpha_s} F_L$$

meaning that at low $x$, to a good approximation $F_L$ is a direct measure for the gluon distribution.

A direct measurement of $F_L$ can be performed if the cross section $\sigma(E_p) \sim F_2(x, Q^2) + f(y) F_L(x, Q^2)$ is measured at fixed $x$ and $Q^2$ but variable $y$. 
This can only be performed if the collision energy \( \sqrt{s} \) is varied, for instance by reducing the proton beam energy from 920 GeV to 460 GeV at HERA. Then \( F_L(x, Q^2) \) can be directly measured with reduced uncertainties from the difference of cross sections: \( F_L \sim C(y) \ast (\sigma(E_p^1) - \sigma(E_p^2)) \). The measurement of DIS at HERA at lower proton energies is foreseen for the end of the run in 2007 in order to perform the first direct measurement of \( F_L \) in the low \( x \) regime.

The structure function \( xF_3 \) can be obtained from the cross section difference between electron and positron unpolarised data

\[
x F_3 = \frac{Y^+}{2Y^-} \left[ \tilde{\sigma}^-(x, Q^2) - \tilde{\sigma}^+(x, Q^2) \right].
\]

The dominant contribution to \( xF_3 \) arises from the \( \gamma Z \) interference. In leading order QCD the interference structure function \( xF_3^{\gamma Z} \) can be written as

\[
x F_3^{\gamma Z} = 2x \left[ e_u a_u (U - \bar{U}) + e_d a_d (D - \bar{D}) \right],
\]

with \( U = u + c \) and \( D = d + s \) thus provides information about the light quark axial vector couplings \((a_u, a_d)\) and the sign of the electric quark charges \((e_u, e_d)\). The averaged \( xF_3^{\gamma Z} \), determined by H1 and ZEUS for a \( Q^2 \) value of 1500 GeV\(^2\), is shown in Fig. 8.

3.3. PARTON DISTRIBUTION FUNCTIONS

The NC and CC cross section measurements are used in a common fit in order to extract the parton distribution functions (pdf’s) [16, 17]. The shapes for the quark \( q(x, Q^2) \) and gluon \( g(x, Q^2) \) distributions are not given by theory and thus need to be parameterised as a function of \( x \) at a given scale \( Q^2_0 \) and evolved using DGLAP equations to any \((x, Q^2)\) point at which the cross section has been measured. The theoretical cross section can therefore be accurately calculated as a function of the pdf’s parameters. A \( \chi^2 \) is then built using the measurements and the predictions for all measurements points and minimised to extract the non-perturbative pdf’s parameters. Since the number of parameters (typically 10) is much lower than the number of measurements (several hundred) the fit also constitutes a very powerful test of QCD. The structure functions from the fit are compared with data in Fig. 10. The parton distribution functions are extracted using the decomposition of the structure function described above. As an example, the pdf’s obtained for \( Q^2 = 10 \text{ GeV}^2 \) are shown in Fig. 12. The valence distributions peak at \( x \approx 1/3 \) as expected from simple counting with \( u_v \) twice as large as \( d_v \). The gluon distribution is rising at low \( x \). The knowledge of the proton structure deduced from inclusive CC/NC cross section measurements
can be used to calculate the rate of exclusive processes leading to a specific final state $FS$ from the convolution of the parton level cross section with pdf's, for instance: $\sigma_{ep \rightarrow FS} = \sigma_{eq \rightarrow FS} \otimes q(x, Q^2)$. This factorisation can also be used to calculate the cross section of processes produced in proton–proton collisions using the pdf's measured in DIS.

### 3.4. STUDY OF THE NUCLEON SPIN IN POLARISED $ep$ COLLISIONS

The nucleon spin can be decomposed as following:

$$S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma (\mu^2) + \Delta g (\mu^2) + L^z (\mu^2) + L^x (\mu^2).$$  \hspace{1cm} (12)

Here $\Delta \Sigma (\Delta g)$ describes the integrated contribution of quark and anti-quark (gluon) helicities to the nucleon helicity and $L_z^z \ (L_x^z)$ is the $z$ component of the orbital angular momentum among all quarks (gluons) at a given scale $\mu^2$. The main puzzle has been the observation that, contrary to naive expectation, the quark contribution does not account for the nucleon spin.

The HERMES experiment at HERA (schematically shown in Fig. 13) measures the collision of the polarised $e^\pm$ beam with a polarised target [18]. The spin-dependent DIS cross section can be parametrised by two structure functions $g_1$ and $g_2$, where $g_2$ is negligible and $g_1$ is given by:

$$g_1^{p,n} (x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left[ \Delta q^{p,n} (x, Q^2) + \Delta \bar{q}^{p,n} (x, Q^2) \right].$$

Here $\langle e^2 \rangle = \sum_q e_q^2 / N_q$ is the average squared charge of all involved quark flavors, and $\Delta q(x, Q^2) = q_+ (x, Q^2) - q_- (x, Q^2)$ is the quark helicity distribution for massless quarks of flavor $q$ in a longitudinally polarised nucleon in the “infinite momentum frame”.

The structure function $g_1$ is related directly to the cross section difference:

$$\sigma_{LL} = \frac{1}{2} (\sigma_{L} - \sigma_{\perp}) / 2, \text{ where longitudinally (L) polarised leptons (→) scatter on longitudinally (L) polarized nuclear targets with polarisation direction either parallel or anti-parallel \(\Rightarrow, \Leftarrow\) to the spin direction of the beam. The relationship to spin structure functions is:}

$$\frac{d^2 \sigma_{LL} (x, Q^2)}{dx \, dQ^2} = \frac{8 \pi a_{1}^{2} y}{Q^4} \times \left[ 1 - \frac{y}{2} - \frac{y^2}{4} \gamma^2 \right] g_1 (x, Q^2) - \frac{y}{2} \gamma^2 g_2 (x, Q^2),$$ \hspace{1cm} (13)

where $\gamma^2 = Q^2 / v^2$. 

Measurements of $g_1$ for the proton, deuteron and neutron are shown in Fig. 14. They can be used to extract the contribution of sea and valence quarks to the proton spin [18]. Within some theoretical assumptions, this contribution is found to be $\Delta \Sigma_{(Q^2=5\text{ GeV}^2)} = 0.33 \pm 0.04$, which leaves a significant fraction for the gluon contribution to the proton spin.

**4. EXCLUSIVE MEASUREMENTS AT HERA**

Proton structure and the QCD can be investigated in more detail using the measurement of the hadronic final state. A large variety of phenomena can be measured at HERA: jets, charm, beauty, diffractive processes and so on. Only a selection of these measurements is briefly described here.

**4.1. JET PRODUCTION AND STRONG COUPLING MEASUREMENT**

Due to the asymptotic freedom property of the strong interaction, the quarks or gluons produced with high energy during the scattering cannot exist as free particles and must form hadrons. The hadronisation process leads to “jets” of quasi-stable particles that are measured in the detectors. The DIS events contain most of the time a single jet corresponding to the scattered parton. In the so-called Breit frame of reference (the virtual photon rest frame) this scattered quark acquire no transverse momentum w.r.t the virtual photon direction. The jets have therefore also no transverse momentum along $\gamma^*$ direction. The picture of DIS scattering in the Breit frame (shown in Fig. 15) shows that large $E_T$ jets are produced only as a result of gluon radiation. As a consequence, the jet production rate in the Breit frame is sensitive to the strong coupling $\alpha_s$. The full acceptance and high granularity of the H1 and ZEUS detectors at HERA allow a precise reconstruction of the hadronic final state and consequently the measurement of jet production. The measured cross section is used to extract the strong coupling as a function of the energy scale of the gluon radiation ($E_T$). Results [19] are shown in Fig. 15. The decrease of the strong coupling with increasing scale (decreasing distance) is observed, confirming the hypothesis of asymptotic freedom of QCD and the prediction as formulated in equation 6.

**4.2. THE HEAVY FLAVOUR CONTENT OF THE PROTON**

An interesting feature of deep inelastic scattering is the production of heavy quarks, namely charm $c$ or beauty $b$ [20]. The production can be seen as the interaction between the electron and a heavy quark produced in a short time
fluctuation of a gluon. The production of heavy quarks is particularly interesting from theoretical perspective, since at low $Q^2$, where long range effects may hamper the convergence of QCD perturbative calculation, the mass of the heavy quarks provide a “large” scale and enable a different approximation of the process. At high $Q^2$, the quarks can be treated as massless and “generated” in the parton distribution functions from gluon splitting.

The measurement of DIS processes with a heavy quark in the final state requires special experimental techniques to identify beauty or charm hadrons. Indeed, the heavy quarks “hadronise” into heavy mesons or baryons which subsequently decay into lighter hadrons. They are identified in the hadronic final state of DIS events as resonances with known masses. For instance $D^*$ mesons are identify in the golden decay mode $D^* \rightarrow D \pi \rightarrow K \pi^+ \pi^-$. An alternative experimental technique make use of the long lifetime of heavy hadrons, which give rise to displaced decay vertices in the event. These vertices can be reconstructed using silicon detectors. These detectors provide very precise measurements and allow for the reconstruction of the decay vertices with a precision of a few hundreds microns, enough to identify for instance beauty hadrons which fly typically 2 mm before their decay into stable particles. The reconstruction of displaced (secondary) vertices “tag” therefore heavy quarks in DIS events.

The reduced cross section of DIS processes with a heavy quark ($c$ or $b$) in the final state can be parameterised in terms of charm or beauty structure functions:

$$\sigma_r^{c/b\bar{b}} = F_2^{c/b\bar{b}} - \frac{V}{Y_+} F_L^{c/b\bar{b}}$$

The measurement of heavy quark production in DIS allows to extract the “heavy” structure functions and therefore the charm or the beauty content of the proton. This content can be compared with the nominal content in light quarks. Fig. 16 shows the measurements obtained at HERA at high $Q^2$ for the charm and beauty fractions. It shows around 20% charm and 2% beauty in the proton, in good agreement with the prediction from a NLO QCD fit.

4.3. THE SEARCH FOR EXOTIC RESONANCES

As explained in the introduction, the known hadrons are composed of two or three quarks. Nevertheless, hadrons containing more than three quarks are not forbidden within the present theory of strong interactions. The search for resonances decaying to $K^n$ in the fixed-target experiments data revealed an evidence for the existence of a narrow baryon resonance with a mass of around 1530 MeV and positive strangeness [23–26]. This hadron may be explained as a
bound state of five quarks, \textit{i.e.} as a pentaquark, $\Theta^+ = uudd\bar{s}$ \cite{27}. The quantum numbers of this state also allow decays to $K^0_S p$.

The rich hadronic final state obtained in DIS from the hadronisation of the quark ejected from the proton is a very good laboratory to search for exotic resonances, like for instance resonances composed of more than three quarks. A strange pentaquark decay mode $K^0_S p$ have been searched by ZEUS collaboration. The invariant mass spectrum is shown in Fig. 17. The results support the existence of such state, with a mass of $1521.5 \pm 1.5(\text{stat.}) + 2.8 - 1.7(\text{syst.})$ MeV and a Gaussian width consistent with the experimental resolution of 2 MeV \cite{28}. The observation is not confirmed by a similar analysis performed by H1.

Fig. 17 – Example of a signal attributed to an exotic resonance which can be assimilated to an pentaquark state $\Theta^+ = uudd\bar{s}$ with a mass of approximately 1530 MeV.

Searches for other types of pentaquarks were also performed \cite{29, 30}. A candidate for an anti-charmed pentaquark $\Theta_c^+ = uudd\bar{c}$ was reported by the H1 collaboration \cite{30}. The decays $\Theta_c \rightarrow D^* p$ were searched for in the $ep$ data collected at HERA I. The obtained invariant mass spectrum, shown in Fig. 17, indicate a resonance with a mass of $3099 \pm 3(\text{stat.}) \pm 5(\text{syst.})$ MeV and a measured Gaussian width of $12 \pm 3$ MeV, compatible with the experimental resolution. This signal was however not confirmed by the ZEUS experiment \cite{31}.

In spite of a large number of positive signals for pentaquarks, the non-unanimous observation together with a lack of understanding of the production mechanisms leads to the conclusion that the experimental situation needs to be improved by high statistics dedicated experiments.
4.4. DIFFRACTION

The electron-proton interactions can also proceed not via direct electron-proton scattering but via a colour-less object, evaporated from the proton. This sort of interactions, called also "diffractive", occur in about 10% of DIS processes [32]. Such "soft" interactions involve slow gluon exchanges and long distances and cannot be calculated in the perturbative QCD. They are commonly discussed in terms of exchanges with net vacuum quantum numbers, though the exact nature of these exchanges is not well known.

The observation of high transverse momentum jet production in diffractive $p\bar{p}$ scattering [33] introduced the possibility of understanding the diffractive exchange in terms of partons. The presence of processes of the type $ep \rightarrow eXP$ in deep-inelastic scattering (DIS) at low Bjorken-$x$ at the HERA collider [34] offers a uniquely well controlled environment in which to study the QCD properties and structure of diffraction. Several measurements of the semi-inclusive cross section for this ‘diffractive DIS’ process have been made by the H1 [35–38] and ZEUS [39–43] collaborations.

The hadronic final state of any DIS event may be broken down into two systems $X$ and $Y$, separated by the largest gap in the rapidity distribution of the hadrons relative to an axis defined by the exchanged boson and the proton in their centre of mass frame [37]. If the masses $M_X$ and $M_Y$ of these two systems are small compared with the mass $W$ of the full hadronic final state, the two systems are expected to be separated by a large rapidity gap and a colourless exchange of well defined four-momentum may be considered to have taken place between them.

Fig. 18 – A scheme of the diffractive interaction in $ep$ collisions and the definition of the associated variables.

In addition to the usual DIS variables $x, Q^2$ and $y$ defined in Fig. 1, new kinematic variables are used to characterise the diffractive exchange. They are illustrated in Fig. 18. The longitudinal momentum fractions, $x_{IP}$ of the colourless
exchange with respect to the incoming proton, and $\beta$ of the struck quark with respect to the colourless exchange, are then defined by

$$x_{IP} = \frac{q \cdot (P - p_Y)}{q \cdot P}, \quad \beta = \frac{Q^2}{2q \cdot (P - p_Y)}.$$  

Here, $p_Y$ is the four-momentum of the $Y$ system and $\beta x_{IP} = x$. The squared four-momentum transferred at the proton vertex is

$$t = (P - p_Y)^2.$$  

The neutral current data are presented in the form of a ‘diffractive reduced cross section’ $\sigma^{D(3)}_r$.

$$\frac{d^3\sigma^{ep\rightarrow\kappa XY}}{dx_{IP} dx dQ^2} = \frac{2\pi \alpha^2}{xQ^4} Y_+ \cdot \sigma^{D(3)}_r(x_{IP}, x, Q^2),$$

where $Y_+ = 1 + (1 - y)^2$. Similarly to inclusive DIS, the reduced $e^p$ cross section depends on the diffractive structure functions $F^{D(3)}_2$ and $F^{D(3)}_L$ in the one-photon exchange approximation according to

$$\sigma^{D(3)}_r = \frac{F^{D(3)}_2(x_{IP}) - \frac{y^2}{Y_+} F^{D(3)}_L}. \quad (17)$$

For $y$ not too close to unity, $\sigma^{D(3)}_r = F^{D(3)}_2$ holds to very good approximation.

The diffractive scattering (DDIS) have a striking experimental signature. In normal DIS events, the hadronic final state distribution reflects the color connection that occurs between the proton remnant and the scattered parton. Conversely, the hadronic final state in a DDIS event is disconnected from the proton, and therefore no activity is observed in the detector close to the outgoing proton direction. This leads to a rapidity gap (a region without detected particles) around the outgoing proton beam. The topology corresponds to a small mass of the observed hadronic system ($\text{low } M_Y$). This striking experimental signature is used to identify DDIS events and to measure their production cross section. An example of a triple differential measurement of the reduced diffractive cross section is shown in Fig. 19 [44].

The detailed explanation of hard diffraction has become a major challenge in the development of our understanding of the strong interaction at high energies and low $x$ values [45]. A wide variety of models has been put forward to interpret the dynamics of diffractive DIS as well as its relationships to inclusive DIS and to diffractive hadron-hadron scattering [46–52]. A general theoretical framework is provided by the proof [53] of a hard scattering QCD collinear
Fig. 19 – An example of reduced differential diffractive cross section measurement for $x_{IP} = 0.03$: (left) as a function of the fraction of momentum carried by the struck parton $\beta$ at various $Q^2$ values and (right) as a function of $Q^2$ in various $\beta - x$ bins.

factorisation theorem [54–56] for semi-inclusive DIS cross sections such as that for $ep \rightarrow eXp$. As illustrated in Fig. 20a, this theorem implies that the concept of ‘diffractive parton distribution functions’ (DPDFs) [55, 57] may be introduced, representing conditional proton parton probability distributions under the constraint of a leading final state proton with a particular four-momentum. Empirically, a further factorisation has been found to apply to good approximation,

Fig. 20 – Schematic illustration of the neutral current diffractive DIS process $ep \rightarrow eXp$, proceeding via virtual photon exchange. The dotted lines in (a) and (b) show the points at which the diagram can be divided under the assumptions of QCD hard scattering collinear factorisation and proton vertex factorisation, respectively.
whereby the variables which describe the proton vertex factorise from those
describing the hard interaction [37, 38], as illustrated in Fig. 20b. According
to this ‘proton vertex’ factorisation, the shape of the DPDFs is independent of the
four-momentum of the final state proton. The dependence of the PDF
normalisation on the proton four-vector can be parameterised conveniently using
Regge asymptotics, which amounts to a description of diffraction in terms of the
exchange of a factorisable ‘pomeron’ (\(IP\)) [58] with universal parton densities [59].

Diffractive DIS data is used to extract DPDFs. The proton vertex
factorisation is assumed at low fractional proton energy losses, \(x_{IP}\). At larger \(x_{IP}\),
a separately factorisable sub-leading exchange (\(IR\)), with a different \(x_{IP}\) dependence
and partonic composition, is considered. The DPDF’s are parameterised in terms
of a quark component (singlet) and a gluon distribution, defined at a given scale
\(Q_0^2\) and evolved using the DGLAP equations.

The diffractive quark singlet and gluon distributions are shown together
with their uncertainties in Fig. 21 (left). At low \(Q^2\), both the quark singlet and the
gluon densities remain large up to the highest \(z\) values accessed. The quark
singlet distribution is well constrained, with an uncertainty of typically 5–10%
and good agreement between the results of various fit options (Fit A and Fit B).
The gluon distribution has a larger uncertainty of typically 15% at low to moderate
\(z\) and low \(Q^2\), dominated by the influence of the \(Q_0^2\) variation.

As shown in Fig. 21 (right), the fraction of the exchanged momentum carried
by gluons integrated over the range \(0.0043 < z < 0.8\), corresponding approximately
to that of the measurement, is around 70% throughout the \(Q^2\) range studied.

Further tests of the factorisation properties of diffractive DIS have been made
by comparing predictions using these DPDFs with hadronic final state observables
such as diffractive jet [66] and heavy quark [67] cross sections. These tests have
shown a remarkable internal consistency within the HERA DIS data. In contrast,
the DPDFs extracted in DIS are not expected to be directly applicable to
hadron-hadron scattering [68, 53–55]. Indeed diffractive factorisation breaks down
spectacularly when the DPDFs from [37] are applied to diffractive \(p\bar{p}\) interactions
at the Tevatron [69]. However, with the introduction of an additional ‘rapidity gap
survival probability’ factor to account for secondary interactions between the beam
remnants [70], the HERA DPDFs remain an essential ingredient in the
phenomenology of diffraction at the Tevatron and the LHC [71].

5. TESTS OF THE ELECTROWEAK SECTOR

5.1. ELECTROWEAK EFFECTS AT HIGH \(Q^2\)

A combined QCD–electroweak fit of the NC and CC cross section is
performed in order to investigate the sensitivity of HERA data to electroweak
effects [72, 73]. The strategy is to leave free in the fit the electroweak parameters together with the parameterisation of the parton distribution functions. Due to the $t$-channel electron-quark scattering via $Z^0$ bosons, the DIS cross sections at high $Q^2$ are sensitive to the light quark axial ($a_q$) and vector ($v_q$) couplings to the $Z^0$. This dependence includes linear terms with significant weight in the cross section, due to $\gamma Z$ interference which allow to determine not only the value but also the sign of the couplings.

In contrast, the measurements at the $Z$ resonance (LEP1 and SLD) only access $av$ or $a^2 + v^2$ combinations. Therefore there is an ambiguity between axial and vector couplings and only the relative sign can be determined. In addition, since the flavour separation for light quarks cannot be achieved experimentally, flavour universality assumptions have to be made. The Tevatron measurement [74] of the Drell-Yan process $p\bar{p} \rightarrow e^+e^-$ allows access to the couplings at an energy beyond the $Z$ mass resonance, where linear contributions are significant.

The measurements of the $u$–quark and $d$–quark couplings obtained at HERA, LEP and Tevatron are shown in Fig. 22. The data to be collected at Tevatron and HERA as well as the use of polarized $e^\pm$ beams at HERA open interesting opportunities for improved measurements of the light quark couplings in the near future.

Another interesting result is related to the so–called propagator mass $M_w^{prop}$, that enters a model independent parameterisation of the CC cross section:

$$\frac{d^2\sigma_{CC}^\uparrow}{dx dQ^2} = \frac{G_F^2}{2\pi} \left(\frac{M_W}{M^2_W + Q^2}\right)^2 \Phi_{CC},$$

where $G_F$ is the Fermi constant and $\Phi_{CC}$ is the reduced cross section that encapsulates the proton structure in terms of parton distribution functions. If the Fermi constant $G_F$ and the propagator mass are left free in the fit, an allowed region in the $(G_F, M_W^{prop})$ plane can be measured. The result is shown in Fig. 23 (left). By fixing $G_F$ to the very precise experimental measurement, the propagator mass can be extracted and amounts in this analysis to $M_W^{prop} = 82.87 \pm 1.82 (exp.)^{+0.30}_{-0.10} (model)$ GeV, in agreement with the direct measurements.

If the framework of SM model is assumed, the $W$ mass can be considered as a parameter constrained by the SM relations and entering both the cross section and the higher order correction. In this fitting scheme, where $M_W$ depends on the top and Higgs masses, the obtained value from DIS is $M_W = 80.709 \pm 0.205 (exp.)^{+0.048}_{-0.025} (mod) \pm 0.025 (top) \pm 0.033 (th) - 0.084 (Higgs)$ GeV, in good
agreement with other indirect determinations and with the world average. The result is illustrated in Fig. 23 (right). The fit value can be converted into an indirect \( \sin^2 \theta_W \) determination using the relation \( \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} \), assumed in the on mass shell scheme. The result \( \sin^2 \theta_W = 0.2151 \pm 0.0040 \), obtained for the first time in from \( e^\pm p \) collisions, is in good agreement with the value of \( 0.2228 \pm 0.0003 \) obtained from the measurements in \( e^+e^- \) collisions at LEP and SLC.

The \( M_W \) and \( \sin^2 \theta_W \) determinations cannot compete with the precise measurements performed at LEP and Tevatron, but are qualitatively new since the weak interactions proceed at HERA in the \( t \)-channel.

### 5.2. CC CROSS SECTION DEPENDENCE OF THE LEPTON BEAM POLARISATION

The polarisation of the electron beam at HERA II allows a test of the parity non-conservation effects typical of the electroweak sector. The most prominent effect is predicted in the CC process, for which the cross section depends linearly on the \( e^\pm \)-beam polarisation: \( \sigma^{e^\pm p} (P) = (1 \pm P) \sigma^{e^0 p}_{P=0} \). The results [75] obtained for the first time in \( e^\pm p \) collisions are shown in Fig. 12. The expected linear dependence is confirmed and provides supporting evidence for the V-A structure of charged currents in the Standard Model, a property already verified more than 25 years ago by measuring the “inverse” CC process, the polarisation of positive muons produced from \( \nu_\mu \)-Fe scattering [76].

### 5.3. NC CROSS SECTION DEPENDENCE OF THE LEPTON BEAM POLARISATION

Due to the coupling of the \( Z \) boson, the \( e^\pm \) beam polarisation effects can also be measured in NC processes at high \( Q^2 \). The charge dependent longitudinal polarisation asymmetries of the neutral current cross sections, defined as

\[
A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm (P_R) - \sigma^\pm (P_L)}{\sigma^\pm (P_R) + \sigma^\pm (P_L)} = \mp k a_e \frac{F_2^{\pm 2}}{F_2}, \tag{18}
\]

measure to a very good approximation the structure function ratio. These asymmetries are proportional to combinations \( a_{eVq} \) and thus provide a direct measure of parity violation. In the Standard Model \( A^+ \) is expected to be positive and about equal to \(-A^-\). At large \( x \) the asymmetries measure the \( d/u \) ratio of the valence quark distributions according to
The measurement from ZEUS and H1 [77], shown in Fig. 24, are in agreement with the theoretical predictions.

6. SEARCHES FOR NEW PHYSICS IN ep COLLISIONS

6.1. COLLIDERS AT THE ENERGY FRONTIER

The three highest energy colliders providing data are LEP (e+e–), HERA (e+p) and Tevatron (p¯p). Their characteristics are summarised in Table 3. In total, LEP experiments accumulated approximately 3.5 fb–1 for centre-of-mass energy ranging from 89 to 209 GeV. HERA and Tevatron experiments will collect a similar amount of luminosity at the end of their respective data taking periods.

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>e+ – p</td>
<td>H1</td>
<td>ALEPH</td>
<td>CDF</td>
<td></td>
</tr>
<tr>
<td>e–</td>
<td>ZEUS</td>
<td>DELPHI</td>
<td>D0</td>
<td></td>
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<td></td>
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<td>OPAL</td>
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<td></td>
<td></td>
<td>L3</td>
<td></td>
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<tr>
<td>L /expt.</td>
<td></td>
<td>500 pb–1</td>
<td>800 pb–1</td>
<td>4 fb–1</td>
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</table>

The highly energetic collisions of particle beams lead to a variety of primary hard scattering processes. Besides the direct interaction between the colliding particles, the initial state processes (radiation, parton substructure etc.) can lead to a picture where the initial beams produce secondary beams of different particles that enter the true hard scattering. For instance, the direct electron-proton interaction at HERA may take place in elastic scattering. In Deep Inelastic Scattering (DIS), the proton is seen as a bag filled with quarks or gluons and HERA collides (in a “second” mode) electrons with quarks or electrons with gluons. In the same way at LEP the flux of real photons from initial state radiation on one side can collide with the electron beam from the other side or with its associated photon beam and therefore LEP can function as e – γ or γ – γ collider. This “second” mode functioning for the considered colliders is summarized in Table 4. Although this picture of the hard scattering is schematical
Table 4

Possible parton-parton interactions at colliders with electron and/or proton beams

<table>
<thead>
<tr>
<th>Collider</th>
<th>Beams</th>
<th>“Second” mode collisions</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEP</strong></td>
<td>$e^+ - e^-$</td>
<td>$e^+ - \gamma$</td>
<td>full use of the $\sqrt{s}$ dominates at high $P_T$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma - \gamma$</td>
<td></td>
</tr>
<tr>
<td><strong>HERA</strong></td>
<td>$e^+ - p$</td>
<td>$e^+ - q$</td>
<td>elastic/diffraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e^+ - \gamma$</td>
<td>DIS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma - q$</td>
<td>Compton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma - g$</td>
<td>photo–production ($e \gamma \rightarrow$ had.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$q - q$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$q - g$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g - g$</td>
<td></td>
</tr>
<tr>
<td><strong>TEVATRON</strong></td>
<td>$p - \bar{p}$</td>
<td>$q - q$</td>
<td>elastic/diffraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$q - g$</td>
<td>main collision mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g - g$</td>
<td>for high $P_T$ physics</td>
</tr>
</tbody>
</table>

and incomplete, it helps understanding the main features in the capabilities of the three colliders to test the Standard Model and to search for the new physics. The partonic luminosities are shown in Fig. 25. From that picture one can see for instance that HERA collides electrons with quarks at highest energy and luminosity up to 320 GeV. LEP has the priority on $e^- \gamma$ collisions up to its centre-of-mass energy but HERA takes over at higher energies.

The HERA, LEP and Tevatron colliders provide complementary capabilities for the searches of new physics, beyond the Standard Model. The LEP and the Tevatron are “annihilation” colliders, which can produce any fermion-antifermion pair which couples to a boson produced in the $s$-channel. Therefore new particles which do not couple directly to the SM fermions can be produced. Furthermore, the rates for such processes will depend only on the SM gauge couplings. In contrast, HERA is a “scattering” collider, where the exchanged SM boson is in the $t$-channel. Only new bosons that couple both to leptons and quarks could be produced in the $s$-channel of $eq$ collisions and the rate would depend on the non-SM $e^-q$-boson coupling.

This partially explains the dominance of LEP and the Tevatron in searches for pair production of new particles (e.g. $s$-particle production in $R_p$, conserving SUSY) and the competitiveness of HERA in scenarios involving particles with lepton-quark couplings (e.g. leptoquarks or squarks in $R_p$, violating SUSY). In addition, the QCD background, which is very difficult at the Tevatron, is less of
a problem at HERA. This allows the investigation of a wider range of decay
channels and extends the HERA sensitivity to regions of parameter space that are
inaccessible to Tevatron analyses. LEP searches benefit from both low
backgrounds and high luminosity due to the excellent machine performance, but
are limited by the lower centre of mass energy compared to HERA or the Tevatron.

A few searches for new physics at HERA are briefly described below.

6.2. SUSY

A popular extension the Standard Model is supersymmetry (SUSY) [78].
SUSY unifies internal symmetries with Lorentz invariance and associates
supersymmetric partners (s particles) to the known SM particles. Supersymmetric
models provide solutions to many problems of the SM (hierarchy, fine-tuning,
unification) and predict spectacular final states in high-energy particle collisions.
Despite extensive studies at colliders and elsewhere, no trace of SUSY has yet
been detected.

The production of single s particles is possible if the conservation of the
multiplicative quantum number $R_p$ is violated ($R$-parity is $R_p = (-1)^{3B+L+2S}$
where $B, L,$ and $S$ denote the particle’s baryon number, lepton number, and spin
respectively). In $R$–parity violating models, $s$–channel squark production at
HERA via the electron-quark-squark Yukawa coupling ($\lambda$) is possible. A special
case is the stop ($\tilde{t}$) which in many SUSY scenarios is the lightest squark.

Searches for $R_p$ violating SUSY at HERA [80] have excluded scenarios
where s quark masses are below 275 GeV for a Yukawa coupling of electroweak
strength. The searches involved all possible decays of the squarks (both direct
$R_p$–violating and gauge decays) and are therefore sensitive to a large class of
models, corresponding to a wide scan over the parameter space. Excluded
domains in the SUSY parameter space are shown in Fig. 26.

6.3. LEPTOQUARKS

Leptoquarks are hypothetical bosons which couple to a lepton and a quark
via a Yukawa coupling (denoted $\lambda$). In the Standard model, both quarks and
leptons occur in left-handed $SU(2)$ doublets and right-handed $SU(2)$ singlets. The
symmetry between quarks and leptons leads to the cancellation of triangle
anomalies which make the SM renormalizable. Leptoquarks appear in theories in
which this symmetry is more fundamental.

Leptoquarks (LQs) are color triplets, which would be pair produced in
either $q\bar{q}$ or $gg$ interactions at $pp$ or $pp$ colliders. Because they carry electroweak
charge, they would also be pair produced in $e^+e^-$ collisions. Only standard model
gauge couplings are involved in pair production; therefore the cross sections
depend neither on the quark-lepton-LQ Yukawa coupling nor on the quark and
lepton generations to which the leptoquark couples. In contrast, leptoquarks
would be singly produced via the Yukawa coupling in a lepton-quark collision.
Searches at electron-proton colliders are sensitive only to LQs which couple to
electrons and the sensitivity to LQs which couple to second and third generation
quarks is far below that of first-generation LQs. Leptoquarks are usually (but not
always) assumed to be generation diagonal. Models in which LQs couple to
more than one generation of quarks or leptons would induce flavor-changing
neutral currents or lepton flavor violation respectively [81].

The model of Buchmüller, Rückl and Wyler (BRW) [82], in which
leptoquarks couple to a single generation of SM fermions via chiral Yukawa
couplings which are invariant under \( SU(3) \times SU(2) \times U(1) \) is often used to classify
possible leptoquark species. In the BRW model baryon and lepton numbers
(\( B \) and \( L \)) are conserved; there exist ten possible leptoquark species characterized
by the chirality of the coupling, the spin (\( J = 0 \) or 1), the weak isospin (\( T = 0, 1/2, \) or 1), and the fermion number, \( F = 3B + L = 0 \) or 2.

The experimental signature of the leptoquarks is a narrow peak in the
electron–jet or neutrino–jet mass spectra. In the absence of such observation,
exclusion limits on the model parameters are calculated. An example is shown in
Fig. 27. For a coupling of electroweak strength \( \lambda = 0.3 \), leptoquarks lighter than
\( \sim 290 \) GeV are excluded by both ZEUS and H1 [83].

6.4. SEARCHES FOR EXCITED FERMIONS

In the Standard Model, the fermion masses span more than 6 orders of
magnitude, from neutrinos with masses of the order of 1 eV to the top quark, the
heaviest known fermion with a mass of 174 GeV. This fermion mass hierarchy is
one of the greatest puzzles of the Standard Model (SM). It can naturally be
explained if the SM fermions are composite, so that various fermion masses can
be built from different ground states of the composing particles. In this case
excited states of the known fermion may also exist and be produced at colliders.

A minimal extension [84] of the SM is used to incorporate excited fermions
(\( F^* \)). Considering only the electroweak interactions, the excitation part of the
lagrangian is:

\[
L_{F^*F} = \frac{1}{2\Lambda} F_R \sigma^{\mu\nu} \left[ g f' \frac{2}{3} \partial_\mu W_\nu + g' f'' Y \frac{2}{3} \partial_\mu B_\nu \right] F_L + \text{h.c.},
\]  

where the new weights \( f \) and \( f' \) multiply the SM coupling constants \( g \) and \( g' \)
corresponding to the weak \( SU(2) \) and electromagnetic \( U(1) \) sectors respectively.
The corresponding gauge boson fields are denoted by \( W \) and \( B \). The matrix
\[ \sigma_{\nu \nu} = (i/2) \left[ \gamma^\mu, \gamma^\nu \right] \], \tau are the Pauli matrices, and \( Y \) is the weak hypercharge. The compositness scale \( \Lambda \) reflects the range of the new confinement force and together with the couplings \( f \) and \( f' \) determines the production cross section and the branching ratios of the excited fermions. Effects related to compositness can also appear via contact interactions, an alternative not considered here.

Excited neutrinos can be produced in electron–proton collisions at HERA via the \( t \)-channel charged current (CC) reaction \( e^\pm p \to \nu^* X \). The cross section is much larger in \( e^-p \) collisions than in \( e^+p \) collisions due to the helicity enhancement, specific to CC-like processes. The most recent analysis uses a data sample corresponding to an integrated luminosity of 114 pb\(^{-1}\) data sample collected by the H1 collaboration.

The excited neutrinos are searched for in the following decay channels: \( \nu^* \to \nu \gamma, \nu Z, eW \). The \( W \) and \( Z \) bosons are reconstructed in the hadronic channel \( W, Z \to jets \). The analysis covers 80\% (70\%) of the total branching ratio for \( f = -f' \) \( (f = f') \). For the events selected in the \( \nu \gamma \) and \( \nu Z \) channels, the neutrino is assumed to be the only non-detected particle in the event and its kinematics is reconstructed assuming the balance of the transverse momenta and the conservation \( \sum (E - P_z) = 2E_{\text{beam}} = 55.2 \text{ GeV} \). The invariant mass of the excited neutrino candidates reconstructed in the three channels described above is shown in Fig. 28. No deviation with respect to the SM prediction is observed in these spectra.

In the absence of a signal for excited neutrino production, limits on the production cross section are calculated using a frequentist approach [87]. The data events are counted in a mass window around a given \( M_{\nu^*} \) hypothesis and used together with the corresponding SM prediction to calculate an upper limit at 95\% CL on the number of \( \nu^* \) events, which is then translated into a limit on \( \nu^* \) production cross section. The width of the mass window is varied as a function of \( M_{\nu^*} \) in order to optimise the expected limit, obtained by replacing the observed by the expected number of events. The obtained limits on the cross section are translated into exclusion limits in the plane \( (f/\Lambda, M_{\nu^*}) \), assuming \( f = f' \) or \( f = -f' \) (Fig. 29). For \( f = -f' \) (maximal \( \gamma \nu \nu^* \) coupling) and assuming \( f/\Lambda = 1/M_{\nu^*} \), excited neutrinos with masses below 188 GeV are excluded at 95\% CL.

The present results greatly extend previous searched domains at HERA and confirm the HERA unique sensitivity for excited neutrinos with masses beyond LEP reach.
6.5. RARE EVENTS WITH ISOLATED ENERGETIC LEPTONS

The luminosity accumulated by each of the two collider–mode detectors, H1 and ZEUS, amounts to roughly 300 pb\(^{-1}\) in \(e^+p\) collisions and close to 200 pb\(^{-1}\) in \(e^-p\). This data sample enables the search for rare phenomena, with cross sections around or below 1 pb. One such process is the production of \(W\) bosons, for which the total production cross section is around 1.3 pb\(^{-1}\), calculated including NLO-QCD corrections [88]. If the \(W\) boson decays leptonically, the corresponding events contain an energetic, isolated lepton and significant missing energy due to the escaping neutrino.

Such events have been observed at HERA by the H1 collaboration [89] (an example is shown in Fig. 30). Moreover, an excess of events with large hadronic transverse momentum \(P_T^X\) was reported after the first data taking period HERA I (1994–2000, 118 pb\(^{-1}\)), where 11 events are observed with \(P_T^X > 25\) GeV for a Standard Model (SM) expectation of 3.5 ± 0.6. The ZEUS collaboration also performed a search for this event topology, within an analysis aimed at a search for anomalous top production [90], but did not confirm the excess observed by H1. Recent results from the H1 analysis [91] performed including all available data up to July 2006 (442 pb\(^{-1}\)) and a new ZEUS analysis [92] using a data sample corresponding to an integrated luminosity of 432 pb\(^{-1}\) are now available.

The distribution of events in the H1 analysis as a function of \(P_T^X\) is shown separately in \(e^+p\) and \(e^-p\) data samples in Fig. 31. This result indicates a slight excess of events at large \(P_T^X\) originating from the \(e^+p\) data sample. The excess observed by H1 in \(e^+p\) data has a significance of 2.7 \(\sigma\) but is not confirmed by the ZEUS analysis. In the \(e^-p\) data sample, a good agreement with the SM is observed by both H1 and ZEUS.

The excess in \(e^+p\) collisions can originate from a new interaction, dependent on the fermion number, like predicted for instance within some supersymmetric scenarios [93, 94]. The anomalous production of single top in \(ep\) collisions can also induce events of this type [95]. Indeed, although the Standard Model cross section is of less than 1 fb [96, 97], in some extended theories the top quark is predicted to undergo flavour changing neutral current (FCNC) interactions, which could lead to a sizeable top production cross section. FCNC interactions are present in models which contain an extended Higgs sector [98], Supersymmetry [99], dynamical breaking of the electroweak symmetry [100] or an additional symmetry [101]. However, the asymmetry between \(e^+p\) and \(e^-p\) collisions cannot be explained by this scenario.

Within the Standard Model (SM) the production of multilepton events in \(ep\) collisions is possible mainly through photon-photon interactions, where quasi-real photons radiated from the incident electron and proton interact for producing a
pair of leptons $\gamma \gamma \rightarrow \ell^+ \ell^-$ [102]. Events with two or three visible leptons (electrons or muons) have been measured for the first time in electron-proton collisions at HERA. An example of such event is shown in Fig. 32. Good overall agreement with the Standard Model prediction is observed. In Fig. 33 (left) the spectra of invariant mass of the two highest $P_T$ leptons in the events and the sum of transverse momenta of all leptons are shown.

In the multi-electron analysis, several events with invariant mass of the two highest $P_T$ electrons $M_{12} > 100$ GeV have been observed in an analysis of HERA I data [103]. Combining all channels, four events are observed with a scalar sum of lepton transverse momenta ($\sum P_T$) greater than 100 GeV, compared to a SM expectation of $1.1 \pm 0.2$. The four events with $\sum P_T > 100$ GeV are observed in $e^+p$ collisions only where the SM expectation is of $0.6 \pm 0.1$.

A possible non-standard process leading to events with multiple leptons is the production of a doubly charged boson $H^{\pm \pm}$, which appear as part of an extension of the Higgs sector by one triplet [104–106]. This type of bosons are predicted in left–right symmetric extensions of the Standard Model [107] and can be light enough to be produced at colliders [108]. They couple, with an unknown strength $\lambda$, to leptons. It could be produced in $ep$ collision by radiation off the lepton line and may decay into a pair of leptons, leading to events with several isolated leptons. In absence of a significant signal, limits on this model are calculated [109]. They are shown in Fig. 33 (right) for the case of a doubly charged Higgs boson coupling to $e\mu$. The sensitivity of HERA data extends well beyond the other colliders reach.

### 6.6. THE MODEL INDEPENDENT NEW PHYSICS SEARCH

The data can also be investigated in an model independent approach in order to search for deviations from the Standard Model predictions. The idea is to define a common phase space for all types of final state identified particles. The events are then classified according to the particle content. Kinematical quantities are defined, like the mass and the scalar transverse momentum, and a non-biased search algorithm is applied in order to look for local deviations that may appear due to for instance to a hypothetical multi–channel decay of a heavy particle.

The analysis has also been performed by the H1 collaboration [110]. “Objects” are defined from particle identification: electron ($e$), muon ($\mu$), photon ($\gamma$), jet ($j$) and neutrino ($\nu$) (or non-interacting particles). All final states are analysed having at least two objects with a transverse momentum ($P_T$) above
20 GeV and in the polar angle range $10^\circ < \theta < 140^\circ$. All selected events are then classified into exclusive event classes (e.g. $ej$, $jj$, $j\nu$) according to the number and types of objects detected in the final state. The event samples selected in the different classes are shown in Fig. 34 for a recent analysis of the data collected from $e^+p$ collisions. A very good agreement is found for nearly all those topologies which is a great achievement, taking into account the complexity of the final states that are studied.

The general search at high $P_T$ gives a global view of the physics rates as a function of the final state topology and require a good understanding of the Standard Model and of the detector. This type of analysis is necessary for the searches program at present and future colliders, as it provides an extra security belt against the unexpected phenomena that may occur in a new pattern, different from what is predicted from the existing models.

7. HERA AND THE LHC

In 2008 the Large Hadron Collider (LHC) will provide first collisions at a centre-of-mass energy of 14 TeV. Main physics goals of this experimental complex [111] is to establish the mechanism of the symmetry breaking of the Standard Model. The simplest mechanism is attributed to a scalar field, also called the Higgs boson, whose ground state breaks the explicit symmetry assumed in the Standard Model. The Higgs boson is considered at present the main candidate for explaining the masses of the particles.

Beyond the Standard Model, many theories and extensions predict a plethora of new particles with masses below 1 TeV, for which signals may be detected at LHC. Since the proton beams will collide at a centre-of-mass energy never reached before, the question of the proton structure is crucial for the understanding of standard and non-standard physics signals at LHC.

Fig. 35 shows the kinematic range in $x$ and $Q^2$ reached at LHC, compared to HERA and Tevatron. For the production of a new particle with moderate mass (100÷300 GeV), the domain of low values of $x$ and high $Q^2$ is relevant. It can be deduced that the study of the phenomena at very low $x$ at HERA and the understanding of the proton structure in this regime are crucial for the physics at LHC.

The impact of the HERA data [112] on the gluon density determination at low $x$ is illustrated in Fig. 36. The measurements of the inclusive cross sections together with the measurements of the exclusive final states (like heavy quark or

1 Note however that for the understanding of the cold baryonic matter a detailed knowledge of the strong interactions is crucial, since, as explained in the beginning of this paper, the momentum content of the nucleon is dominated by gluons, which are massless.
jet production) at HERA ar of crucial importance for the determination of the gluon density at low $x$. The knowledge of the parton densities in this range of $x$ from HERA measurements can be extrapolated in the LHC domain at larger $Q^2$ using the DGLAP equations.

8. OUTLOOK

The physics of deep inelastic scattering (DIS) is one of the most fundamental branches of high energy physics. The experimental method, pioneered by Rutherford to investigate substructure using highly energetic particle collisions, is today one of the most powerful tools to scrutinize the baryonic matter. Its fundamental building blocks, the quarks, were discovered in the first break-up of the proton at SLAC in 1968. The mediators of the strong force, the gluons, were discovered in the late seventeens. Since then, the Standard Model of particle physics, including the theory of the strong force (Quantum Chromodynamics) has become a well established theory. The last quark, the top, was discovered in 1994, again in high energy proton collisions. The knowledge of the structure of baryonic matter, dominating the visible universe, has made huge progress in the last decades, thanks to an impressive effort to unravel the nucleon structure in fixed target experiments and at the HERA $ep$ collider. With the advent of the new “Large Hadron Collider”, which will begin proton–proton collisions at a centre-of-mass energy of 14 TeV in 2008, or by enabling even more ambitious DIS experiments [113] beyond HERA, the question of the next matter substructure may be answered.

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Fig. 5 – The HERA complex: the scheme including the injectors (left) and the kinematic plane accessible at HERA compared to former fixed target experiments (right).

Fig. 6 – The two collider mode detectors at HERA: H1 (left) and ZEUS (right).
Fig. 7 – The integrated luminosity as a function of time collected at HERA in electron– and positron–proton collisions.

Fig. 8 – Event displays of a neutral current scattering event measured by H1 (left) and charged current scattering event measured by ZEUS (right).
Fig. 9 – Left: the charged current and neutral current cross section as a function of $Q^2$ measured in $e^p$ collisions at HERA. Right: the charged current reduced cross section $\sigma_{CC}$ as a function of $x$ for various $Q^2$ values measured in electron– and positron–proton collisions.

Fig. 10 – The determination of the structure functions $F_2$, $F_L$, and $xF_3$ from HERA measurements.
Fig. 11 – Left: The measurement of $F_2$ as a function of $x$ for $Q^2 = 15$ GeV. Right: Sketch of the correspondence between the $F_2$ shape as a function of $x$ and the quark-parton model.

Fig. 12 – The parton distribution functions extracted from HERA data.
Fig. 13 – Schematic view of the HERMES spectrometer.

Fig. 14 – The measured structure function $g_1$ for proton, deuteron and neutron. The precise measurement from HERMES is compared with measurements from other experiments.
Fig. 15 – The mechanism of jet production in the Breit frame (left) and the measurements of the strong coupling as a function of the transverse jet momenta (right).

Fig. 16 – The contributions to the total cross section $f_{cc}$ and $f_{bb}$ shown as a function of $x$ for two different $Q^2$ values. The inner error bars show the statistical error, the outer error bars represent the statistical and systematic errors added in quadrature. The $f_{cc}$ from ZEUS obtained from measurements of $D^*$ mesons [21] and the prediction of the H1 NLO QCD fit [22] are also shown.
Fig. 21 – Left: The parton distribution functions of the diffractive exchange extracted from HERA data. Comparison on a linear $z$ scale between the total quark singlet and gluon distributions obtained from the ‘H1 2006 DPDF Fit A’ and the ‘H1 2006 DPDF Fit B’. These two fits differ in the parameterisation chosen for the gluon density at the starting scale for QCD evolution. Right: The $Q^2$ dependence of the fraction of the longitudinal momentum of the diffractive exchange which is carried by gluons integrated over the range 0.0043 < $z$ < 0.8, corresponding approximately to that of the measurement.

Fig. 22 – Axial and vector couplings of the $u$–quark (left) and $d$–quark (right) measured from the combined electroweak–QCD fit at HERA and compared with measurements from LEP and Tevatron.
Fig. 23 – The results of a combined QCD-electroweak fit in $M_{w^\prime}$–$G_{F}$ plane (left) and $M_{w^\prime}$–$M_{w}$ (right).

Fig. 24 – Left: The dependence of the charged current cross section on the electron or positron beam polarisation at HERA. Right: The polarisation asymmetry of the NC cross section at HERA.
Fig. 25 – Differential partonic luminosities \((dL/dM^2)\) at LEP, HERA and Tevatron as a function of the centre-of-mass energy of the parton-parton collision.

Fig. 26 – Exclusion domain of the \(R_g\)-violating coupling as a function of the squark mass (left). The interpretation of these limits in a constrained model based on grand unification (MSUGRA) as an exclusion domain in the plane \(m_0-m_{1/2}\), where \(m_0\) (\(m_{1/2}\)) is the scalar (fermionic) mass parameter at the unification scale.

Fig. 27 – The excluded domain in the plane coupling-mass for leptoquark searches at HERA, compared with searches at LEP and Tevatron.
Fig. 28 – The invariant mass of the excited neutrino candidates reconstructed in the three decay channels.

Fig. 29 – The limits obtained for the ratio $f/\Lambda$ as a function of the excited neutrino mass within two assumptions: $f = -f'$ (left) and $f = f'$ (right, corresponding to a vanishing coupling to the photon and no influence of the $\nu^* \rightarrow \gamma_f$ channel).

Fig. 30 – A display of a recorded event with an energetic isolated muon, a hadronic jet and missing momentum apparent as an imbalance in the transverse $(xy)$ plane.
Fig. 31 – The distributions of the observed events as a function of $P_T^X$ in the H1 analysis in e$^+p$ data and e$^-p$ data (right).

Fig. 32 – A display of a recorded event with three energetic isolated leptons (two muons and one electron) with an total invariant mass exceeding 100 GeV.
Fig. 33 – Left: distributions of the scalar sum of the transverse momenta of leptons compared to expectations. Right: exclusion limits obtained for a doubly charged Higgs boson coupling to $e\mu$ with a strength $\lambda_{e\mu}$.

Fig. 34 – The result of the H1 general search. The data (points) and Standard Model expectation (histogram) for all event classes with a SM expectation greater than 0.1 events are shown.
Fig. 35 – The kinematic domain reached at LHC.

Fig. 36 – The parton densities extracted from the DIS cross section measurements. Left: the result and the uncertainties obtained without HERA data. Right: HERA data is included.