The structure of the Troika: Proton, Photon and Pomeron, as seen at HERA *

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Abstract

HERA, the electron-proton collider, enables to probe the proton with a high resolving power due to the deep inelastic scattering reactions at high $Q^2$ values. In the low $Q^2$ region, one can study the properties of the photon. The large fraction of diffractive events found both in the low and high $Q^2$ region allows the study of the Pomeron. A review of what we have learned from HERA so far about the structure of these three objects is presented.

1 Introduction

The ultimate goal of high energy physics is to search for the fundamental constituents of matter and to understand their interactions. This view was already expressed by Newton in the introduction to his book on Optics:

Now the smallest particles of matter cohere by the strongest attraction, and compose bigger particles of weaker virtue; and many of these may cohere and compose bigger particles whose virtue is still weaker, and so on for diverse successions, until the progression ends in the biggest particles on which the operations in chemistry, and the colors of natural bodies depend, and which by cohering compose bodies of a sensible magnitude. There are therefore agents in nature able to make the particles of bodies stick together by very strong attractions. And it is the business of experimental philosophy to find them out.

There are two ways of studying structure of matter: the static way and the dynamic one. In the first approach, symmetry arguments like the ones used by Gel-Mann and Neeman led to the construction of a ‘Mendeleev table’ of the known particles, which eventually brought Gel-Mann and Zweig to postulate the existence of quarks. In the dynamic way one tries to ‘look’ at the particles. This is the ‘Rutherford way’ in which one bombards the target with particles of known identity and searches for structure through the study of the outcome of the bombardment. This was used in the electron–proton deep inelastic scattering (DIS) experiments at SLAC. The underlying assumption was that one uses a projectile whose properties are well known, who behaves like a pointlike structureless particle. Any structure that is being observed following the collision is assigned to the proton and its constituents. This way, the study of the SLAC DIS experiment showed that the DIS cross section behaves like that expected from the interaction of electrons with pointlike particles, called partons, which were later on shown to have the expected properties of quarks, namely spin $\frac{1}{2}$ and fractional charge. This is the quark–parton model (QPM).

1.1 DIS Kinematics

The SLAC DIS experiment introduced the use of some important kinematic variables relevant to the notion of ‘looking’ at the structure of a particle. In figure 1 a lepton with mass $m_l$ and four-vector $k(E_l, \vec{k})$ interacts with a proton with mass $m_p$ and four-vector $P(E_p, \vec{p})$ through the exchange of a gauge vector boson, which can be $\gamma$, $Z^0$ or $W^\pm$, depending on the circumstances. The four-vector of the exchanged boson is $q(q_0, \vec{q})$.

With these notations one can define the following variables,

\begin{align*}
q & = k - k' \\
\nu & \equiv \frac{P \cdot q}{m_p} \\
y & \equiv \frac{P \cdot q}{P \cdot k} \\
W^2 & = (P + q)^2 \\
s & = (k + P)^2.
\end{align*}
The meaning of the variables $\nu$ and $y$ is most easily realized in the rest frame of the proton. In that frame $\nu$ is the energy of the exchanged boson, and $y$ is the fraction of the incoming lepton energy carried by the exchanged boson. The variable $W^2$ is the squared center of mass energy of the gauge–boson proton system, and thus also the squared invariant mass of the hadronic final state. The variable $s$ is the squared center of mass energy of the lepton proton system.

The four momentum transfer squared at the lepton vertex can be approximated as follows (for $m_l, m'_l \ll E, E'$),

$$q^2 = (k - k')^2 = m_l^2 + m_l'^2 - 2k k' \approx -2E E'(1 - \cos \theta) < 0 .$$

(6)

The scattering angle $\theta$ of the outgoing lepton is defined with respect to the incoming lepton direction. The variable which is mostly used in DIS is the negative value of the four momentum transfer squared at the lepton vertex,

$$Q^2 \equiv -q^2 .$$

(7)

One is now ready to define the other variable most frequently used in DIS, namely the dimensionless scaling variable $x$,

$$x \equiv \frac{Q^2}{2p \cdot q} .$$

(8)

To understand the physical meaning of this variable, one goes to a frame in which masses and transverse momenta can be neglected - the so-called infinite momentum frame. In this frame the variable $x$ is the fraction of the proton momentum carried by the massless parton which absorbs the exchanged boson in the DIS interaction. This variable, defined by Bjorken, is duly referred to as Bjorken-$x$.

The diagram in figure 1 describes both the processes in which the outgoing lepton is the same as the incoming one, which are called neutral current reactions (NC), as well as those in which the nature of the lepton changes (conserving however lepton number) and which are called charged current processes (CC). In the NC DIS reaction, the exchanged boson can be either a virtual photon $\gamma^*$, if $Q^2$ is not very large and then the reaction is dominantly electromagnetic,
or can be a $Z^0$ which dominates the reaction at high enough $Q^2$ values and the process is dominated by weak forces. In case of the CC DIS reactions, only the weak forces are present and the exchange bosons are the $W^{\pm}$.

1.2 The proton structure function $F_2$

The inclusive Born cross section of a NC DIS reaction can be expressed (for $Q^2 \ll m_Z^2$) as,

$$\frac{d^2\sigma^{\text{Born}}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \frac{y^2}{2} 2xF_1 + (1 - y)F_2 \right],$$

(9)

where $\alpha$ is the electromagnetic coupling constant. The two structure functions $F_1$ and $F_2$ are related to the transverse and longitudinal $\gamma^* p$ cross sections [1].

The relation between the values of $F_2$ and their meaning as far as the structure of the proton is concerned can be best seen in a figure adopted from the book of Halzen and Martin [2]. In figure 2 one sees what are the expectations for the distribution of $F_2$ as function of $x$ given a certain picture of the proton. The static approach mentioned above could explain most

![Figure 2](image_url)

Figure 2: *The expected dependence of $F_2$ on $x$ given a certain scenario of the structure of the proton.*

properties of the known particles with the proton being composed of three valence quarks.
The first measurements of $F_2$ [3] indeed confirmed this picture and the QPM was constructed. Later measurements [4] showed that sea quarks and gluons are also present in the proton, as the bottom part of figure 2 shows.

Clearly in order to have a good picture of the structure of the proton one needs to ‘see’ the partons and thus needs the means to have a good resolving power. If we denote by $\Delta$ the sizes one can resolve inside the proton, the higher the virtuality of the exchanged gauge boson in figure 1, the smaller $\Delta$ gets,

$$\Delta \sim \frac{\hbar c}{\sqrt{Q^2}} = \frac{0.197 \text{ GeV fm}}{\sqrt{Q^2}}.$$  \hspace{1cm} (10)

Thus for $Q^2 = 4 \text{ GeV}^2$, $\Delta = 10^{-14}\text{cm}$; for $Q^2 = 400 \text{ GeV}^2$, $\Delta = 10^{-15}\text{cm}$; and for $Q^2 = 40000 \text{ GeV}^2$, $\Delta = 10^{-16}\text{cm}$.

1.3 The HERA collider

![Figure 3: The $x$–$Q^2$ kinematic plane of some of the fixed target and of the HERA collider DIS experiments.]

How does one achieve high $Q^2$ values? One can show that the following relation holds between $Q^2$, $x$, $y$ and $s$,

$$Q^2 \approx xys,$$  \hspace{1cm} (11)
which means that $Q_{\text{max}}^2 \approx s$. Therefore in order to reach large $Q^2$ values one needs to build a large $s ep$ collider, which is what was done at DESY with the HERA collider.

HERA [5] is the first $ep$ collider, where a beam of 27.5 GeV electrons (or positrons) collides with a beam of 820 GeV protons yielding a center of mass energy of 300 GeV, or $s \approx 90000$ GeV$^2$. \footnote{Presently the proton beam energy was increased to 920 GeV, increasing the center of mass energy to 318 GeV and $s$ to 101200 GeV$^2$.} It has increased the available kinematic $x-Q^2$ plane by two orders of magnitude going up in $Q^2$ and down in $x$. This can be seen in figure 3 which shows the range of existing measurements of some fixed target DIS experiments (SLAC [6], BCDMS [7], E665 [8], NMC [9]) together with the HERA measurements by the H1 [10] and ZEUS [11] collaborations.

During the period 1994–1997 the HERA collider has delivered an integrated luminosity of more than 70 pb$^{-1}$ out of which about 47 bp$^{-1}$ could be used for physics analyses. At present much effort is concentrated on a luminosity upgrade program, to come into effect in the year 2000, which will deliver an integrated luminosity of about 1 fb$^{-1}$ till the year 2005.

### 1.4 Low-$x$ at HERA

A closer look at figure 3 reveals two facts, one obvious and the other quite surprising. The two HERA collaborations strive to $Q^2$ values as high as possible. With the high statistics 1996–1997 data, the experiments have measured some DIS events with $Q^2 \sim 40000$ GeV$^2$. However, surprisingly, there is an effort also to go to as low $Q^2$ as possible, which also allows measuring at very low $x$ values. The reason for trying to reach very low $Q^2$ and low $x$ values can be seen from figure 4. In this figure, the dependence of the proton structure function $F_2$ on Bjorken $x$ is shown for three values of $Q^2$. One sees a clear rise of the structure function with decreasing $x$. However, as $Q^2$ gets smaller this rise is less steep. What does this plot tell us? In order to understand it, let us first look at the variable $x$. It is related to $Q^2$ and to $W$ (the $\gamma^* p$ center of mass energy) as,

\[
W^2 = Q^2 (\frac{1}{x} - 1) + m_p^2 \approx \frac{Q^2}{x},
\]

\footnote{\textit{Figure 4: The proton structure function $F_2$ as function of $x$ for three $Q^2$ values.}}
where the approximate relation is good for low $x$ values. Thus for fixed $Q^2$, going in the low $x$ directions means increasing $W$.

The proton structure function $F_2$ can be related to the total $\gamma^* p$ cross section $\sigma_{\gamma^* p}$ through the relation,

$$ F_2 = \frac{Q^2(1-x)}{4\pi^2\alpha} \frac{Q^2}{Q^2 + 4m^2x^2} \sigma_{\gamma^* p} \approx \frac{Q^2}{4\pi^2\alpha} \sigma_{\gamma^* p}, $$

(13)

where we have used the Hand [12] definition of the flux of virtual photons, and again the approximate expression holds for low $x$ values. Thus, the behaviour seen in figure 4 can be interpreted as a rising $\gamma^* p$ cross section with increasing $W$, where the increase gets steeper as $Q^2$ increases. How does this steepness decrease as one goes to lower and lower values of $Q^2$? Is there a sharp or a smooth transition? What happens at $Q^2 = 0$ when the photon is real?

1.5 Low $Q^2$ at HERA

These questions motivated the HERA experimentalists to try to measure the behaviour of the structure function at low $Q^2$ and also to measure the real photoproduction cross section in the high $W$ region of HERA. How does one do low $Q^2$ physics in a machine which was built to reach highest possible $Q^2$ values? A look at equation (6) shows that the value of $Q^2$ is determined by the energies of the incoming ($E$) and the outgoing ($E'$) electrons and by the scattering angle $\theta$ of the outgoing electron with respect to the incoming one,

$$ Q^2 = 2EE'(1 - \cos \theta). $$

(14)

To get to low values of $Q^2$, the angle $\theta$ has to be small and therefore the scattered electron remains in the beam pipe. However, if one can arrange to measure the outgoing electron at very low scattering angles in a special detector, one has a handle of measuring low $Q^2$ photons, with the possibility to go down to the quasi–real photon case for extremely small angles.

The two experiments, H1 and ZEUS, have each built a small calorimeter at a distance of about 30 m from the interaction point which allows to detect electrons which were scattered by less than 5 mrad with respect to the incoming electron direction. This ensures that the virtuality of the exchanged photons is in the range $10^{-8} < Q^2 < 0.02 \text{ GeV}^2$, with the median $Q^2 \approx 10^{-5} \text{ GeV}^2$. A diagrammatic example of an event produced by a quasi–real photon, denoted as a photoproduction event, is shown in figure 5. In this event the scattered electron is detected in the electron calorimeter. This calorimeter is part of the luminosity detector, which includes also a photon detector at a distance of about 100 m from the interaction point.

The way to tag events with $Q^2$ in the range of 0.1-1 GeV$^2$ is through two methods. One methods is based on moving the position of the interaction vertex towards the incoming electron beam. By shifting the vertex in this direction one increases the possibility to measure low-angle scattered electrons in the rear part of the main calorimeter. The other method is similar to that in the photoproduction case described above. It consists of building a special calorimeter to detect the small-angle scattered electron. This was done by building two parts of a small calorimeter around the beam pipe which accordingly was named the beam-pipe calorimeter (BPC). Both methods are diagrammatically described in figure 6.

It is thus clear from the above discussion that HERA has also become a source of high $W$ quasi–real photons. In fact, the highest $W$ photon beams before HERA were in the range of 20 GeV and HERA has increased this by one order of magnitude. This allows among other things to study the structure of the photon at low $x$ values.
1.6 The concept of the structure of the photon

What do we mean by ‘the structure of the photon’? The photon is the gauge particle mediating the electromagnetic interactions and thus one would expect it to be an elementary point-like particle. How can one talk then about the structure of the photon? We know from low $W$ data that when the photon interacts with hadrons it behaves like a hadron. This property is well described by the vector dominance model (VDM) [13] in which the photon turns first into a hadronic system with the quantum numbers of a vector meson before it interacts with the target hadron. The justification of this picture was given by Ioffe [14] who used time arguments. Just like a photon can fluctuate in QED into a virtual $e^+e^-$ pair (figure 7a) it can also fluctuate into a $q\bar{q}$ pair (figure 7b). As long as the fluctuation time $t_f$ is small compared to the interaction time $t_{int}$ the photon will interact directly with the hadron. However if $t_f \gg t_{int}$ the interaction will be between the $q\bar{q}$ pair and the hadron and will look like a hadronic interaction. The fluctuation time of a photon with energy $E_\gamma$ which is large compared to the hadronic mass $m_{q\bar{q}}$
Figure 7: Fluctuation of a photon into (a) an $e^+ e^-$ pair, (b) a $q \bar{q}$ pair.

into which the photon fluctuates ($E_\gamma \gg m_{q\bar{q}}$) is given by,

$$t_f \simeq \frac{2E_\gamma}{m_{q\bar{q}}^2}.$$  \hfill (15)

This is the case for a real photon. For a virtual photon $\gamma^*$ the fluctuation time is given by,

$$t_f \simeq \frac{2E_{\gamma^*}}{m_{q\bar{q}}^2 + Q^2}.$$  \hfill (16)

The interaction time with a proton is of the order of its radius, $t_{int} \approx r_p \sim 1$ fm. Thus while a high energy real photon develops a structure due to its long fluctuation time compared to the interaction time, a highly virtual photon has no time to acquire a structure before probing the proton.

The structure of real photons has been indeed studied in $e^+ e^-$ interactions where the photon structure function $F^\gamma_2$ has been measured in a similar DIS type of experiment as on the proton. A diagram describing this is shown in figure 8 where the proton target is replaced by a quasi-real photon target at the vertex where the electron has a very small scattering angle. The $x$

Figure 8: Diagram describing a DIS process on a quasi-real photon using the reaction $e^+ e^- \rightarrow e^+ e^- X$.

values reached in these experiments were not small due to the fact that the available $W$ of the $\gamma^*\gamma$ system was relatively small.
As stated above, also at HERA one can study the photon structure. The exchanged photon, which at high $Q^2$ is a probe, can change its role at very low $Q^2$ and become a quasi-real photon target. It can be probed by a high transverse momentum parton from the proton. We shall discuss this in more details in section 3.

The high $W$ values attained at HERA give a large lever arm to study the energy behaviour of the total photoproduction cross section $\sigma_{\text{tot}}(\gamma p)$. Does it show the same behaviour as the total hadron-hadron cross sections? The latter were shown by Donnachie and Landshoff [15] to have a simple behaviour, independent on the incoming hadron, and well described by the Regge model.

Donnachie and Landshoff (DL) succeeded to describe all available $\bar{p}p$, $pp$, $K^\pm p$, and $\pi^\pm p$ total cross section values by a simple parameterization of the form $\sigma_{\text{tot}} = Xs^{0.0808} + Ys^{-0.4525}$, where $s$ in the square of the total center of mass energy and $X$ and $Y$ are parameters depending on the interacting particles. The value of $X$ is constrained to be the same for particle and anti-particle beams to comply with the Pomeranchuk theorem [16]. The power of the first term is connected in the Regge picture to the intercept of the exchanged Pomeron at $t=0$, ($\alpha_{IP}(0) = 1.08$), while the second term comes from the intercept of the Reggeon ($\alpha_{IR}(0) = 0.5475$). The total cross section data of $\bar{p}p$, $pp$ and $\pi^\pm p$ are shown in figure 9 together with the DL parameterization.

One of the first measurements at HERA was that of the total $\gamma p$ cross section $\sigma_{\text{tot}}(\gamma p)$. The measurement showed that the hadronic behaviour of the photon, observed at lower energies, holds also in the HERA $W$ range. The measurements of H1 [17] and ZEUS [18], shown in figure 10, agree well with the expectations of the DL parameterization for photoproduction.

![Figure 9: The total cross section data of $\bar{p}p$, $pp$ and $\pi^\pm p$ as function of the center of mass energy $\sqrt{s}$. The DL parameterization is shown as the solid lines.](image)

1.7 Diffraction in photoproduction and DIS - the Pomeron

If the photon behaves like a hadron, one expects to see diffractive processes at HERA energies. Indeed it turns out that about 40 % of the photoproduction events are due to diffractive processes. The diffractive reactions are described by diagrams in which the exchange carries the
quantum number of the vacuum, is a colorless object and is referred to in the Regge language as the Pomeron trajectory. The existence of such a trajectory was first suggested by Gribov [23] in order to avoid contradictions with unitarity in the crossed channel. The trajectory was named after Pomeranchuk by Gel-Mann. In a reaction in which a Pomeron [24] is exchanged the proton remains intact or is being diffractively dissociated into a state with similar quantum numbers (Gribov-Morrison rule [25]). Thus there is a large rapidity gap between the proton or its dissociated system and the hadrons belonging to the system into which the photon diffracted. These large rapidity gap events were observed in the photoproduction sample at HERA.

One of the big surprises at HERA were the observation of large rapidity gap events also in the DIS events [20, 21]. The existence of such events meant that also a virtual photon can diffract. This indicated that a process of DIS which is believed to be a hard process because of the presence of a large scale, $Q^2$, can also possess properties like diffraction which are expected in a soft, low scale reactions. This interplay [22] of soft and hard processes will be discussed later. The observation of diffractive processes in the DIS sample opened up the possibility of studying the structure of the Pomeron in a DIS type experiment as depicted in figure 11.
Let us finish this section by figure 12 which shows events resulting from electron–proton interactions, as seen in the ZEUS detector (left part of each picture). The initial electron and proton are in the beam pipe and not seen in the detector. The electron enters the detector from the left and the proton from the right. The right part of each picture shows a lego plot of the transverse energy flow as function of the spatial angle.

The three events depicted on the left side of the page are three different processes: NC DIS (top) in which the scattered electron performs an almost U–turn and one of the partons of the proton emerges as a jet; CC DIS (center), where the initial electron turns into a neutrino which is undetected and one of the hit partons from the proton emerges as a jet, thus producing an unbalance in the transverse energy; photoproduction reaction (bottom), a process where the scattered electron emerges at a very small angle and thus remains undetected in the beam pipe and the quasi–real photon interacts with one of the partons of the proton producing two
high transverse momentum jets. The three events on the right hand side of the page are similar processes, respectively, with the distinction that the proton remains intact also after the interaction, producing a large rapidity gap in the forward part of the detector, indicating that the reaction is diffractive in nature and pointing to the presence of the Pomeron.

1.8 The ‘Fathers’

We have so far introduced the concept of the structures of the proton, the photon and the Pomeron, all of which can be studied at HERA, and details of which will be described in the next sections. We will conclude this lengthy introductory section with the pictures of the ‘fathers’ of these three objects: Rutherford (proton), Einstein (photon) and Gribov (Pomeron). Also shown is a picture of Pomeranchuk who gave his name to the Pomeron and made remarkable contributions to the theory of hadron-hadron interactions.

Figure 13: Rutherford  Figure 14: Einstein  Figure 15: Gribov