The legacy of HERA - the first decade

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Abstract

The $ep$ HERA collider started operation in summer of 1992. This talk summarizes some of the highlights of physics results obtained since then and discusses their impact on our understanding of Quantum Chromodynamics (QCD).
1 Preamble

This report is based on a talk, presented at DIS2000 in Liverpool, with the purpose to summarize shortly the legacy of HERA during the first decade of its operation. The talk was given to an audience working in the field. For the benefit of the reader who is less familiar with the subject, the proceedings version has been extended to include an appendix with definitions of the kinematical variables used in the text.

2 Introduction

The main motivation for building the HERA ep collider was to continue and study the inner structure of matter and the nature of forces in a way similar to that of Rutherford, by probing the proton with higher and higher gauge-boson virtuality, $Q^2$, in order to resolve smaller and smaller distances. This way of probing the proton is known as deep inelastic scattering (DIS).

The plane showing the fraction of the proton’s momentum carried by the probed parton, $x$, and the virtuality $Q^2$ of the probing photon, is shown in figure 1 and is impressive. It shows how HERA has extended the kinematic reach in both direction in $Q^2$, low and high, and in the low $x$ region, by few orders of magnitude.

![Figure 1: The $x$-$Q^2$ kinematic plane of some of the fixed target and of the HERA collider DIS experiments.](image-url)
3 The rise of $F_2$ with decreasing $x$

Before this talk, I polled the view of several eminent people as to what they consider to be the highlights of HERA so far. All of them unanimously put as number one the surprising sharp rise of $F_2$ with decreasing $x$ \footnote{1}, an example of which is shown in figure \ref{fig:fig2}. The DGLAP evolution equations predict the rise of the parton distributions with decreasing $x$. Why is then the observed rise so surprising? The physical quantity which is measured is $F_2$. To decompose $F_2$ into quarks, we need the ‘impulse approximation’ to be valid. This means that the configuration of the Fock states into which the proton fluctuates has to be ‘frozen’ during the interaction time. This condition leads \footnote{2} to a relation between the $Q^2$ of the probing photon and some other scales like quark masses, $m_q$, quark transverse momentum $k_T$’s and $x$. The fluctuation time, $\tau_f$, is inversely proportional to the mass squared of the probed configuration, $\tau_f \sim 1/M^2$. The interaction time, $\tau_{\text{int}}$, is inversely proportional to the photon virtuality, $\tau_{\text{int}} \sim 1/Q^2$. The ‘freezing’ condition for the use of impulse approximation requires $\tau_f \gg \tau_{\text{int}}$ or,

$$Q^2 \gg \sum_i \frac{(m_q^2 + k_{iT}^2)}{x_i}. \quad (1)$$

It is therefore highly non trivial that at very low $x$ the expectations of the DGLAP evolution equations, which apply to partons, remain valid for $F_2$. However, HERA teaches us that at $x \sim 10^{-3}$ the impulse approximation may be valid down to $Q^2 \sim 1.5 \text{ GeV}^2$. As a summary of this point I would like to quote Peter Landshoff: \textit{The amazing discovery of HERA is the rapid

![Figure 2: The proton structure function $F_2$ as function of $x$ at a fixed value of $Q^2=15\text{GeV}^2$.}
rise of $F_2$ at small $x$. This remains a challenge for theory: there is no respectable theoretical understanding.

4 Diffraction in DIS

The second subject, unanimously acclaimed as highlight, is the observation of abundant diffraction in DIS [3, 4]. This came as a surprise because if $F_2$ is an incoherent sum of quarks, a DIS process on a quark can not be diffractive because of color. A diffractive DIS reaction could happen only if the Fock state of the proton at the origin includes colorless objects.

If this were indeed the case, one would expect that diffractive DIS processes would be soft in nature, contrary to the accumulated evidence. One of the most striking behaviour of these large rapidity gap events is that they have a similar energy behaviour as that of the total inclusive cross section [3], as shown in figure 3, not expected in soft processes. Does that mean that these diffractive DIS processes are all hard?

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.pdf}
\caption{The ratio of the diffractive to total DIS cross sections as function of $W$, for given kinematical cuts, as indicated in the figure.}
\end{figure}
5 Soft-hard interplay at low $x$

When one thinks about a DIS process involving partons, the first intuition is to think of it as a hard process. This however turns out not to be the case. The best way to understand this is when the interaction is viewed in the proton rest frame. The photon fluctuates into a $q\bar{q}$ pair, which can either be a large spatial configuration, or a small one. The aligned jet model of Bjorken [5], leading to scaling properties of $F_2$, assumes that only large configurations contribute to DIS cross section. That would make DIS a predominantly soft process. The small configurations lead to scaling violation, as expected in QCD. To the extend to which scaling violation introduces only logarithmic corrections to scaling, one is led to conclude that, even within QCD, DIS is indeed predominantly soft. To me, it came as a cultural shocks to learn that DIS does not necessarily mean a hard process.

5.1 Large and small configurations

To confirm the validity of the picture above, we would like to isolate events in which we know that the photon predominantly fluctuates into a small configuration. This is achieved either by studying events initiated by longitudinal photons ($\gamma^*_L$) and looking at the behaviour of $\sigma_L$, or by studying exclusive vector meson electroproduction and deeply virtual Compton scattering (DVCS).

![Figure 4: The dependence of the $W$ exponent $\lambda$ on $Q^2$, for the total $\gamma^*p$ cross section, $\sigma_{tot}$, the longitudinal one, $\sigma_L$ and the transverse one, $\sigma_T$.](image)

Figure 4: The dependence of the $W$ exponent $\lambda$ on $Q^2$, for the total $\gamma^*p$ cross section, $\sigma_{tot}$, the longitudinal one, $\sigma_L$ and the transverse one, $\sigma_T$. 
Since, unfortunately, we did not measure the ratio $R = \sigma_L/\sigma_T$ of the longitudinal to transverse cross sections at HERA, I used as an exercise the parameterization of $R$ by Badelek, Kwiecinski and Stasto [6] together with that of ALLM97 [7] as a good representation of $\sigma_{tot}(\gamma^* p)$, to calculate the effective $\gamma^*p$ energy dependence of the cross section of $\sigma_L$ and $\sigma_T$ separately, assuming a $W^{\lambda}$ dependence. The result is shown in figure 4. As one sees, $\sigma_L$ has a very steep rise with $Q^2$, as expected from a small configuration process, reaching the value of 0.5 at $Q^2 \sim 1000 \text{ GeV}^2$.

The energy dependence of the cross section for photoproduction of vector mesons [8], shown in figure 5, indeed confirmed that when the photon is squeezed into a small size, there is a definite change in the $W$ behaviour, as expected from pQCD, which connects the $W$ behaviour with the rise of the gluons. In the case of $J/\psi$ this happens already at $Q^2=0$, due to the presence of the charm quarks. For the lighter vector mesons, it happens around $Q^2=10 \text{ GeV}^2$, as seen from the $\phi/\rho^0$ ratio [8], shown in figure 6, and which reaches the expected value of $2/9$ at that $Q^2$. 

Figure 5: The $W$ dependence of the total photoproduction cross section together with the cross section for photoproduction of vector mesons.
The other property of hard exclusive processes is the universal slope of the diffractive peak. In Regge language this means a decreasing slope $\alpha'$ of the Regge trajectory. This is shown in figure 7 where the Pomeron trajectory is presented as obtained from elastic photoproduction of $\rho^0$, $\phi$ and $J/\psi$ \cite{8}. One sees a clear flattening in case of the $J/\psi$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure6.png}
\caption{The ratio of the cross sections of $\phi$ and $\rho^0$ as function of $Q^2$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure7.png}
\caption{The Pomeron trajectory as obtained from elastic photoproduction of $\rho^0$, $\phi$ and $J/\psi$.}
\end{figure}
5.2 The gluon and saturation?

The inclusive diffraction structure function [1], presented in figure 8, shows a very different behaviour from that of the proton structure function [9], shown in figure 9. While the proton structure function shows positive scaling violation at low $x$ and negative one at high $x$, the diffractive structure function shows practically only positive scaling violation, and may reach scaling at a large values of $\beta$. QCD factorization was proven to hold also in the inclusive diffraction case and thus DGLAP evolution equations could be applied. However it turned out that for the evolution equations to be able to describe the $Q^2$ behaviour of the data, a large diffractive gluon component is required [4].

This brings me to talk about the gluon in the proton. What have we learned about the gluon? From the scaling violation, using the impressive measurements at HERA, shown in figure 9, the precision of the gluon determination has improved tremendously, as shown in figure 10 [9]. The direct gluon determination from charm production is in very good agreement with the indirect ones from scaling violation. However, when trying to stretch the evolution equations down to low $Q^2$, as presented in figure 11 for $Q^2 = 1 \text{ GeV}^2$, one finds a strange behaviour of the gluon at low $x$ [10].
Figure 10: The gluon momentum density distribution as function of $x$ for different fixed values of $Q^2$.

Figure 11: The gluon momentum density distribution as function of $x$ for different fixed values of $Q^2$.

What is this strange behaviour of the gluons at low $x$ and low $Q^2$ tell us? If anything 'strange' is happening, the gluons will feel it first because of the $9/4$ color factor: $\sigma_{ggp} = (9/4)\sigma_{q\bar{q}p}$. One can calculate the probability $P^D_g$ that an interaction on the gluon is associated with diffraction. For a value of $Q^2=4.5\text{GeV}^2$ and $x<10^{-3}$ this comes out to be $P^D_g \simeq 0.4$ [11], which is very close to the black disc limit of 0.5. Does this mean that we see some kind of saturation (unitarity effects)? Such saturation effects could lead to the suppression of 'large' $q\bar{q}$ configuration and lead to the breakdown of DGLAP evolution in this region. This can in fact be nicely observed when $F_2$ is plotted as function of $Q^2$ for fixed $y$ [12], displayed in figure [12] where one sees the approximate scaling down to $Q^2 \sim 2 \text{GeV}^2$ and then the $1/Q^2$ decrease of $F_2$ towards the low $Q^2$ region. This behaviour, and also that of the Caldwell plot [13], shown in figure [13], are well described by the saturation model of Golec-Biernat and Wuesthoff [14].

This section can be summarized by a quotation from Al Mueller’s message: The turnover at small $Q^2$ (and small $x$) along with the success of the Golec-Biernat Wuesthoff model in describing that turnover (along with diffractive scattering) suggest that unitarity limits have been reached when $Q^2 \approx 1 - 2 \text{GeV}^2$ in the low $x$ region at HERA. In parton language this is saturation in the small $x$ wave function of the proton.
Figure 12: The proton structure function $F_2$ as function of $Q^2$ for fixed values of $y$.

Figure 13: The slope of $F_2$ with respect to $Q^2$ as function of $x$ at given $Q^2$ values.

6 The photon - probing the vacuum

HERA, the machine designed to teach us about the proton, turned out to be a good tool for studying the structure of both the real and the virtual photon.

A clear two component structure of the real photon has been observed at HERA [15]. The gluon distribution in the photon has been extracted and also shows a rise with decreasing $x$ [16]. HERA thus provides an alternative way to that of the $e^+e^-$ collider to measure the photon structure function and to extract parton distributions in the photon.

Studies of these type in the DIS regime showed that also a virtual photon can have a two component structure at low $x$ even at virtualities as high as $Q^2 \sim 50 \text{ GeV}^2$ [17]. This of course raises the question: is the virtual photon probing the structure of the proton or are the partons from the proton probing the structure of the photon? Who is probing whom? In fact, in the proton rest frame $x$ can be given a spatial meaning: the coherence length can be written as $l_c = 1/(2m_p x) \approx 0.1 \text{ fm}/x$ which in the low $x$ region can be very large, much larger than the
radius of the proton. Thus at low $x$ we are actually not studying the structure of the proton. To put it in Bjorken’s words: *The important spacetime regions are neither in the valence region of the hadron nor in the “valence” region of the photon probed.* At low $x$ we are probing the structure of the vacuum.

## 7 Very large $Q^2$ region

The subject of the very large $Q^2$ region actually belongs to the future legacy of HERA, which the HERA upgrade will produce. So far it produced a ‘text-book’ result showing that the cross section of NC and CC reactions meet at $Q^2 \approx M_Z^2$. Recently, the higher statistics data also showed clearly the effect of the electroweak interference and the first measurements of $x F_3$ were obtained. Searches for deviation from the SM caused excitement. Limits on exotic processes were obtained and await higher luminosity data.

Our discussion in the previous section clearly indicates that in order to study the interior of the proton, one needs not only to go to higher values of $Q^2$ but also to $x$ values in excess of 0.1. The HERA upgrade should provide the luminosity necessary for obtaining high enough statistics in the high $Q^2$ high $x$ region.

## 8 Discussion

The sharp rise of $F_2$ with decreasing $x$, the diffraction in DIS, should we have been surprised? Some say yes, some say - in retrospect- no. The fact, however, is that we were surprised and unprepared. The original design of the detectors was not really well suited for the low $x$, low $Q^2$ physics. None of the DIS MC generators had diffractive processes. We also took seriously parton distributions which predicted a flat $F_2$ at low $x$.

To summarize the lesson learned from the low $x$ physics at HERA, we have observed a tremendous progress in understanding of QCD dynamics for high energy interactions and we might be faced with the existence of a new QCD regime with high parton densities.

Another legacy of HERA was pointed out by James Stirling: *Studying QCD at HERA has given us great confidence that we can very precisely predict LHC cross sections. Indeed, it is under active consideration to use Standard Model $Z$ cross sections to measure the LHC luminosity, and it is only because the proton structure is pinned down so well by HERA that we can trust the theoretical calculations.*

HERA has actually elevated QCD almost to the status of QED, in the sense that QED processes are used to measure luminosities at HERA. Not that there were doubts in the correctness of QCD. However, QCD is a complicated theory, and thus we can say that HERA in the year 2000 is a glorious triumph of minds dealing with QCD.

Did we however get a better picture of the proton? Rutherford’s experiment allowed him to say that most of the atom is empty with a nucleus at its center. How do we see the
proton? Some describe the proton as being a 'Thompson' like proton: 'soup' of gluons filled with pointlike quark 'raisins'. Other see it as a 'Rutherford' like proton: 3 centers of pointlike parton clouds. Asking Lonya Frankfurt, his reply was that the outer 20% of the proton is a pion cloud, while nothing is known about the inner 80%. Maria Krawczyk brought to my attention the view of Altarelli, Cabbibo, Maiani and Petronzio [19], who view the proton as 3 constituent quarks, each of which is a complex object made out of pointlike partons. Where are all these partons located in the proton? It would be nice to be able to stand in front of a class and tell the students, just as Rutherford did about the atom, how the proton looks like. The HERA upgrade program will hopefully give us the answer.

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Appendix

DIS Kinematics

A diagram describing a DIS process on a proton is shown in figure 14. 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 \( q(q_0, \vec{q}) \).

\[ q = k - k' \]  
\[ \nu \equiv \frac{P \cdot q}{m_p} \]  
\[ y \equiv \frac{P \cdot q}{P \cdot \vec{k}} \]  
\[ W^2 = (P + q)^2 \]  
\[ s = (P + k)^2 \]  

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 \( m_l, m'_l \ll E, E' \)),

\[ q^2 = (k - k')^2 = m_l^2 + m'_l^2 - 2kk' \approx -2EE'(1 - \cos \theta) < 0 \]  

Figure 14: Diagram describing a DIS process on a proton.

With these notations one can define the following variables,
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,

\[
Q^2 \equiv -q^2 .
\]  

(8)

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

\[
x \equiv \frac{Q^2}{2P \cdot q} .
\]  

(9)

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 14 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 \( W^\pm \).

**Kinematics of diffractive scattering**

The variables used to analyze diffractive scattering are introduced for \( ep \) DIS.

A diagram for diffractive scattering in DIS, where the diffracted state is separated from the scattered proton by a large rapidity gap (LRG), is presented in figure 15 and all the relevant
four vectors are defined therein. In addition to the usual DIS variables, defined above, the
variables used to describe the diffractive final state are,

\[ t = (P - P')^2, \]
\[ x_p = \frac{q \cdot (P - P')}{q \cdot P} \approx \frac{M_X^2 + Q^2}{W^2 + Q^2}, \]
\[ \beta = \frac{Q^2}{2q \cdot (P - P')} = \frac{x}{x_p} \approx \frac{Q^2}{Q^2 + M_X^2}. \]

\[ x_p \] is the fractional proton momentum which participates in the interaction with \( \gamma^* \). It is
sometimes denoted by \( \xi \). \( \beta \) is the equivalent of Bjorken \( x \) but relative to the exchanged object.
\( M_X \) is the invariant mass of the hadronic final state recoiling against the leading proton, \( M_X^2 = (q + P - P')^2 \). The approximate relations hold for small values of the four-momentum transfer
squared \( t \) and large \( W \), typical of high energy diffraction.

To describe diffractive DIS, it is customary to choose the variables \( x_p \) and \( t \) in addition to
the usual \( x \) and \( Q^2 \) in the cross section formula. The diffractive contribution to \( F_2 \) is denoted
by \( F_2^D \) and the corresponding differential contributions are

\[ F_2^{D(3)} = \frac{dF_2^D}{d x_p}, \quad F_2^{D(4)} = \frac{dF_2^D}{d x_p d t}. \]

The contribution from the longitudinal structure function is omitted for simplicity.

The four-fold differential cross section for \( ep \) scattering can be written as

\[ \frac{d^4 \sigma_{ep}^D}{dx_p dt dx Q^2} = \frac{2\pi\alpha^2}{x Q^4} \left[ 1 + (1 - y)^2 \right] F_2^{D(4)}(x, Q^2, x_p, t). \]

The structure function \( F_2 \) is related to the absorption cross section of a virtual photon by
the proton, \( \sigma_{\gamma^*p} \). For diffractive scattering, in the limit of high \( W \) (low \( x \)),

\[ F_2^{D(4)}(x, Q^2, x_p, t) = \frac{Q^2}{4\pi^2\alpha} \frac{d^2 \sigma_{\gamma^*p}^D}{d x_p d t}. \]