Physics Results from HERA

Christian Kiesling

Mac-Planck-Institute for Physics, Föhringer Ring 6, D-80805 München

Abstract. We present recent data on inclusive and diffractive scattering in deep-inelastic electron-proton reactions at HERA and review the analysis of these data in terms of parton distribution functions. While the main part of the deep-inelastic scattering cross section is well understood in terms of the partonic structure of the proton, the diffractive exchange, being a sizeable fraction of the total cross section, is still under intensive discussion. The extraction of the partonic nature of diffractive exchange is based on the factorization property of QCD, and reveals a clear dominance of gluonic exchange. A direct measurement of the gluon structure of the proton can be achieved by lowering the center-of-mass energy for HERA. These data, combined with the corresponding data from the high energy running, will allow a model-free extraction of the longitudinal structure function, both in inclusive and diffractive scattering, and thus allow for a direct measurement of the gluon distributions in both processes.

Keywords: electron-proton scattering, neutral/charged currents, diffraction, parton distributions

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INTRODUCTION

A prime motivation to discuss HERA data at a workshop covering the physics from colliders to cosmic rays is the fact that electron-proton reactions can be viewed as collisions of ultra-high-energy photons - emitted by the electron - with nuclear matter. Comparing to the cosmic energy spectrum, the HERA collider provides a photon beam equivalent to 50 TeV on a stationary proton target, lying about half way (on a logarithmic scale) between the “knee” and the “ankle”, i.e. at about almost $10^{14}$ eV. Such high energy photon-proton collisions, which are governed by the strong interaction, are of upmost importance for observational astrophysics, in particular for the understanding of the interactions of ultra-high-energy cosmic photons with our atmosphere which serves, in many cases, as target and detector.

Quantum Chromodynamics (QCD) is expected to describe the strong interactions between quarks and gluons. At distances small compared to the nucleon radius, or equivalently large momentum transfer $Q^2$, where the strong coupling $\alpha_s$ is small, perturbative QCD (pQCD) gives an adequate quantitative account of hadronic processes. The total cross sections for high energy reactions, however, are usually dominated by long range forces (“soft interactions”), where a satisfactory understanding of QCD still remains a challenge. In our present understanding, the soft, or non-perturbative, part of the hadronic reaction is described by structure functions, which in essence contain the momentum probability distributions of the scattering partners, the quarks and gluons.

A large fraction of these soft interactions, characterized by an almost energy-independent cross section, is mediated by color-singlet (vacuum quantum number) exchange, and is termed “diffractive”. In hadronic interactions, diffraction is well de-
scribed by Regge theory (see, e.g., [1]), which is formulated as a $t$-channel exchange of a leading trajectory, called the “Pomeron” trajectory. In the high energy limit, pomeron exchange dominates over all other contributions to the scattering amplitude and thus represents an essential feature of strong interactions. In recent years there has been considerable interest in studying “hard diffraction” (diffractive processes at large $Q^2$) in order to understand the exchange at the parton level.

The electron-proton collider HERA is an ideal place to study hard diffraction in deep-inelastic scattering (DIS) and therefore provides powerful new experimental input to study the strong interaction of hadrons. Since the high-energy limit of virtual-photon-proton reactions is equivalent to the low Bjorken $x$ regime in DIS, gluons are expected to dominate both the diffractive and non-diffractive exchange.

In this report we summarize the recent data from the high energy running of HERA with polarized electrons, and discuss the extraction of the parton distribution functions using inclusive as well as dijet data. We then discuss the idea of factorization which is basic to the analysis of diffractive data in terms of universal diffractive parton distribution functions. The results of pQCD fits to the diffractive data, including dijet production are presented, as well as the observation of a clear breakdown of factorization in diffractive photoproduction. Finally an outlook is given to the last three months of HERA running (April to June, 2007), which will be devoted to the measurement of the longitudinal structure functions, both for inclusive and diffractive processes.

**RECENT RESULTS FROM INCLUSIVE SCATTERING**

Inclusive $ep$ scattering can be divided into two distinct classes: Neutral currents (NC) reactions ($ep \to eX$), and Charged Currents (CC) reactions ($ep \to vX$). In NC reactions, a photon or a $Z^0$ may be exchanged between the electron and a quark emitted from the proton. The corresponding double-differential cross section $d^2\sigma/dxdQ^2$ can be described in the following way:

$$\frac{d^2\sigma(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[ F_2 - \frac{y^2}{Y_+} F_L + \frac{y}{Y_+} xF_3 \right]$$  \hspace{1cm} (1)

Here, the three (positive definite) structure functions $F_2$, $F_L$ and $xF_3$ depend both on $x$ and $Q^2$, and contain the (non-perturbative) parton distribution functions (PDFs). The scaling variable $y$ is related to $x$ and $Q^2$ via $Q^2 = sxy$, where $s$ is the square of the electron-proton center-of-mass energy. The functions $Y_+$ are purely kinematic and are given by $Y_+ = 1 \pm (1 - y)^2$. While the $x$ dependence of the structure functions are not calculable from first principles, their $Q^2$ dependence is predicted by perturbative QCD (e.g. DGLAP evolution). For pure photon exchange, only the structure functions $F_2$ and $F_L$ are present.

At low $Q^2$ and low $y$ the structure functions $xF_3$ (from $Z^0$ exchange) and $F_L$ (suppressed by the factor $y^2$) can be safely neglected (small contributions from $F_L$ are modeled using pQCD). In this case the structure function $F_2$ can be extracted at each point of $x$ and $Q^2$ from the double-differential cross section. The corresponding measurements [2, 3] from HERA I (pre-polarization period up to the year 2000, correspond-
FIGURE 1. Measurements of the structure function \( F_2(x, Q^2) \) from H1 [2] and ZEUS [3]. The data show clear evidence for scaling violations, as expected from gluon contributions to the cross section. The scaling violations are very well described by pQCD. At low \( Q^2 \), the data from some fixed target experiments are also shown.

...ing to an integrated luminosity of about 120 pb\(^{-1}\) are shown in fig. 1. The data, most importantly the \( Q^2 \) dependence, are very well described by NLO pQCD.

Figure 2 shows the combined (unpolarized) data on the differential cross section \( d\sigma/dQ^2 \) for NC and CC reactions, both for electron and positron beams. One observes a convergence of the cross sections towards high \( Q^2 \) for the NC and CC cross sections, which are very well described by the Standard Model, predicting similar cross sections for NC and CC reactions at large \( Q^2 \), related to “electroweak unification”. A closer look reveals a suppression towards large \( Q^2 \) of the \( e^+p \) NC cross section relative to \( e^-p \), which is explained by the different sign in front of the structure function \( xF_3 \) for electrons and positrons (see eq. 1). A much larger difference is noticeable for the CC cross sections. Here, the difference comes mainly from two sources, namely from the valence quarks (\( u \) quarks react with electrons, \( d \) quarks with positrons), and from the helicity suppression in the parity-violating \( e^\pm p \) CC reactions. At the parton level, parity violation in the CC reactions leads to the initial state \( e^-u \) in \( e^-p \) CC reactions with total \( J_z = 0 \), while in \( e^+p \) CC reactions the initial state \( e^+d \) has \( J_z = 1 \), forbidding backward-scattering.
After a massive upgrade of the machine and the two collider detectors in the years 2001 and 2002, HERA has provided another 400 pb$^{-1}$ per experiment. In addition, the lepton beams can be polarized longitudinally by means of spin rotators, turning the natural transverse polarization (being built up within about 35 minutes after full acceleration) into a longitudinal one. Typical polarizations of about 40% (both signs) have been routinely achieved. Using the longitudinal lepton polarization, parity-violating effects can be studied also in NC processes. In order to cancel the dominating (parity-conserving) photon-exchange, polarization asymmetries need to be formed. The corresponding asymmetries $A^\pm$ (+ stands for positron, − for electron beams) are defined as

$$A^\pm = \frac{\sigma^\pm(\hat{P}_R) - \sigma^\pm(\hat{P}_L)}{\sigma^\pm(\hat{P}_R) + \sigma^\pm(\hat{P}_L)} \cdot \frac{2}{\hat{P}_R - \hat{P}_L}. \quad (2)$$

The quantities $\hat{P}_{R,L}$ are the right-/left-handed lepton polarizations, respectively. At large $Q^2$, where the effects from parity violation are expected to be largest, statistics, unfortunately, is quite low due to the damping of the cross section by the propagator term. In order to obtain the best statistics from HERA, an attractive solution would be the combination of the data from both experiments. This, in fact, has been recently attempted [6] for the polarization asymmetries. The measurements of the quantities $A^+$ and $A^-$, individually for H1 and ZEUS, and in combination, are shown in fig. 3. At low $Q^2$, where the contribution from $Z^0$ exchange is small, the polarization asymmetries vanish. However, at large $Q^2$, a clear effect is visible, with a relative sign between the two asymmetries as
FIGURE 3. Data [6] from H1 and ZEUS on the polarization asymmetries $A^+$ and $A^-$ in NC reactions, together with predictions from respective QCD analyses (top row). In the lower part, the combined data from H1 and ZEUS for the polarization asymmetries are shown (see text).

expected from the Standard Model. The probability that the data are compatible with a zero-effect is less than $3.1 \times 10^{-3}$ for the combined measurement.

Any theoretical prediction of inclusive scattering (as well as other more differential observables, such as dijet cross sections or heavy quark production, just to name two examples) needs a universal set of PDFs as input. Generally, a physically motivated functional ansatz for the PDFs as functions of Bjorken $x$ is chosen for the various parton distribution at a low starting scale $Q_0$ (typically around 1-2 GeV). Since the $Q^2$ evolution of the PDFs is predicted by pQCD by means of the DGLAP equations, the free parameters of the PDFs at $Q_0$ can be determined from a highly over-constrained set of equations, using the data over a wide range in $Q^2$. A recent determination of the PDFs from ZEUS [7], using also the new data from the polarized leptons, is shown in fig. 4. Here, the PDFs of the valence quarks, the sea quarks, and the gluon are shown for $Q^2 = 10$ GeV$^2$. The error bands given correspond to a combination of experimental and theoretical errors. The relative uncertainties of the PDFs (not shown) clearly lack
**FIGURE 4.** Results of QCD fits to the inclusive data from the ZEUS experiment [7]. The PDFs of the valence and sea quarks are shown, as well as the distribution for the gluon (note the different scale factors for better display).

precision at large $x$, due to the strongly falling cross sections at large $x$ and $Q^2$ (compare also the PDFs towards $x \to 1$).

**DIFFRACTION AT HERA**

Similar to inclusive scattering, it can be shown within QCD that the cross section for diffractive processes in deep-inelastic diffractive $ep$ scattering (DDIS) factorizes into universal diffractive parton densities (DPDFs) of the proton and process-dependent hard scattering cross sections (QCD factorization [8]). Figure 5 sketches the generic diffractive process in electron-proton scattering at HERA, $ep \to eXY$, displaying also the relevant kinematic variables in the virtual-photon proton reaction. A colorless exchange produces two hadronic systems $M_X$ and $M_Y$, with a total invariant mass $W$ (i.e. the virtual-photon proton center-of-mass energy). At high values of $W$ the colorless exchange leads to a large rapidity gap between the states $X$ and $Y$, void of particles, which provides a unique signature for diffractive events. If the system $M_Y$ is just the intact scattered proton, the diffractive process is called "photon-dissociation".

To select diffractive events coming from photon dissociation, several techniques are used by the two HERA experiments. The cleanest way is to directly detect the scattered proton in so-called *Roman pots*. This method was exploited by both H1 [9] and
ZEUS [10]. The Roman pot method also gives access to a measurement of the momentum transfer $t$ at the lower vertex (see fig. 5). The evident drawback of this method is low statistics due to the limited acceptance of the Roman pots.

High statistics diffractive samples can be obtained using the characteristic properties of the hadronic final state, either by large rapidity gaps (H1 and ZEUS, see, e.g. [11]), or by the so-called $M_X$-method, employed by ZEUS [12].

**Theoretical Analysis of Diffraction at HERA**

The diffractive exchange carries a fraction $x_\mathbb{P}$ of the initial proton’s longitudinal momentum. The subscript $\mathbb{P}$ in $x_\mathbb{P}$ derives from the frequently used association of diffractive exchange with the “Pomeron”. The variable $\beta (= x/x_\mathbb{P})$ is the fractional longitudinal momentum carried by a charged constituent within the Pomeron. With these additional variables, the fully differential diffractive cross section $\sigma^{D(4)}$, neglecting contributions from $Z^0$ exchange, can be defined, in analogy to the conventional deep inelastic scattering (see eq. 1), as

$$\frac{d^4 \sigma^{D(4)}}{dx_\mathbb{P} dt d\beta dQ^2} = \frac{2\pi \alpha^2}{BQ^4} Y_+ F_2^{D(4)} \left[ \frac{y^2}{Y_+} - F_L^{D(4)} \right]$$

Similarly to the case of the inclusive cross section, the longitudinal contribution $F_L^{D(4)}$ can be safely neglected, except at large values of $y$. If the outgoing proton is not detected one has to integrate eq. 3 over $t$.

Though not proven rigorously in pQCD, one may further suppose that the shapes in $\beta$ and $Q^2$ of the parton distributions within the diffractive exchange are independent of $x_\mathbb{P}$ and $t$. This is equivalent to the picture of a diffractive pseudo-particle exchange, the Pomeron, with a partonic structure independent of the Pomeron kinematics. Correspondingly, the diffractive structure function $F_2^{D(4)}$ is then given:

$$F_2^{D(4)}(x_\mathbb{P}, t, \beta, Q^2) = f_{\mathbb{P}/p}(x_\mathbb{P}, t) F_2^\mathbb{P}(\beta, Q^2).$$
This model for diffractive exchange was proposed first by Ingelman and Schlein [13] and is also often called the resolved Pomeron model, where $f_{P/p}(x_P, t)$ is the Pomeron flux factor (see, e.g., [1]). The variable $\beta$ then corresponds to the longitudinal momentum fraction of the struck parton within the Pomeron.

With these assumptions, the diffractive parton densities $f_i^D$ can be factorized into a Pomeron flux term, depending only on $x_P$ and $t$, and a set of parton densities, depending only on $\beta$ and $Q^2$, characterizing the Pomeron’s partonic structure:

$$f_i^D(\beta, Q^2, x_P, t) = f_{P/p}(x_P, t) \cdot f_i(\beta, Q^2).$$

The validity of the above Regge factorization ansatz has been studied experimentally and was found to be consistent with the data for low values of $x_P < 10^{-2}$, see, e.g., dijet and $D^*$ production in DDIS, which are reasonably well described by NLO calculations of the underlying photon-gluon fusion processes (see, e.g., [14]).

**QCD Analyses of Diffractive Data**

With the experimental support of Regge factorization (within the present precision), QCD fits have been performed by the H1 Collaboration [11] in leading order (LO) and next-to-leading order (NLO), using the DGLAP formalism to evolve the non-
perturbative DPDFs in $Q^2$. Similar fits were also done recently by the ZEUS Collaboration [15]. The DPDFs in both analyses are modeled in terms of a light flavor singlet distribution $s(z)$, consisting of $u$, $d$, and $s$ quarks and their anti-quarks with $u = d = s = \bar{u} = \bar{d} = \bar{s}$, and a gluon distribution $g(z)$. Here, $z$ is the longitudinal momentum fraction of the parton entering the hard sub-process with respect to the diffractive exchange, such that $z = \beta$ for the lowest order quark-parton model process, and $0 < \beta < z$ for higher order processes. The quark singlet and gluon distributions are parameterized by a set of polynomials, at a scale $Q^2_{\text{min}} \approx 2$ GeV$^2$ in the case of H1. Figure 6 shows the fit result [16] from a combined analysis of diffractive dijet production and inclusive diffractive for the quark singlet and the gluon distributions as functions of $z$ for two values of $Q^2$ (dark-shaded bands). Also shown are the results of two recent fits [11] to inclusive diffractive (light-shaded band and dotted line. The fits latter two are mainly distinguished by the complexity of the gluon parameterization, and both describe equally well the inclusive diffractive data. The dijet data, however, seem to prefer the more simple gluon distribution.

The QCD fits to diffractive data indicate that the gluonic contributions dominate the partonic content, the resulting momentum fraction carried by gluons amounts to about 70 % (ZEUS [17] arrive at a very similar conclusion concerning the gluon dominance in the DPDFs). The QCD fits (both from H1 and ZEUS) reproduce well all features of the data, most importantly the positive scaling violations which persist up to high values of $\beta$. This feature of a “late” turnover of the scaling violations in DDIS from positive to negative (at $\beta \sim 0.5$) is in contrast to the situation in DIS, where the turnover in the proton structure happens around $x \sim 0.15$.

**Diffractive Photoproduction**

As mentioned above, diffractive dijet (and charm) production is well described with NLO QCD fits to inclusive diffractive data. However, when a similar procedure is applied to diffractive jet production at the Tevatron, the observed rate is overestimated by one order of magnitude [18]. This breakdown of factorization was successfully explained by Kaidalov et al. [19] as being caused by rescattering from the additional spectator quarks in the proton remnant, which are not present in the virtual photon in DDIS.

In diffractive dijet photoproduction, on the other hand, there are two contributions, one where the photon directly participates in the hard scattering subprocess (“direct photon”), and another where a parton from the diffractive exchange scatters from a partonic fluctuation of the photon (“resolved photon”). The momentum fraction carried by the photon constituent in the resolved case is denoted by $x_\gamma$. Evidently, for the direct case $x_\gamma$ is close to unity. The resolved photon part in dijet photoproduction resembles hadron-hadron scattering and should therefore receive a suppression, similar to the $\bar{p}p$ case. Kaidalov et al. [19] have indeed predicted a suppression factor $R \simeq 0.34$ for the resolved photon contribution in diffractive dijet photoproduction at HERA.

The H1 collaboration [20] has measured this process (see fig. 7) in the kinematic regime $Q^2 < 0.01$ GeV$^2$ and $165 < W < 240$ GeV. An NLO program by Frixione et al. [21], interfaced to the H1 NLO DPDF’s, is used to compare to the data. The
corresponding predictions are also shown in the figure. It is interesting to note that for the H1 calculation both the direct and the resolved photon contributions need to be scaled down by roughly the same factor of 0.5. In a recent analysis, the ZEUS collaboration [22], on the other hand, sees no significant suppression using the DPDFs of H1. This may, however, not be in contradiction, since in the H1 analysis a low cut $E_T > 4$ GeV was employed for the jets, while the ZEUS analysis limits the phase space of the jets to $E_T > 7.5$ GeV.

THE LAST THREE MONTHS

As can be seen from eq. 1 and 3, the double differential cross section at $Q^2$-values where the influence of $Z^0$-exchange can still neglected, depends on two structure functions, $F_2$ and $F_L$. At fixed center-of-mass energy both functions cannot be determined at the same time. In order to extract the structure function $F_2$ from the data, the phase space has to be selected carefully in order to minimize the effect from the longitudinal structure function $F_L$ (see eq. 1). This is usually done by restricting the phase space to small values of $y$, which enters squared as a factor multiplying $F_L$. Small residual contributions are corrected for by using the expectation from pQCD. Measuring $F_L$ at large values of $y$, as has been done by H1 [2] is based on a prediction for $F_2$ from which the measured cross section is subtracted. Again this procedure needs theoretical input to extrapolate $F_2$ into regions of high $Q^2$ according to the DGLAP equations. It is evident that such a procedure does not provide a model-free extraction of the longitudinal structure function. The only way to do this rigorously is to perform another measurement at a different $y$, but at the same values of $x$ and $Q^2$. For the last three months of its active data taking period, HERA’s proton energy will be lowered from 920 to 460 GeV. Due to the increased emittance, the HERA luminosity at this energy will be smaller ($\mathcal{L} \approx E_p^{-2}$), but about 12-15 pb$^{-1}$ can still be expected at the reduced center-of-mass energy. Figure 8 shows the expectation for measurements of $F_L$, corresponding to integrated luminosity of 10 (30)
FIGURE 8. Simulation of a measurement of $F_2(x,Q^2)$ based on data at two different proton energies at 920 (30 pb$^{-1}$) and 460 GeV (10 pb$^{-1}$) for the H1 experiment [23]. The inner error bars show the statistical accuracy, and the total error bars represent the total accuracy of the measurement, adding the statistical and systematic uncertainties in quadrature.

pb$^{-1}$ accumulated at $E_p = 460$ (920) GeV in the H1 experiment [23]. Similar accuracy is obtained with corresponding measurements using the ZEUS detector [24]. With the data taken at lower energy, also the longitudinal structure function for diffractive scattering ($F_L$) can be determined, although with somewhat reduced accuracy.

SUMMARY AND CONCLUSIONS

HERA is colliding electrons and protons with a total center-of-mass energy of 320 GeV, equivalent to a photon beam of 50 TeV on a stationary proton target. For inclusive scattering, a series of textbook measurements with high precision have been performed by H1 and ZEUS, indicating the validity of pQCD from very low momentum transfer of a few GeV$^2$ up to the kinematic limit. At very large $Q^2$, electroweak effects are observed which are nicely described by the Standard Model.

Diffractive exchange governs the bulk of the total cross section in hadronic interactions and also contributes a substantial part to deep-inelastic electron-proton scattering at HERA. The nature of the diffractive exchange can be studied through QCD fits to inclusive diffractive data. The common conclusion of the is that diffractive exchange is dominated by gluons, contributing about 70% %). Using the DPDFs obtained from the LO and NLO QCD fits, diffractive production of dijets and open charm in DDIS is well described. On the other hand, using the HERA DPDFs, a strong suppression of the
cross section is required to explain the Tevatron diffractive dijet data. This suppression is quantitatively explained by rescattering effects of the spectator partons not involved in the hard scattering process. There is no clear picture yet for the diffractive dijet photoproduction at HERA. A dijet suppression similar to the one observed at the Tevatron may depend on the minimum $E_t$ required in the jet selection, as suggested by the analyses of H1 (low threshold, suppression seen), and ZEUS (high threshold, probably no suppression).

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