QCD: Quantum Chromodynamic Diffraction

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Abstract

The first measurements of the diffractive structure function $F_2^{D(3)}$ at HERA are discussed. A factorisable interpretation in which a partonic structure is assigned to the pomeron is investigated through QCD analyses in which both the quark and gluon densities are permitted to vary freely. A method of measuring the longitudinal structure function of the pomeron without changing the $ep$ centre of mass energy is presented. The possibility that the pomeron structure may receive a large contribution from gluons, relative to quarks, at high $\beta$ is highlighted, and the experimental signatures which may support such a structure are reviewed.

1 Introduction

The phenomenology of high energy diffraction succeeds in correlating many of the features of high energy hadron–hadron interactions in terms of relatively few parameters. However since the advent of QCD as the theory of hadronic physics, it has been clear that ultimately there must be an understanding of this phenomenology in terms of QCD. With the advent of the $ep$ collider HERA, for the first time it has become possible to probe the regions of proton structure involved in the diffractive interactions which form the bulk of the proton interaction cross section at high energy.

Recently the H1 and ZEUS collaborations have quantified the diffractive contribution to the proton structure function by measuring the “diffractive structure function” $F_2^{D(3)}$ (see [1, 2] for details of the analyses). These measurements are made as a function of three kinematic variables, $x$, $\beta$ and $x_F$, or equivalently $\beta$, $Q^2$ and $x_F$, which are defined as follows:

$$x = \frac{-q^2}{2P \cdot q}, \quad x_F = \frac{q \cdot (P - P')}{q \cdot P}, \quad Q^2 = -q^2, \quad \beta = \frac{-q^2}{2q \cdot (P - P')}. \tag{1}$$

Here $q$, $P$ and $P'$ are the 4–momenta of the virtual boson, the incident proton, and the final state colourless remnant $R_\gamma$ (proton or low mass excited state) respectively [1, 2].

1 From talks given in the diffractive session at the Workshop on Proton, Photon and Pomeron Structure, Durham, September 1995
Note that $x = \beta x_p$. A structure function is defined in analogy with the decomposition of the unpolarised total $ep$ cross section:

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

(2)

where $X$ is the hadronic system excluding the colourless remnant $R_c$. For these measurements, no accurate determination of $t = (P - P')^2$ was possible, and the measured structure function $F_2^{D(3)}$ was evaluated from the differential cross section $\frac{d^3\sigma_{ep\rightarrow eXR_c}}{d\beta dQ^2 dx_p} = \int \frac{d^4\sigma_{ep\rightarrow eXR_c}}{d\beta dQ^2 dx_p dt} dt$ such that

$$\frac{d^3\sigma_{ep\rightarrow eXR_c}}{d\beta dQ^2 dx_p} = \frac{4\pi\alpha^2_{em}}{\beta Q^4} \left\{ 1 - y + \frac{y^2}{2} \right\} F_2^{D(3)}(\beta, Q^2, x_p)$$

(3)

where $R^{D(4)}$ is set to 0 for all $t$ following the original procedure of [3]. An excellent fit to all data points, irrespective of $\beta$ and $Q^2$, is obtained assuming a dependence $x_p^n$ with a single exponent (H1: $n = 1.19 \pm 0.06(stat.) \pm 0.07(syst.)$, 94% C.L., ZEUS: $n = 1.30 \pm 0.08(stat.)^{+0.09}_{-0.11}(syst.)$). Such a universal dependence is expected naively if the diffractive deep-inelastic process involves the interaction of a virtual photon with a (colourless) target in the incident proton whose characteristics are not dependent on $x_p$, and which carries only a small fraction of the proton’s momentum. Furthermore, the values for $n$ are consistent with that expected if the diffractive mechanism may be encapsulated in the parameterisation that describes “soft hadronic” diffractive interactions, namely the pomeron ($IP$) with $\alpha(t) = \alpha_P(0) + \alpha't$ and $\alpha_P(0) = 1.085$, $\alpha' = 0.25$ GeV$^{-2}$ [4, 5]. The diffractive structure function may therefore be written in the “factorisable” form

$$F_2^{D(3)}(\beta, Q^2, x_p) = f(x_p) F_2^{IP}(\beta, Q^2)$$

(4)

with $f(x_p) \propto x_p^{-n}$, and the natural interpretation of $F_2^{IP}(\beta, Q^2)$ is then that of the deep-inelastic structure of the diffractive exchange ($IP$).

2 QCD Analysis of the H1 Data

In order to investigate the $\beta$ and $Q^2$ dependencies of $F_2^{D(3)}$ it is convenient to define an integral of $F_2^{D(3)}$ over a fixed range in $x_p$ which, assuming the simple factorisation of (4), is proportional to the structure function of the $IP$:

$$\tilde{F}_2^D(\beta, Q^2) = \int_{x_pL}^{x_pH} F_2^{D(3)}(\beta, Q^2, x_p) \, dx_p = F_2^{IP}(\beta, Q^2) \cdot \int_{x_pL}^{x_pH} f(x_p) \, dx_p$$

(5)

This procedure avoids the need to specify the theoretically ill-defined normalisation of the diffractive flux, and permits direct comparison of the data with any theoretical model. The H1 data for $\tilde{F}_2^D(\beta, Q^2)$ are shown in figure [1]. The lack of any substantial dependence of $\tilde{F}_2^D(\beta, Q^2)$ on $Q^2$ and the substantial contribution at $\beta < 1$ suggests that the structure resolved by the electron in high $Q^2$ diffractive interactions may be partonic in origin [6].
Figure 1: Dependence of $\tilde{F}_2D$ on $Q^2$ (a) and $\beta$ (b); superimposed are the results of two LO log $Q^2$ DGLAP QCD fits. The dashed line shows a fit in which at the starting scale, $Q^2 = 4\text{ GeV}^2$, diffraction is attributed to the exchange of only quarks ($\chi^2$/dof of $13/12, 37\%\text{C.L.}$). The solid line shows a fit in which both quarks and gluons may contribute to the diffractive mechanism at $Q^2 = 4\text{ GeV}^2$ ($\chi^2$/dof = $4/9, 91\%\text{C.L.}$). The data are those published in [2]. The fitted quark singlet (c) and gluon (d) densities as a function of $\beta$ for different values of $Q^2$.

The interpretation of $\beta$ is then that of the appropriate Bjorken scaling variable in deep-inelastic diffraction. This hypothesis may be tested by introducing parton densities for the pomeron such that (in the leading log $Q^2$ approximation)

$$F_2^P(\beta, Q^2) = \sum_{i=1,n} e_i^2 \beta \left[ q_i(\beta, Q^2) + \bar{q}_i(\beta, Q^2) \right]$$

(6)

where $q_i(\beta, Q^2)$ are the density functions for the $n$ quark flavours considered. The evolution of these parton density functions with $Q^2$ may then be calculated using the DGLAP evolution equations, and the range of possible solutions for the parton densities which are compatible with the data investigated by a standard QCD fit procedure.

However, it has been observed that the lack of any fall of $\tilde{F}_2D$ with increasing $Q^2$ at large $\beta$ contrasts with the violations of scale invariance exhibited by the structure function of a typical hadron [1]. For example, the proton structure function $F_2$ rises with increasing $Q^2$ for $x < \sim 0.15$, and falls with increasing $Q^2$ for $x > \sim 0.15$. This decrease at high $x$ is an inevitable consequence of DGLAP QCD evolution for an object with a structure built from the evolution of “valence” quarks in which the latter predominate at large Bjorken–$x$. By analogy, a structure function for which any violation of scale invariance amounts to an increase with log $Q^2$ at high Bjorken–$x$ ($\beta$), is likely to have a large gluon, relative to quark, parton density at high $\beta$.

To quantify any substantive evidence for a gluonic contribution to $\tilde{F}_2D$, H1 performed an analysis in which the DGLAP evolution equations were solved numerically in the
leading (LO) and next-to-leading order (NLO) log$Q^2$ approximations[6]. Starting from a scale $Q^2_0 = 4$ GeV$^2$, the following forms were assumed for the quark flavour singlet distribution $\sum(\beta) = \sum_i \beta [q_i(\beta) + \bar{q}_i(\beta)]$ and gluon distribution $G(\beta) = \beta g(\beta)$ at an initial scale of $Q^2_0 = 4$ GeV$^2$:

$$\sum(\beta) = A_1 \beta^{A_2} (1 - \beta)^{A_3}$$

(7)

$$G(\beta) = B_1 \beta^{B_2} (1 - \beta)^{B_3}$$

(8)

No momentum sum rule was imposed. These parton densities were evolved to higher $Q^2$ and compared with the measurements of the $\beta$ dependence of $\tilde{F}_2^D$ taking into account fully both the statistical and systematic contributions to the uncertainty in the measured data. The results of two LO fits are shown, superimposed on the data, in figure 1. Though a solution in which only quarks contribute to the pomeron structure at the starting scale (dashed line) does not qualitatively reproduce the rise of $\tilde{F}_2^D$ with $Q^2$ at all values of $\beta$, this solution provides a statistically acceptable description of the data ($\chi^2/$dof = 13/12, 37\%C.L.) The addition of a gluon density at $Q^2_0$ results in an excellent description of $\tilde{F}_2^D(\beta,Q^2)$ ($\chi^2$/dof = 4/9, 91\%C.L.) which reproduces the rise with log $Q^2$ at higher $\beta$. In this solution, shown by the solid curve in figure 1 at $Q^2_0 = 4$ GeV$^2$ the gluons carry $\sim 90\%$ of the momentum of diffractive exchange, and the fitted gluon density is very hard, tending to $\beta = 1$, indicating that the structure of diffraction may involve the leading exchange of a single gluon (figure 1c,d). Repeating the analysis at NLO reduces somewhat the fraction of the momentum carried by gluons.

### 3 $F_L^{IP}$ and Violations of Factorisation

A NLO analysis allows a prediction for the longitudinal structure function of the pomeron, $F_L^{IP}$, to be calculated. This prediction may then be tested directly against the data since the wide range in $x_F$ accessible at HERA results in a large variation in $e^p$ centre of mass energy. Thus for a genuinely factorisable cross section of the form (3) with $R^{IP} = F_L^{IP}/(F_2^{IP} - F_*^{IP})$ greater than 0, the $F_2^{D(3)}$ extracted from the data with the assumption that $R^{IP} = 0$ will be modified from the expectation of the factorisable expression (4) by a multiplicative factor $\psi(\beta,Q^2,y)$ where

$$\psi(\beta,Q^2,y) = \left[ \frac{2(1 - y) + \frac{y^2}{1 + R^{IP}(\beta,Q^2)}}{2(1 - y) + y^2} \right]$$

(9)

Thus $F_L^{IP}$ may be extracted directly from the data at fixed $e^p$ centre of mass energy (in contrast to $F_*^{IP}$) by measuring such apparent deviations from factorisation. The correspondence between $F_L^{IP}$ extracted in this way, and the prediction of a QCD analysis would allow the validity of this factorisable approach to be tested at NLO.

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A non–singlet contribution is not considered as a $0^+$ exchange is assumed, despite the fact that meson exchange contributions to the measured cross section are possible. This assumption is supported insofar as the data for $F_2^{D(3)}$ may be parameterised by a single trajectory with intercept close to unity.
4 Global QCD Analysis of H1 and ZEUS Data

At this point we extend the H1 analysis by considering both the H1 [1] and ZEUS [2] data. A leading log combined fit to these two measurements of $F_2^{D(3)}(\beta, Q^2, x_{\perp})$ is performed assuming the factorisable form (4) with $f(x_{\perp}) = x_{\perp}^{-n}$ and permitting the parameterisation of the parton densities at the starting scale $Q^2_0$ and the exponent $n$ to vary simultaneously. Table 1 summarises the results of this study, which are compared with the data in figure 2. In the first fit all seven parameters are allowed to vary whilst $\Lambda$ is fixed at 200 MeV. The second fit illustrates how the results change when $\Lambda$ is set to 255 MeV. Fits 3 and 4 show how the parameters change if the value of $n$ is fixed to an intermediate value, and to the value determined by ZEUS respectively. The obtained $\chi^2$/dof confirms observation of H1 and ZEUS that the present data are in a very good agreement with the factorisable form (4) of $F_2^{D(3)}$. The fitted parameter $n$ is in an excellent agreement with the H1 value ($n = -1.19$), although fixing it to the ZEUS value ($n = -1.30$) in the fit does not lead to a significant deterioration of the fit quality.

The form of the fitted quark flavour singlet and gluon density functions are shown as a function of $\beta$ for different values of $Q^2$ in figure 3. The normalisation of the pomeron flux is somewhat arbitrary: any constant factor may be shifted between the pomeron flux and structure function in (4). Here the pomeron flux parameterisation of Berger et al. [7] and Streng [8] was used to define absolutely the normalisation of parton densities in the pomeron. With this normalisation the momentum sum $\int_0^1 d\beta \Sigma(\beta) + G(\beta)$ is 1.7.

Figure 2: (Left) - $F_2^P(\beta, Q^2)$ from H1 (closed circles) and ZEUS (open circles) measurements compared to the Fit 1 result (solid line). ZEUS data were rescaled by factor 1.76. (Right) - parton distributions in the pomeron from Fit 1 of Table 1 for $Q^2 = 4$ (solid), 12 (dotted) and 50 GeV$^2$ (dashed line).
| Parameters | Fit 1 | Fit 2 | Fit 3 | Fit 4 |
|------------|-------|-------|-------|-------|
| $-n$       | 1.179 | 1.179 | 1.25  | 1.30  |
| $A_1$      | 0.066 | 0.068 | 0.034 | 0.021 |
| $A_2$      | 0.29  | 0.31  | 0.19  | 0.11  |
| $A_3$      | 0.72  | 0.76  | 0.79  | 0.84  |
| $B_1$      | 1.22  | 1.01  | 1.05  | 0.72  |
| $B_2$      | 3.13  | 3.22  | 2.90  | 2.51  |
| $B_3$      | 0.31  | 0.21  | 0.34  | 0.27  |
| $\Lambda$ | 200   | 255   | 200   | 200   |
| $\chi^2$/dof | 114/96 | 114/96 | 116/96 | 120/96 |

Table 1: Fit results to $F_2^{D(3)}$ diffractive structure function data from H1 and ZEUS experiments. $\Lambda_{QCD}$ is fixed in all fits. The parameterisation is identical to that used in the H1 fit, and is described in equations (7) and (8). Only statistical errors were taken into account in the fits.

and the contribution to this sum from gluons is 85% at $Q^2 = 4$ GeV$^2$ falling to 75% at $Q^2 = 200$ GeV$^2$, in agreement with the H1 analysis. The form of the gluon density at the starting scale $Q^2_0 = 4$ GeV$^2$ is similar to that obtained in the H1 analysis, confirming the conclusion that the persistence of a rise of $F_2^{D(3)}$ with log$Q^2$ can only be reproduced by a large gluon (relative to quark) distribution at large $\beta$. However, it is worth repeating that the demand for such a gluon density cannot be demonstrated conclusively given the magnitude of the total errors of the measurements. A plethora of gluon distributions have been shown to yield a reasonable description of the HERA data [9, 10, 6, 11] and so in the absence of more accurate data the gluon density in the pomeron remains essentially unconstrained.

5 Summary and Outlook

The analyses discussed here demonstrate that the H1 and ZEUS data are compatible with a factorisable interpretation [12] in which the deep–inelastic diffractive structure is governed by a partonic structure for the pomeron. Whether such an approach provides more than merely a compact parameterisation of the $F_2^{D(3)}$ data relies crucially on the universality of these parton densities. Theoretically, the collinear factorisation supporting such universality is predicted to break down in diffractive jet production in hadron–hadron collisions, but the mechanism responsible for this breakdown is not expected in ep scattering [13]. Although, factorisation has not been proven rigorously for any diffractive process [14, 15], at this workshop there was general agreement that there is some justification for the leading log$Q^2$ approximation for $\beta < 1$.

Experimentally, the goals are clear. More accurate measurements of $F_2^{D(3)}$ over as wide a kinematic range as possible are essential. The QCD analyses suggest that the region of high $\beta$ is of great theoretical interest, where the potentially large gluon density may give rise to a large $F_2^P$. Measurements at very high $y$ are sensitive to the longitudinal component of the cross section and will test the validity of DGLAP evolution beyond the leading log$Q^2$ approximation. Measurements at $x_F > 0.05$ will establish whether additional exchanges ($f, \pi, \rho, \ldots$) contribute to the production of large rapidity gaps at
HERA. The universality of the parton densities extracted from QCD analyses such as those presented here can be tested directly by exclusive measurements. The wide range in gluon densities compatible with the HERA data provide a wide range of predictions for the production of inclusive charm and high $E_T$ jets, and the possibility that the presence of an additional hard scale ($m_c$, high $E_T$, high $t$) could change the energy ($x_F$) dependence should be investigated. In conclusion, the simple factorisable model in which universal parton densities are ascribed to the pomeron has fulfilled the most basic requirement of describing the inclusive diffractive cross section, but it has yet to be tested in any substantial way.

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