PARTONIC STRUCTURE OF THE POMERON*

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The first measurement of diffractive processes in deep inelastic scattering at the HERA collider is analysed in terms of a "soft" pomeron exchange model. The partonic structure of the pomeron which emerges in this picture is determined using the QCD parton model. The important role of the gluonic component in the partonic interpretation of the data is particularly emphasized.

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1. Introduction

The recent measurements performed by the H1 and ZEUS collaborations at the DESY electron-proton collider HERA [1–4] have shown that there is a significant diffractive contribution in deep inelastic scattering. To be precise, diffractive deep inelastic scattering is the process

$$e + p \to e' + X + p' , \tag{1}$$

where there is a large rapidity gap between the diffractively produced system X and the recoil proton p' (or excited proton state). In principle the scattered electron e' and the scattered proton p' can be identified and their momenta measured. In this case the cross section for the diffractive process (1) is characterized in the leading twist approximation by two structure functions $dF_2^D/dx_{\mathbb{P}}dt$ and $dF_L^D/dx_{\mathbb{P}}dt$ in analogy with the decomposition of the unpolarized inclusive ep cross section:

$$\frac{d\sigma^D}{dx dQ^2 dx_{\mathbb{P}} dt} = \frac{4\pi^2\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)\frac{dF_2^D(x,Q^2,x_{\mathbb{P}},t)}{dx_{\mathbb{P}}dt} - \frac{y^2}{2}\frac{dF_L^D(x,Q^2,x_{\mathbb{P}},t)}{dx_{\mathbb{P}}dt}\right] , \tag{2}$$

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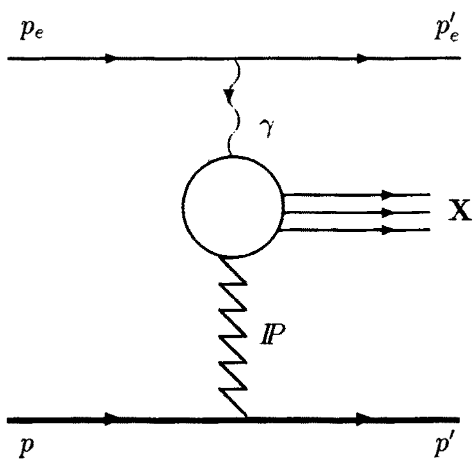
where the kinematical variables are defined as follows:

$$Q^2 = -q^2 \qquad x = \frac{Q^2}{2pq} \qquad y = \frac{pq}{p_e p}$$
$$t = (p-p')^2 \qquad \beta = \frac{Q^2}{2q(p-p')} \qquad x_{I\!P} = \frac{x}{\beta} \tag{3}$$

and $q = p_e - p'_e$, where p_e, p'_e, p and p' are the four momenta of the initial electron, final electron, initial proton and the recoil proton respectively.



No accurate determination of t variable has so far been possible for the measurement of the diffractive structure function at HERA. Therefore, the structure function integrated over t

$$F_2^{D(3)}(x, Q^2, x_{I\!P}) = \int_{-\infty}^{0} dt \; \frac{dF_2^D(x, Q^2, x_{I\!P}, t)}{dx_{I\!P}dt} \tag{4}$$

was evaluated from the cross section (2). The longitudinal component was neglected in the original procedure of [2, 4] because of anticipated smallness of the longitudinal structure function and the measured y values, $y < 0.5$.

The main observation is that the structure function $F_2^{D(3)}$ factorizes

$$F_2^{D(3)}(x, Q^2, x_{I\!P}) = x_{I\!P}^{-n} \; F(\beta, Q^2) \; , \tag{5}$$

where $\beta = x/x_{\mathbb{P}}$. The exponent n is found to be independent of β and Q^2, and equal to

$$n = 1.19 \pm 0.06(\text{stat.}) \pm 0.07(\text{syst.}) \quad (6)$$
$$n = 1.30 \pm 0.08(\text{stat.})^{+0.08}_{-0.14}(\text{syst.}) \quad (7)$$

for the H1 and ZEUS measurements respectively [2, 4].

Such a universal dependence is expected in models of diffractive interactions (1) based on the concept of an exchange of a pomeron — an object which carries vacuum quantum numbers [5, 6]. In that case a virtual photon, emitted by the incoming electron, scatters off a colourless object (pomeron), which carries a small fraction $x_{\mathbb{P}} < 0.1$ of the incoming proton momentum. This kinematical condition leads to a rapidity gap between the outgoing proton p', which stays almost intact, and the diffractive system X, produced as a result of the virtual photon-pomeron deep inelastic scattering. The function $F(\beta, Q^2)$ in factorization formula (5) is proportional to a pomeron structure function defined in analogy with the proton structure function $F_2(x, Q^2)$. The β variable plays a role of the Bjorken variable x and, if a simple partonic interpretation of the pomeron structure function is valid, gives the fraction of the pomeron's momentum carried by a partonic constituent of the pomeron. In a more refined approach the QCD-improved parton model can be applied and the partonic content of the pomeron can be studied just as in the proton case.

In essence this is the Ingelman–Schlein ([5]) model. In this paper we show that the diffractive deep inelastic scattering data from HERA are described by such a model. In this way we investigate the partonic structure of the pomeron.

2. The Ingelman–Schlein model

In this approach the diffractive structure function $dF_2^D/dx_{\mathbb{P}}dt$ is written in the factorizable form

$$\frac{dF_2^D}{dx_{\mathbb{P}}dt}(x, Q^2, x_{\mathbb{P}}, t) = f(x_{\mathbb{P}}, t)\; F_2^{\mathbb{P}}(\beta, Q^2)\;, \quad (8)$$

where as usual $\beta = x/x_{\mathbb{P}}$ and $f(x_P, t)$ is the pomeron "flux factor" which, if the diffractively recoil system is a single proton, has the following form [6, 8]

$$f(x_P, t) = N\; \frac{B^2(t)}{16\pi}\; x_{\mathbb{P}}^{1-2\alpha(t)}\;, \quad (9)$$

where $B(t)$ describes the pomeron coupling to a proton, see ([13]) for details, and N is a normalization factor. The function

$$\alpha(t) = \alpha(0) + \alpha'\, t \quad (10)$$

is the Regge trajectory of the pomeron. The model is based on the ("soft") pomeron exchange, which means that the intercept $\alpha(0) = 1.086$ and the slope $\alpha' = 0.25 GeV^2$. These values were obtained from the analysis of the high energy behaviour of total and elastic hadron-hadron cross sections ([10]).

As we noted above $F_2^{\boldsymbol{P}}(\beta, Q^2)$ is the pomeron structure function with the variable β playing the role of the Bjorken scaling variable. The factorization property (8) then follows as a direct consequence of the single pomeron-exchange mechanism of diffraction and the assumption that the pomeron is described by a single Regge pole.

The HERA measurements are found to satisfy factorization property (8). Comparison of the observed values of the exponent n with that of formula (8), after t integration, shows that the data confirms dominance of the "soft" pomeron exchange, since the "hard" or perturbative pomeron with intercept $\alpha_P(0) \approx 1.5$ would give much steeper behaviour proportional to $x_{\boldsymbol{P}}^{-2}$ or so.

In the region of large Q^2 the pomeron structure function $F_2^{\boldsymbol{P}}(\beta, Q^2)$ is expected to be described in terms of the QCD parton model which leads to a logarithmic violation of the Bjorken scaling, implied by perturbative QCD. In the leading logarithmic approximation the pomeron structure function is related in a conventional way to the quark $q_i^{\boldsymbol{P}}(\beta, Q^2)$ distributions in a pomeron:

$$F_2^{\boldsymbol{P}}(\beta, Q^2) = 2 \sum_{i=1}^{N_f} e_i^2 \; \beta \; q_i^{\boldsymbol{P}}(\beta, Q^2) \, , \tag{11}$$

where e_i are the quark charges and N_f is a number of active flavours (note that $q_i^{\boldsymbol{P}} = \bar{q}_i^{\boldsymbol{P}}$). The quark densities $q_i^{\boldsymbol{P}}(\beta, Q^2)$ and the gluon density $g^{\boldsymbol{P}}(\beta, Q^2)$ of the pomeron evolve in Q^2 according to the Altarelli–Parisi evolution equations. However, it is necessary to provide input distributions at some reference scale $Q^2 = Q_0^2$, since only the evolution is specified by perturbative QCD. The parton distributions in a pomeron at the initial scale $Q_0^2 = 4 GeV^2$ were estimated in papers [11]–[13] using the "soft" pomeron interaction properties and "triple-Regge" phenomenology. In the following we present the results of the analysis of Ref. [13].

First, it was assumed that the pomeron's flavour content is the same as that of the proton. Then, the quark distributions were parametrized in terms of a single function, the quark-singlet distribution, $\Sigma^{\boldsymbol{P}}(\beta) = \sum_i \beta(q_i^{\boldsymbol{P}}(\beta) + \bar{q}_i^{\boldsymbol{P}}(\beta))$. The following parametrization was found for $Q_0^2 = 4\mathrm{GeV}^2$

$$\Sigma^{\boldsymbol{P}}(\beta) = 0.0528 \, \beta^{-0.08} \, (1-\beta) + \; 0.801 \, \beta \, (1-\beta) \; . \tag{12}$$

The "soft" term, proportional to $\beta^{-0.08}$, results from the triple-Regge limit of the diffractive process (1) which applies when $\beta \to 0$, see [13] for details.

The relatively small magnitude of the coefficient is a direct consequence of the small magnitude of the triple-pomeron coupling. The second term, which dominates for $\beta \sim 1$, results from an assumption that in this region of β the "soft" pomeron couples to a quark-antiquark pair with a form factor depending on a virtuality of the pair, see [7].

The gluon distribution in a pomeron has a similar form

$$\beta\, g^{I\!P}(\beta) = 0.218\, \beta^{-0.08}\, (1-\beta) + \, 3.30\, \beta\, (1-\beta)\ . \tag{13}$$

As before the "soft" term, dominating for small β, results from the triple Regge limit. The analytical form of the second term, important for large β, was assumed to be the same as for quarks and its coefficient was calculated assuming that the longitudinal momentum sum rule holds:

$$\int_0^1 d\beta\, \beta\, \Big(\sum_i (q_i^{I\!P}(\beta) + \bar{q}_i^{I\!P}(\beta)) + g^{I\!P}(\beta)\Big) = 1\ . \tag{14}$$

The above parametrization allows, via the evolution equations, the diffractive structure function (8) to be determined at any value of Q^2 accepted in perturbative QCD. The results are compared to HERA data, now given in terms of a new diffractive structure function $F_2^{D(2)}$ defined as

$$F_2^{D(2)}(\beta, Q^2) = \int_{x_{I\!P L}}^{x_{I\!P H}} F_2^{D(3)}(\beta, Q^2, x_{I\!P})\, \mathrm{d}x_{I\!P}\ , \tag{15}$$

where β is fixed during the integration. Therefore, assuming the simple factorization formula (8), we see that the function $F_2^{D(2)}$ is proportional to the pomeron structure function $F_2^{I\!P}$. We find that generally the Bjorken scaling is observed, up to a possible mild (logarithmic) scaling violations. This fact favours a partonic interpretation of the pomeron structure function $F_2^{I\!P}$.

In Fig. 1 the solid curves show $F_2^{D(2)}$, obtained using the above parametrization as the initial condition for Q^2 evolution. The comparison is done for H1 and ZEUS data separately, because of different integration limits in (15) used by these experiments, see [2, 4] for details. It should be noted that the increase of the computed pomeron structure functions $F_2^{D(2)}$ with increasing Q^2, up to the value $\beta \sim 0.4$, is related to the relatively large gluon distribution (13) in a pomeron which has a "hard" $(1-\beta)$ spectrum at $\beta \sim 1$. This effect is nicely confirmed by the data, even for $\beta = 0.65$ the measured $F_2^{D(2)}$ rises with Q^2. The above behaviour of the pomeron structure function $F_2^{D(2)}$ is in contrast to the behaviour of the proton structure $F_2(x, Q^2)$, which starts to decrease with increasing Q^2 already for $x \sim 0.1$.

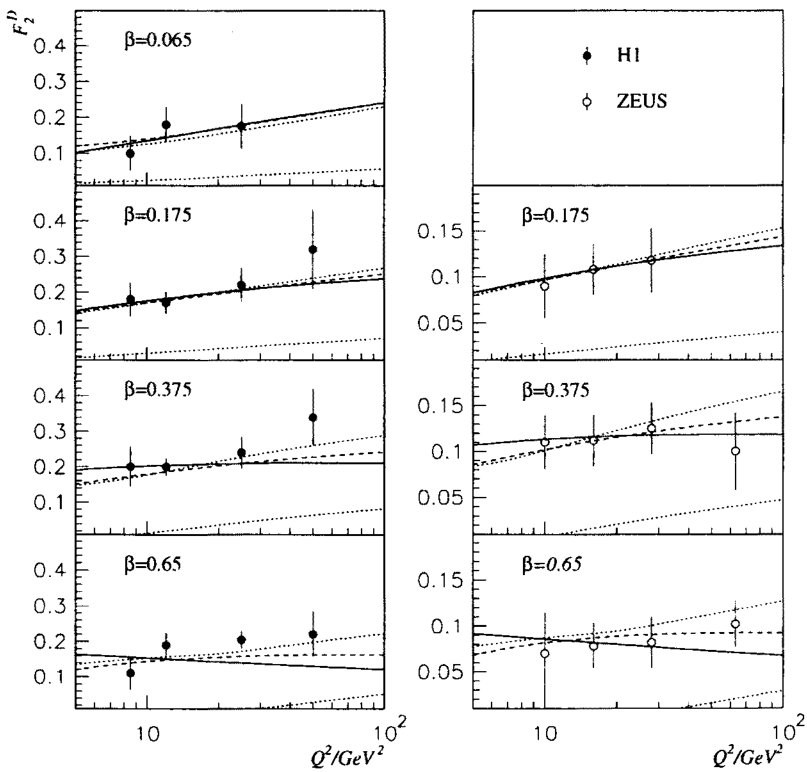


Fig. 1. Comparison of the diffractive structure function F_2^D obtained in analyses of this paper with H1 and ZEUS data. The solid curves correspond to the estimation described in Section 2, while the dashed and dotted ones come from the massless (Fit 1) and the massive c quark (Fit 3) fits, respectively. The dotted curves at the bottom show the charm contribution $F_2^{D(c)}$ to the F_2^D structure function obtained in the massive fit (the upper dotted curves).

The presented parametrization, however, cannot account for the rise of the diffractive structure function for the highest measured value of β. The reason is simple, the relatively hard gluon spectrum is not hard enough. In order to understand this, let us consider the equation for the logarithmic slope of $F_2^{\boldsymbol{P}}$, resulting from the Altarelli–Parisi equations

$$\frac{\partial F_2^{\boldsymbol{P}}(\beta)}{\partial log(Q^2)} = \frac{\alpha_s}{2\pi} \int_\beta^1 dz P_{qq}(z) F_2^{\boldsymbol{P}}(\frac{\beta}{z}) + \frac{\alpha_s}{2\pi}\, \delta \int_\beta^1 dz P_{qg}(z) \frac{\beta}{z} g(\frac{\beta}{z}) \,, \qquad (16)$$

where $\delta = \sum_{i=1}^{N_f} e_i^2$. The gluon term is always positive, while the first one could be negative, especially for large β values, because of virtual emissions. Thus, $F_2^{D(2)}$ rises with Q^2 for large β only when the gluon distribution is large enough at $\beta \approx 1$.

The gluon distribution of the pomeron at large β is the most difficult density to estimate. In fact the analytical form of the second term in (13) is somewhat arbitrary and the momentum sum rule (14) used to determined its coefficient is also a source of controversy. The point is that the normalization of the pomeron flux N in (8) is arbitrary: any constant factor may be transferred from the pomeron flux to the pomeron structure function [14]. Therefore, the magnitude of the momentum sum depends on convention.

Lacking new theoretical ideas to estimate the gluon distribution of the pomeron, the only way to tackle the problem is to perform a QCD fit to the diffractive structure function data.

3. Pomeron parton distributions from QCD fits

In order to clarify the gluonic content of a pomeron, we perform a global QCD fit to the diffractive data, published by the H1 and ZEUS collaborations. A first attempt along this line was done in [15] using only H1 data. We take the Regge factorizable form

$$F_2^{D(3)}(x, Q^2, x_{\mathbf{P}}) = x_{\mathbf{P}}^{-n}\; F_2^{\mathbf{P}}(\beta, Q^2)\,, \tag{17}$$

where the partonic form (11) of $F^{\mathbf{P}}$ is assumed.

The $x_{\mathbf{P}}^{-n}$ factor anticipates the dominant dependence of the pomeron flux (9) on $x_{\mathbf{P}}$ after the t integration. The exponent n and parameters of the parton densities at the starting scale Q_0^2 are allowed to vary simultaneously in the fit. Leading order Altarelli–Parisi evolution is used with four massless flavours. The parameter Λ_{QCD} in the running coupling constant α_s is fixed at 200 MeV in all fits. The momentum sum rule (14) is not imposed, therefore, the normalization of the momentum sum, as well as the relative quark and gluon contributions, are determined by the fit itself. Only statistical errors are taken into account.

The following forms of the singlet-quark and gluon distributions at the initial scale $Q_0^2 = 4$ GeV^2 are used

$$\Sigma^{\mathbf{P}}(\beta) \;=\; A_1\, \beta^{A_2}\, (1-\beta)^{A_3}\,, \tag{18}$$

$$\beta g^{\mathbf{P}}(\beta) \;=\; B_1\, \beta^{B_2}\, (1-\beta)^{B_3}\,, \tag{19}$$

whereas the nonsinglet quark distribution is set to zero.

TABLE I

The results of the fits to $F_2^{D(3)}$ diffractive structure function data from H1 and ZEUS experiments. $\Lambda_{\rm QCD}$ is fixed at 200 MeV in all fits. The fitted parameters are described in the text. Only statistical errors are taken into account.

Parameters	Fit 1	Fit 2	Fit 3
n	1.18	1.30 (fix)	1.19
A_1	0.066	0.021	0.069
A_2	0.29	0.11	0.44
A_3	0.72	0.84	0.60
B_1	1.22	0.72	1.16
B_2	3.13	2.51	5.00
B_3	0.31	0.27	0.000
χ^2/dof	114/96	120/96	110/96

Table I summarizes our results. In the first fit all seven parameters are allowed to vary. The second fit shows how the parameters change if the value of n is fixed at the value determined by ZEUS. These two fits assume that all four flavours are massless, while in the last fit the charm flavour c is massive. In this case

$$F_2^{\boldsymbol{P}}(\beta,Q^2) = F_2^{\boldsymbol{P}(u,d,s)}(\beta,Q^2) + F_2^{\boldsymbol{P}(c)}(\beta,Q^2,m_c^2)\ , \tag{20}$$

where $F_2^{\boldsymbol{P}(u,d,s)}$ is given by QCD formula (11) with three massless flavours, and the charm contribution $F_2^{\boldsymbol{P}(c)}$ is driven by the gluon distribution function

$$F_2^{\boldsymbol{P}(c)}(\beta,Q^2,m_c^2) = e_c^2\ \frac{\alpha_s(\mu_h^2)}{\pi} \int\limits_{a\beta}^{1} dy \frac{\beta}{y} C_2\left(\frac{\beta}{y},\frac{m_c^2}{Q^2}\right) g^{\boldsymbol{P}}(y,\mu_c^2)\,, \tag{21}$$

where $a = 1+4m_c^2/Q^2$ and $\mu_c^2 = 4m_c^2$. The form of the C_2 function as well as more details can be found in Ref. [12]. The charm contribution is different from zero above the threshold for $c\bar{c}$ pair production, $Q^2(1-\beta)/\beta > 4m_c^2$. Note that there is no c quark distribution in this approach.

The values of χ^2/dof confirms the observation made by H1 and ZEUS that the present data are in good agreement with the factorizable form (17) of $F_2^{D(3)}$. The fitted parameter n is in excellent agreement with the H1 value ($n = 1.19$), although fixing it to the ZEUS value ($n = 1.30$) does not lead to a significant deterioration of the quality of the fit. Therefore, our analysis supports the idea of the dominance of the "soft" pomeron exchange in diffractive HERA data [2, 4].

The results of our studies are compared with the data in Fig. 1. The dashed curves show $F_2^{D(2)}$ from the massless flavour fit (Fit 1), while the dotted ones correspond to the fit with a massive c quark (Fit 3). The dotted curves at the bottom of each plot show the massive charm contribution $F_2^{\mathbf{P}(c)}$ to the $F_2^{D(2)}$ structure function in Fit 3 (the upper dotted curves). The curves from both fits give a reasonable description of the data, leading to a persistent rise of $F_2^{D(2)}$ with $log(Q^2)$, even for the largest value of β. It is worthwhile to pointing out that the massive charm description offers an additional mechanism for the growth of $F_2^{D(2)}$, especially for large β and for values of Q^2 well above the $c\bar{c}$ pair production threshold.

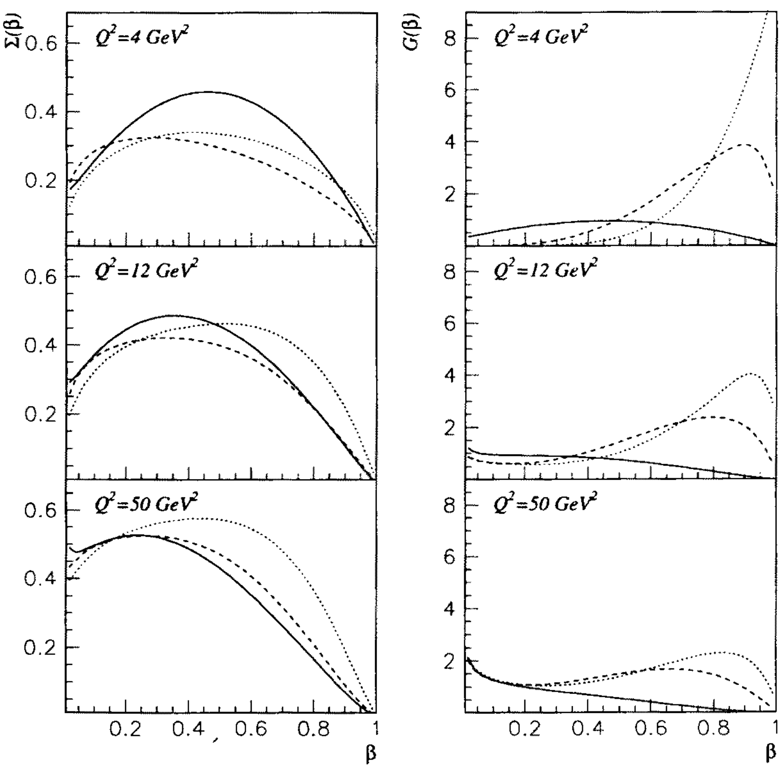


Fig. 2. The singlet and gluon distributions in the pomeron as functions of β for different values of Q^2. The solid curves results from the estimation of Section 2, the dashed and dotted ones are given by the massless (Fit 1) and massive (Fit 3) fits respectively. All distributions are normalized in accordance with the pomeron flux (9) normalization $N = 2/\pi$.

Our singlet-quark and gluon distributions are plotted in Fig. 2 as functions of β for different values of Q^2. The continuous curves correspond to the parametrization presented in the previous section, the dashed and the dotted ones result from the massless and massive fits, respectively. Their normalization is determined by the choice $N = 2/\pi$ in the pomeron flux, following the convention of Refs. [6, 7, 9]. With this normalization the momentum sum rule (14) equals 1.7 for the parton distributions of the massless fit. The contribution to this sum from gluons is 85% at $Q_0^2 = 4\mathrm{GeV}^2$, falling to 75% at $Q_0^2 = 200\mathrm{GeV}^2$.

The form of the gluon density at the initial scale $Q_0^2 = 4\,\mathrm{GeV}^2$ confirms the conclusion that the persistence of the rise of $F_2^{D(2)}$ with $log(Q^2)$ can only be reproduced by a large gluon (relative to quark) distribution at $\beta \sim 1$. However, it is worth repeating that the demand for such a gluon density cannot be demonstrated conclusively given the magnitude of the errors on the present data. In fact, within these errors, all our gluon distributions give a reasonable description of the HERA data.

4. Summary

The analyses presented here show that the HERA diffractive deep inelastic scattering data can be described by a model in which the hard scattering of the virtual probe occurs on a colorless object with partonic structure. This object, a "soft" pomeron, appears naturally in the factorizable model of Ingelman and Schlein. The partonic distributions in the pomeron can be determined using the QCD parton model, where the Altarelli-Parisi evolution equations play an important role, especially for the determination of the gluonic content of a pomeron. Our analyses suggest that, within the present accuracy, a broad range of gluon distribution parameterizations is allowed. There is a strong indication, however, that the gluons constitute a large component of a pomeron, carrying most of a pomeron's momentum. It will be interesting to see whether more precise measurements confirm this indication.

The potentially large gluon distribution can manifest itself in a significant heavy c flavour contribution to the diffractive structure functions and may also give rise to a large longitudinal structure function $dF_L^D/dx_{\mathbb{P}}dt$, which was neglected in the first analyses.

More accurate measurements of the diffractive processes in deep inelastic scattering, over as wide a kinematical range as possible, will allow many important theoretically questions to be addressed. The region of high β will clarify the gluon distribution problem. Measurements at very high y will allow the study of the longitudinal component of the diffractive cross section (3), whereas measurements at $x_{\mathbb{P}} > 0.05$ will test the pomeron factorization picture, which may be violated due to lower lying reggeon exchanges $(f, \rho, \pi, ...)$. The universality of the extracted pomeron parton distributions may also be tested, by using them to describe exclusive hard diffractive scattering processes [16, 17, 18].

In conclusion, deep inelastic diffraction is a promising subject for further experimental and theoretical studies in the coming years.

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