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DIFFRACTIVE STRUCTURE FUNCTION $F_{\rm L}^{\rm D}$ FROM THE ANALYSIS WITH HIGHER TWIST*

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We make predictions for the diffractive longitudinal structure function $F_{\rm L}^{\rm D}$ to be measured at HERA, based on the DGLAP fits of diffractive parton distributions with an additional twist-4 term. This term describes the diffractive $q\bar{q}$ production from longitudinal photons. The twist-4 contribution significantly changes predictions for $F_{\rm L}^{\rm D}$ obtained in the pure DGLAP analysis.

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1. Introduction

We are interested in diffractive deep inelastic scattering (DDIS) at HERA which provides a very interesting example of processes with a clear interplay between hard and soft aspects of QCD interactions. In addition to the scattered electron and proton a diffractive system forms, which is well separated in rapidity from the scattered proton. The most important observation made at HERA is that diffractive processes in DIS are not rare, they constitute up to 15% of all deep inelastic events [1–4].

In our analysis the diffractive structure functions, $F_2^{\rm D}$ and $F_{\rm L}^{\rm D}$, are given by the decomposition into the leading and higher twist contributions

$$F_{2,{\rm L}}^{\rm D} = F_{2,{\rm L}}^{\rm D(tw2)} + F_{\rm L}^{\rm D(tw4)} + \dots \,. \tag{1}$$

The leading twist-2 part depends logarithmically on the photon virtuality Q^2 in the Bjorken limit while the twist-4 part is suppressed by an additional power of $1/Q^2$. However, for DDIS this contribution plays especially important role since it dominates over the twist-2 one in the region of small

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diffractive masses $M^2 \ll Q^2$. Thus it cannot be neglected. Physically, the twist-4 contribution is given by the $q\bar{q}$ production from the *longitudinally* polarized virtual photons. The effect of this production, which we are going to present in this analysis, is particularly important for the longitudinal diffractive structure function $F_{\rm L}^{\rm D}$ which is supposed to be measured in the last runs of HERA.

2. Twist-2 contribution

The leading twist-2 part of the diffractive structure functions is given in terms of diffractive parton distributions (DPD) through the standard collinear factorization formulae [5–8]. In the next-to-leading logarithmic approximation we have

$$F_2^{\rm D(tw2)} = S_{\rm D} + \frac{\alpha_{\rm s}}{2\pi}\left\{C_2^{\rm S}\otimes S_{\rm D} + C_2^{\rm G}\otimes G_{\rm D}\right\}\,, \tag{2}$$

$$F_{\rm L}^{\rm D(tw2)} = \frac{\alpha_s}{2\pi}\left\{C_{\rm L}^{\rm S}\otimes S_{\rm D} + C_{\rm L}^{\rm G}\otimes G_{\rm D}\right\}\,, \tag{3}$$

where $\alpha_{\rm s} = \alpha_{\rm s}(Q^2)$ is the strong coupling constant, $C_{2,{\rm L}}^{\rm S,G}(z)$ are coefficients functions known from inclusive DIS [9, 10] and the convolution reads

$$(C\otimes F)(\beta) = \int\limits_{\beta}^{1} dz\, C\left(\frac{\beta}{z}\right) F(z)\,. \tag{4}$$

The terms proportional to $\alpha_{\rm s}$ constitute the next-to-leading logarithmic approximation. The quantities $S_{\rm D}$ and $G_{\rm D}$ are built from diffractive quark ($q_{\rm D}^f$) and gluon ($g_{\rm D}^f$) distributions:

$$S_{\rm D} \;=\; \sum_{f=1}^{N_f} e_f^2\, \beta\left\{q_{\rm D}^f(\beta,Q^2;x_{I\!P},t) + \overline{q}_{\rm D}^f(\beta,Q^2;x_{I\!P},t)\right\} \tag{5}$$

and

$$G_{\rm D} = \beta\, g_{\rm D}(\beta,Q^2;x_{I\!P},t)\,. \tag{6}$$

The diffractive parton distributions depend on four variables $(\beta,Q^2;x_{I\!P},t)$. From Eq. (5) we see that β, given by the formula

$$\beta = \frac{Q^2}{M^2+Q^2}\,, \tag{7}$$

plays the role of the Bjorken variable in DDIS. The DPD evolve with Q^2 with the DGLAP evolution equations [11].

In comparison to the inclusive parton distributions, the DPD contain two additional variables $(x_{I\!P}, t)$. They do not influence evolution but play the role of the parameters. However, the form of the initial conditions for these variables has to be specified. We do this assuming *Regge factorization*:

$$
\begin{aligned}
q_{\rm D}^f(\beta, Q^2; x_{I\!P}, t) &= f_{I\!P}(x_{I\!P}, t)\; q_{I\!P}^f(\beta, Q^2)\,,\\
g_{\rm D}^f(\beta, Q^2; x_{I\!P}, t) &= f_{I\!P}(x_{I\!P}, t)\; g_{I\!P}^f(\beta, Q^2)\,.
\end{aligned} \tag{8}
$$

The motivation for such a factorization is a model of diffractive interactions with a pomeron exchange [12]. In this model $f_{I\!P}$ is the pomeron flux

$$
f_{I\!P}(x_{I\!P}, t) \;=\; N\,\frac{F_{I\!P}^2(t)}{8\pi^2}\, x_{I\!P}^{\,1-2\,\alpha_{I\!P}(t)}\,, \tag{9}
$$

where $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t$ is the pomeron Regge trajectory and

$$
F_{I\!P}^2(t) \;=\; F_{I\!P}^2(0)\,{\rm e}^{-B_{\rm D}|t|} \tag{10}
$$

is a formfactor which describes the pomeron coupling to the proton. Following [7] we set $F_{I\!P}^2(0) = 54.4$ GeV^{-2} and the diffractive slope $B_{\rm D} = 5.5$ GeV^{-2} is determined from HERA data.

The quark distributions are flavour independent and are given by a singlet quark distribution $\Sigma_{I\!P}(\beta, Q^2)$:

$$
q_{I\!P}^f(\beta, Q^2) \;=\; \overline{q}_{I\!P}^f(\beta, Q^2) \;\equiv\; \frac{1}{2N_f}\,\Sigma_{I\!P}(\beta, Q^2)\,, \tag{11}
$$

where N_f is a number of active flavours. We fit $\Sigma_{I\!P}(\beta)$ and $G_{I\!P}(\beta)$ at an initial scale $Q_0^2 = 1.5$ GeV^2 to diffractive data from HERA, using the DGLAP evolution equations in the next-to-leading order approximation.

3. Twist-4 contribution

This contribution describes the $q\overline{q}$ diffractive production from the longitudinally polarized virtual photons. Although formally suppressed by $1/Q^2$, it dominates over the vanishing twist-2 contribution for small diffractive masses $M^2 \ll Q^2$ $(\beta \to 1)$ [13–15]. This is why it cannot be neglected in the analysis of diffractive data in DIS.

We used the following form of the twist-4 contribution which has to be added to $F_2^{\rm D(tw2)}$ and $F_{\rm L}^{\rm D(tw2)}$ [16]:

$$
F_{{\rm L}q\bar{q}}^{\rm D(tw4)} = \frac{3\sum_f e_f^2}{16\pi^4 x_{I\!P}}\,{\rm e}^{-B_{\rm D}|t|}\,\frac{\beta^3}{(1-\beta)^4}\int\limits_0^{\frac{Q^2(1-\beta)}{4\beta}} dk^2\;\frac{k^2/Q^2}{\sqrt{1-\dfrac{4\beta}{1-\beta}\dfrac{k^2}{Q^2}}}\,\phi_0^2 \tag{12}
$$

with

$$\phi_0 \;=\; k^2 \int\limits_0^\infty dr\, r\, K_0\!\left(\sqrt{\frac{\beta}{1-\beta}}kr\right) J_0(kr)\, \hat{\sigma}(x_{I\!P}, r)\,, \tag{13}$$

where K_0 and J_0 are Bessel functions. Strictly speaking, formula (12) contains all powers of $1/Q^2$ but the twist-4 part, proportional to $1/Q^2$, is the dominant one.

The function $\hat{\sigma}(x_{I\!P}, r)$ in Eq. (13) is the dipole-proton cross section which describes the diffractive interaction of the quark or gluon dipole with the proton. Following [17] we choose

$$\hat{\sigma}(x_{I\!P}, r) \;=\; \sigma_0 \left\{1 - \exp\left(-r^2 Q_{\rm s}^2\right)\right\}, \tag{14}$$

where $Q_{\rm s}^2 = Q_0^2\, x_{I\!P}^{-\lambda}$ is a saturation scale which gives the energy dependence of the twist-4 contribution. The three parameters of the dipole cross section, σ_0, Q_0^2 and λ, are taken from [17]. This form of the dipole cross section provides a successful description of the inclusive and diffractive data from HERA.

We also consider a reggeon contribution, described in detail in [18], which improves a fit quality through a better $x_{I\!P}-$dependence.

4. Fit results

In our analysis we use diffractive data on $F_2^{\rm D}$ (or reduced cross section $\sigma_r^{\rm D}$) from H1 [1, 2] and ZEUS [3, 4]. These data were obtained in different kinematical regions and using different methods of their analysis, thus we decided to analyse them separately. In all cases we find a good fit quality. A full discussion of the fit details is given in [18].

For each data set we performed two fits: without twist-4 (pure DGLAP fits) and with twist-4 added. Thus we obtained two sets of diffractive paton distributions which allow us to make predictions for the longitudinal structure function $F_{\rm L}^{\rm D}$. The diffractive parton distributions (DPD) from the analysis of H1 data are shown in Fig. 1. They are given in terms of the pomeron parton distributions which can be multiplied by the pomeron flux $f(x_{I\!P}, t)$ to obtain the DPD.

We see that the singlet quark distributions from the two fits are practically the same while the gluon distributions are different. The gluon from the fit with twist-4 is stronger peaked near $\beta \approx 1$ than in the twist-2 fit. This rather surprising result can be understood by looking at the logarithmic slope $\partial F_2^{\rm D}/\partial \ln Q^2$ for fixed β. In the leading logarithmic approximation we have from the DGLAP equations

$$\frac{\partial F_2^{\rm D}}{\partial \ln Q^2} \sim \frac{\partial \Sigma_{I\!P}}{\partial \ln Q^2} = P_{qq} \otimes \Sigma_{I\!P} \,+\, P_{qG} \otimes G_{I\!P} \,-\, \Sigma_{I\!P} \int P_{qq}\,, \tag{15}$$

where the negative term sums virtual corrections. For large β, the measured slope is negative which means that the virtual term must dominate over the positive ones. The twist-4 contribution, added on the r.h.s., has a negative slope which is compensated by a larger gluon distribution in the twist-(2+4) fit, while the quark distribution $\Sigma_{I\!P}$ stays roughly the same since $F_2^D \sim \Sigma_{I\!P}$.

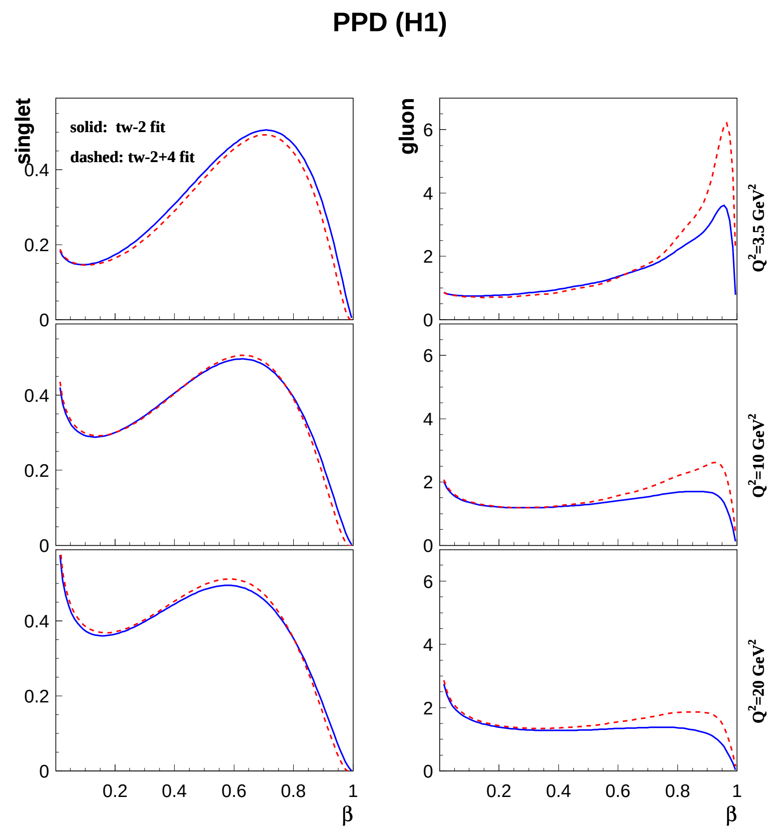

Fig. 1. Pomeron parton distributions: quark singlet (left) and gluon (right) from the H1 data. Solid lines: twist-2 fit; dashed lines: fit with twist-4.

In Fig. 2, we show the diffractive structure functions resulting from the determined parton distributions. As expected, F_2^D is practically the same in both fits. However, the F_L^D curves are significantly different due to the twist-4 contribution (shown as the dotted lines), present in the twist–(2+4) fit. Let us emphasized that both sets of curves were found in the fits which well describe the existing data, especially in the region of β where twist-4 is important. Thus, an independent *measurement* of F_L^D in this region would be an important confirmation of the QCD approach to diffraction.

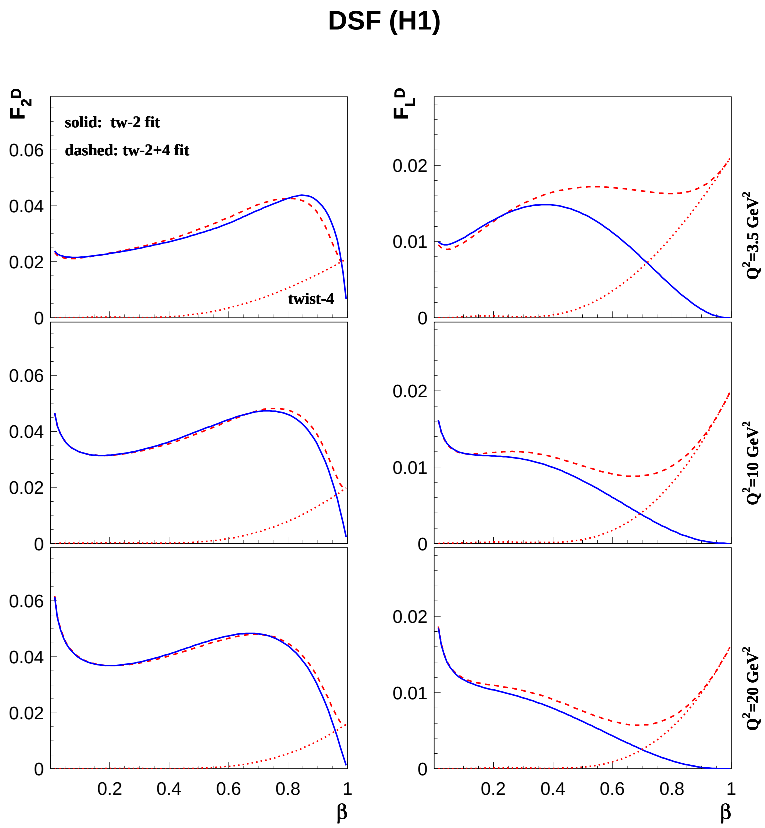

Fig. 2. Diffractive structure functions $F_2^{\rm D}$ (left) and $F_{\rm L}^{\rm D}$ (right) from fits to the H1 data for $x_{I\!P} = 10^{-3}$. Solid lines: twist-2 fit; dashed lines: twist–(2+4) fit; dotted lines: twist-4 contribution.

The importance of the twist-4 contribution for $F_{\rm L}^{\rm D}$ at large β is also shown in Fig. 3 where we present our predictions based on the analysis of the H1 data. The solid curve gives $F_{\rm L}^{\rm D}$ from the pure DGLAP fit while the dashed curves are predictions of the fits with the twist-4 contribution from [15]. The upper curve corresponds to the fit with the original normalization of twist-4 while for the lower curve twist-4 was multiplied by 0.5. Thus, the band reflects the scale of our uncertainty. Let us emphasize that in all three cases shown in this figure, we found a good description of the data. Giving the size of the effect, we conclude that the planned measurements at HERA will have a chance to directly confirm the QCD mechanism of DIS diffraction. A similar analysis performed for the diffractive ZEUS data leads to the same conclusion, see [15] for details.

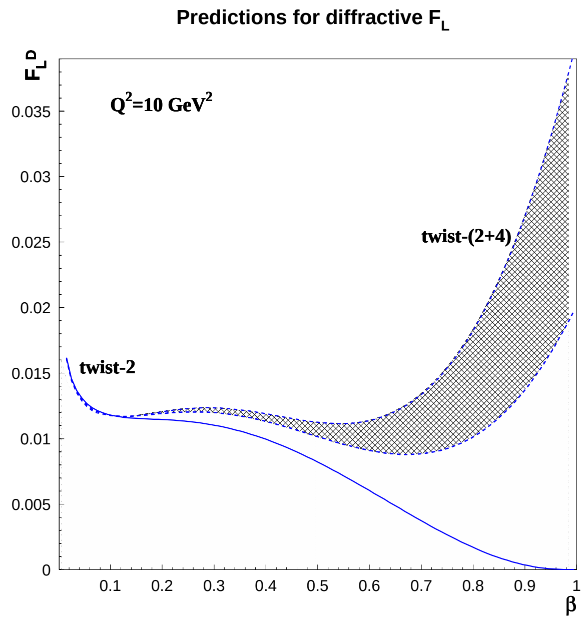

Fig. 3. Predictions for $F_{\mathrm{L}}^{\mathrm{D}}$ for $x_{I\!P} = 10^{-3}$ from fits to H1 data. The solid line: $F_{\mathrm{L}}^{\mathrm{D}}$ from twist-2 fit; dashed lines: $F_{\mathrm{L}}^{\mathrm{D}}$ from fit with twist-4 from [15] multiplied by 0.5 (lower curve) and by 1.0 (upper curve).

5. Summary

We performed the analysis of the diffractive data from HERA determining diffractive parton distributions. In addition to the standard twist-2 formulae, we also considered twist-4 contribution, suppressed by an additional power of $1/Q^2$ but dominating in the region of large β. This contribution comes from the $q\overline{q}$ diffractive production from longitudinally polarized virtual photons.

The twist-4 contribution leads to the diffractive gluon distribution which is stronger peaked at $\beta \approx 1$ than the gluon distribution from the pure twist-2 fits. The main impact of this contribution is on the longitudinal diffractive structure function which is significantly bigger than $F_{\mathrm{L}}^{\mathrm{D}}$ from the twist-2 analysis in the region of $\beta > 0.6$. Thus, an independent measurement of $F_{\mathrm{L}}^{\mathrm{D}}$ in this region at HERA will give a chance to confirm the QCD mechanism of diffractive interactions in DIS.

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