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Higher Twist in Diffractive Dissociation

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Abstract. We comment on the contributions of higher twist in the deep inelastic diffractive dissociation. Particular attention is given to the low mass-region near $\beta = 1$.

1. The diffractive dissociation in deep inelastic scattering lies on the interface between perturbative and nonperturbative QCD, and one expects the diffractive cross section to contain both hard and soft contributions. As a first experimental hint in this direction, one might take the observation that the measured intercept of the Pomeron flux factor tends to be a bit larger than that of the pure soft Pomeron [1]. In this note we propose, as a possible method of separating these distinct contributions to the diffractive cross section, to look into the expansion in inverse powers of Q^2 (twist expansion). We shall argue that, in addition to the (dominant) leading twist term, it is possible to identify non-negligible higher twist pieces, and we comment on their Q^2-evolution. In particular, in the small-mass region ($\beta = 1$) the diffractive production of longitudinal vector mesons as well as the production of hard jets have been shown to belong to higher twist, and their contribution to the diffractive cross section is not small.

In order to account for higher twist in both the transverse and the longitudinal cross section, we make the following ansatz for the diffractive cross section:

$$\frac{d^4\sigma^D}{d\beta dQ^2 dx_{\mathbb{P}} dt} = \frac{\alpha_{em}}{x_{\mathbb{P}} Q^2 \pi}\left(\frac{1+(1-y)^2}{2}\left[\frac{d\sigma_T^D}{d\beta dt} + \frac{Q_0^2}{Q^2}\frac{d\Delta\sigma_T^D}{d\beta dt}\right] + (1-y)\left[\frac{d\sigma_L^D}{d\beta dt} + \frac{Q_0^2}{Q^2}\frac{d\Delta\sigma_L^D}{d\beta dt}\right]\right) \tag{1}$$

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(the subscripts T, L refer to longitudinal and transverse polarization of the photon, resp., and Q_0 denotes an unknown hadronic scale). All four functions σ^D and $\Delta\sigma^D$ depend upon Q^2, β, and $x_{\mathbf{P}}$. In order to illustrate their content let us go through a few simple partonic processes. For convenience we use the proton rest system.

2. To begin with the production of a $q\bar{q}$ pair, we start in the region of large transverse momenta of the quarks where the QCD parton picture is applicable. For the transverse cross section one finds (in the DLA) [2–4]:

$$\left.\frac{d\sigma_T^D}{d\beta dp_t^2 dt}\right|_{t=0} = \sum_f e_f^2 \frac{\alpha_{em}\pi^2\alpha_s^2}{3Q^2} \frac{1-\frac{2\beta p_t^2}{(1-\beta)Q^2}}{\sqrt{1-\frac{4\beta p_t^2}{(1-\beta)Q^2}}} 4\beta^2(1-\beta)^2 \left[\frac{x_{\mathbf{P}}}{p_t^2} g(x_{\mathbf{P}}, \frac{p_t^2}{1-\beta})\right]^2 \quad (2)$$

(a more complete expression can be found in [2]). This formula results from two contributions, the planar Feynman diagrams where both gluons couple to the same quark line, and the nonplanar ones where they are attached to different quark lines. We expect that this model should be reliable in the large-β region. For intermediate or smaller β gluon production has to be taken into account (see below). A careful analysis of the p_T-integral shows that dominant contribution comes from the nonperturbative small-p_T-region, where the longitudinal photon momentum is distributed among the quarks in an asymmetric way (Aligned Jet Model [5]). This is a leading twist contribution, i.e. the cross section goes as $d^2\sigma^D/d\beta dt \sim 1/Q^2$. In this kinematic configuration the interaction of the quark pair with the proton is described by the nonperturbative Pomeron, and the detailed form of the cross section depends upon the way in which the Pomeron is modelled [6]. As a particular example we mention the following rather general feature [7]. Let us assume that the transverse momentum dependence of the unintegrated two gluon structure function $\phi(x, l_t^2)$ is described by an anomalous dimension which depends upon the virtuality Δ of the quark lines (before the interaction with the gluon structure function): $\phi \sim 1/Q_0^2\,(Q_0^2/l_t^2)^{\nu(\Delta)}$ where $\nu(\Delta)$ lies between zero and one and goes to zero (one) as Δ is small (large). Then one finds that in the AJM region the nonplanar coupling of the two-gluon amplitude to the $q\bar{q}$-pair is much weaker than the planar one; this provides a justification of using the picture of a "Pomeron structure function".

The leading twist contribution in the Double Logarithmic Approximation is calculated from (2) by taking the p_t-integral from a lower limit $\sim Q_0$ up to infinity. The twist-four contribution simply arises as a correction term when instead of infinity the true kinematic limit of p_t ($p_t^2 < \frac{Q^2(1-\beta)}{4\beta}$) is considered. Since the true limit requires a reduction of the leading twist result, the twist four-contribution comes with a negative sign, and in the DLA it reads:

$$\frac{Q_0^2}{Q^2}\left.\frac{d\Delta\sigma_T^D}{d\beta dt}\right|_{t=0} = -\sum_f e_f^2 \frac{\alpha_{em}\pi^2\alpha_s^2}{3Q^4} 8\beta^3(1-\beta)\left[x_{\mathbf{P}} g(x_{\mathbf{P}}, \frac{Q^2}{4\beta})\right]^2 \quad (3)$$

It again vanishes as $1-\beta$. Most remarkable is the fact that the suppression factor ($1/Q^2$ relative to the leading twist contribution) is partly compensated by the small-x Q^2-dependent scaling violations inside the gluon structure function. As a result, this higher twist contribution can be substantially larger than one would have expected based upon the naive $1/Q^2$ suppression factor. With increasing Q^2 it dies out more slowly than $1/Q^2$.

Let us now turn to the longitudinal cross section of the same process. We again begin in the large transverse momentum region. The formula analogous to (1) reads [2](for simplicity, we again restrict ourselves to the DLA):

$$\left.\frac{d\sigma_L^D}{d\beta dp_t^2 dt}\right|_{t=0} = \sum_f e_f^2 \frac{\alpha_{em}\pi^2\alpha_s^2}{3Q^4} \frac{4\beta^2 p_t^2}{\sqrt{1-\frac{4\beta p_t^2}{(1-\beta)Q^2}}} \left[\left\{(2\beta-1)\frac{1}{p_t^2}\right.\right. \tag{4}$$
$$\left.\left. + [2(1-\beta)+(1-2\beta)\ln(\beta)]\frac{\partial}{\partial p_t^2}\right\} x_{\mathbb{P}} g(x_{\mathbb{P}}, \frac{p_t^2}{1-\beta})\right]^2$$

In contrast to the transverse case, the p_t-integral is now much less dominated by the small-p_t region. In fact, the cross section is calculable in pQCD, and the twist expansion starts with twist four:

$$\frac{Q_0^2}{Q^2}\left.\frac{d^2\Delta\sigma_L^D}{d\beta dt}\right|_{t=0} = \sum_f e_f^2 \frac{\alpha_{em}\pi^2\alpha_s^2}{3Q^4} 4\beta^2 \left((1-2\beta)^2 \int^{\frac{Q^2}{4\beta}} \frac{d\bar{q}^2}{\bar{q}^2}[x_{\mathbb{P}} g(x_{\mathbb{P}}, \bar{q}^2]^2\right.$$
$$\left. +(2\beta-1)[2(1-\beta)+(1-2\beta)\ln(\frac{\beta}{4})]\left[x_{\mathbb{P}} g(x_{\mathbb{P}}, \frac{Q^2}{4\beta}\right]^2\right) \tag{5}$$

The logarithmic divergence at large $\bar{q}^2$ in the first term provides an extra $\ln Q^2/Q_0^2$ which was not present in the transverse case. Another striking difference compared to the transverse case is the fact that at $\beta = 1$ the longitudinal cross section does not vanish.

The cross section (4) for open $q\bar{q}$ production is closely related to the hard diffractive production of a vector particle [8–10]:

$$\left.\frac{d\sigma^L_{\gamma^* p\to VP}}{dt}\right|_{t=0} = \frac{4\pi^3\Gamma_{V\to e^+e^-} M_V \alpha_s^2(Q^2) T(Q^2)\eta_V^2 |(1+i\frac{\pi}{2}\frac{d}{d\ln x})xg(x,Q^2)|^2}{3\alpha_{em}Q^6} \tag{6}$$

(for more details, see [9,10]). Formally, the production of a single longitudinal vector particle does not seem to belong to twist four: the additional power of $1/Q^2$ can be ascribed to the wave function of the vector meson: compared to the open final state of quark and antiquark it "costs" another power of $1/Q^2$ to "force" the quarks into the bound state. However, when summing over all vector particles, this part of the diffractive cross section has to be counted as twist four: it belongs to the 4-gluon operator in F_2 which has twist four. A crude estimate [11] indicates that the measured cross section of longitudinal vector particles amounts to about 20% of the diffractive cross section.

Summarizing our brief discussion of the open $q\bar{q}$ production (as a realistic model for the region β near 1), we have shown that it provides contributions to three out of the four terms in (1). As to the transverse cross section, the dominant (leading twist) contribution comes from the AJM configuration and cannot be obtained from perturbative QCD. Nevertheless, in this simplest model, we expect the leading twist term to vanish at $\beta = 1$. The twist-four correction comes with a negative sign, and it is enhanced by the square of the gluon structure function which in the small-x region is large and thus compensates a part of the $1/Q^2$ suppression. The longitudinal cross section starts with twist four (so far we have neglected higher orders in α_s). Most important, it is also enhanced by the square of the gluon structure function, and it does not vanish as $1 - \beta$. For the large β region, therefore, the longitudinal (higher twist) cross section dominates over the transverse one (leading twist). Since this part of the cross section is not small, one has to be cautious in applying the leading twist DGLAP evolution equations to the full diffractive cross section, in particular in the region near $\beta = 1$. A complete QCD-based description should be based on (1), and it should allow for the presence of higher twist.

3. Next we address the question of the Q^2 evolution of the diffractive cross section: in addition to the $q\bar{q}$ pair we now have to allow for gluons inside the diffractive system. Most interesting are processes where the Pomeron couples to a gluon: as we have said earlier, for larger masses of the diffractive system (intermediate and smaller β) these configurations should dominate over the simple $q\bar{q}$ state. Also, there is direct experimental evidence for a strong gluonic component of the Pomeron. The "minimal" extension of the $q\bar{q}$ pair production, therefore, is the process $\gamma^* p \to (q\bar{q} + g)p$: a detailed discussion, analogous to that of the $q\bar{q}$ pair presented above, can be found in [12].

In order to address the Q^2 evolution we start with an explicit model, the calculation [13] of the cross section of $\gamma^* p \to (q\bar{q} + ng)p$ in the large mass region $Q^2 \ll M^2 \ll W^2$. The (dominant) leading twist part of this process has been shown to belong to the nonperturbative Pomeron, and the Q^2 evolution inside the diffractive system is described by the normal DGLAP dynamics (note that [13] only considers the DLA. This is in complete agreement with more recent rigorous studies [14–16] which provide a general proof of the validity of the DGLAP evolution equations for the leading twist diffractive structure functions.

Phenomenology based upon the DGLAP equations has been done by several groups [17–19]. However, it is important to note that in these numerical studies two simplifying assumptions are being made. First, in the ansatz (1) the longitudinal part is put equal to zero. In addition, no systematic attempt has been made to subtract from the measured diffractive cross section higher twist contributions. From what we have said before we expect this treatment to become inaccurate, at least, in the region of large β where both production from a longitudinal photon and higher twist becomes non-negligible. In a

more refined analysis both effects should be taken into account. It is therefore necessary to look into the Q^2-evolution of higher twist corrections inside the diffractive cross section. On top of the question of higher twist corrections, the region near $\beta = 1$ also requires a closer look into the resummation of large logarithms of the type $\ln(1-\beta)Q^2$ [20]. This becomes particularly important, as soon as leading-twist parton distributions inside the Pomeron turn out to be large near $\beta = 1$.

The Q^2 evolution of higher twist contributions is a topic of high theoretical interest by itself. General discussions of higher twist can be found in [21,22]. Specific higher twist operators are discussed in [23]. In the context of DIS diffraction, the discussion of higher twist has its very particular aspects. To illustrate this we once more return to the process $\gamma^* p \to (q\bar{q} + ng)p$ of [13]. We simply repeat the saddle point analysis given in this paper, but now in the vicinity of the twist-four point (in the notation of [13], near $\mu = -2$). In contrast to the leading-twist analysis, we now find strong ordering in the transverse momenta which begins already inside the two Pomerons and then continues inside the diffractive system. In particular, the scale $\bar{q}^2$ at the "triple Pomeron vertex" is not soft. In the DLA one finds $Q_0^2 \ll \bar{q}^2 \ll Q^2$: this is why for the "hard Pomeron" between the proton and the diffractive system now the gluon structure function $x_{\mathbb{P}} g(x_{\mathbb{P}}, \bar{q}^2)$ appears. The evolution equation for the twist-four four gluon operator above the "triple Pomeron vertex" is obtained by simply writing an integral equation for the interactions ("rungs") inside the four gluon system, and then taking the derivative with respect to $\ln Q^2/Q_0^2$. The equation is of the form (for fixed α_s):

$$\frac{\partial g_4(\beta, Q^2)}{\partial \ln Q^2} = V \otimes [g(x_{\mathbb{P}}, Q^2)]^2 + K \otimes g_4(\beta, Q^2) \tag{7}$$

(here g_4 denotes the four gluon correlation function, V a vertex function describing the coupling of the Pomerons to the diffractive system, and K the evolution kernel of the four gluon system). The novel feature of this equation is the inhomogeneous term: it expresses the fact that the Q^2 evolution starts already inside the gluon structure functions. In the leading-twist part of the diffractive cross section, the Q^2 evolution starts from some initial distribution of partons inside the Pomeron, i.e. the evolution is confined to the diffractive system. In contrast to this, for the twist four-part the scale $\bar{q}^2$ at the upper end of the Pomeron is not fixed, i.e. it is part of the Q^2 evolution.

There is a clear analogy between (7) and a similar inhomogeneous term in the evolution equation of the photon [24]: here the inhomogeneous term stands for the point-like coupling of the photon to the $q\bar{q}$ pair. Because of the large scale $\bar{q}^2$ at the upper end of the gluon structure functions, the "hard Pomeron" has a small transverse size and also has a "pointlike" coupling. Models for the diffractive structure which have used such a pointlike term have been rather successful in describing the large-β behavior of the diffractive cross section [18,19]. In [4] an evolution equation similar to (7) has been

proposed for the diffractive structure function: we believe that such an evolution equation only applies to the twist-four part of the diffractive structure function, whereas the leading-twist part satisfies the usual DGLAP evolution equation.

In our discussion of the higher twist corrections in the large mass (small β) region we have not yet distinguished between the transverse and the longitudinal photon. The difference between the two cross sections resides in the coupling of the twist-four gluon operators to the photon. In the transverse case, this coupling is negative (cf.eq.(3)), and it does not lead to a logarithm in Q^2, whereas the coupling to the longitudinal photon is positive and provides a logarithm.

Clearly, our argument based upon the analysis of the process $\gamma^* p \to (q\bar{q} + ng)p$ in the large mass region so far only applies to the evolution of twist four gluon operators, which dominate in the region of large diffractive masses. Returning to the small-mass region ($\beta = 1$), quark operators are the most important ones. Using the results in [23] it should be possible to obtain a rather complete description of the twist-four part of the diffractive structure function in the finite mass region. As a result of such analysis, we expect logarithmic corrections to our $q\bar{q}$ model near $\beta = 1$. In the high mass region, so far only the double logarithmic approximation to the evolution equations is available [25,26].

4. In this short note we discussed the role of higher twist in DIS diffractive scattering. We believe that a complete QCD analysis of the diffractive cross section should start from the ansatz (1), and the QCD evolution should be taken into account for both the leading twist and higher twist contributions. A first attempt in this direction has been done in [7,12].

Finally we would like to mention that the discussion of higher twist in the diffractive structure function has important implications for the presence of higher twist also in the deep inelastic structure function F_2 [27]. Based upon the estimate of the diffractive production of longitudinal vector mesons, one would have to conclude that, around $Q^2 = 10GeV^2$ and $x = 10^{-3}$, the twist-four corrections to F_2 are of the order of a few percent. For lower Q^2 one expects these corrections to increase. In the low-Q^2 region, therefore, higher twist cold become rather substantial. On the other hand, there could also be higher twist corrections in the transverse diffractive cross section which come with a negative sign and in F_2 may cancel a part of the longitudinal higher twist contribution. Therefore, further studies of higher twist in both the diffractive cross section and in the deep inelastic structure function F_2 are urgently needed.

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