Diffractive Dijet Photoproduction

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Abstract. We have calculated diffractive dijet production in deep-inelastic scattering (DIS) at low-\(Q^2\) and next-to-leading order (NLO) of perturbative QCD, including contributions from direct and resolved photons. We study how the cross section depends on the factorization scheme and scale \(M_g\) at the virtual photon vertex for the occurrence of factorization breaking. The strong \(M_g\)-dependence, which is present when only the resolved cross section is suppressed, is tamed by introducing the suppression also in the initial-state NLO correction of the direct part.

INTRODUCTION

From a perturbative QCD (pQCD) point of view, the central question for hard diffractive scattering events, characterized by a large rapidity gap devoid of particles in high-energy collisions, is whether they can be factorized into non-perturbative diffractive parton density functions (PDFs) of a colorless object (e.g. a pomeron) and perturbative partonic cross sections. This concept, based on a long-standing proposal by Ingelman and Schlein [1], is believed to hold for the scattering of point-like electromagnetic probes off a hadronic target, such as deep-inelastic scattering (DIS) or direct photoproduction [2], whereas it has been shown to fail for purely hadronic collisions [2, 3].

Factorization is thus expected to fail also in resolved photoproduction, where the photon first dissolves into partonic constituents, before these scatter off the hadronic target. The separation of these two types of photoproduction events is, however, a leading order (LO) concept. At next-to-leading order (NLO) of pQCD, they are closely connected by an initial state singularity originating from the splitting \(\gamma \rightarrow q\bar{q}\) [4], which may play a crucial role in the way factorization breaks down in diffractive photoproduction [5]. Factorization breaking effects are therefore expected to show up first in observables that distinguish between direct and resolved photoproduction, such as distributions in the longitudinal momentum fraction \(x_g\) of partons in the photon [6], the photon virtuality \(Q^2\) [7], or the dependence of the predicted cross sections on the factorization scale \(M_g\) [5]. It is clear that this \(M_g\)-dependence is unphysical and must be remedied also for the case of factorization breaking of the resolved part of the cross section. A proposal how to achieve this has been worked out in our previous work [5] and will be described in the next Section. For demonstrative purposes we restrict ourselves to low-\(Q^2\) DIS using the kinematic framework of our earlier publication [7].
Three groups have recently tried to extract diffractive parton densities from inclusive diffractive DIS data at DESY HERA, treating the Pomeron either as a hadronic object within Regge factorization \([8, 9]\)

\[
f_a^D (x; Q^2; x_P; t) = f_{P=P} (x_P; t) f_a (\beta = x_P; Q^2)
\]

or perturbative QCD \([10]\), but so far only the H1 set has been tested for factorization in a different scattering environment, \(i.e\). in photoproduction of dijets at HERA \([11]\).

**FACTORIZATION SCHEME AND SCALE DEPENDENCE**

A factorization scheme for virtual photoproduction has been defined and the full NLO corrections for inclusive dijet production have been calculated in \([12]\). They have been implemented in the NLO Monte Carlo program JETVIP \([13]\). We have adapted this NLO framework to diffractive dijet production. According to \([12]\), the subtraction term, which is absorbed into the PDFs of the virtual photon \(f_a = g(x_g; M_g)\), is of the form as given in \([5]\). The main term is proportional to \(\ln (M^2_g/Q^2)\) times the splitting function

\[
P_{q_i \gamma} (z) = 2N_c Q_i^2 z^2 + \left(1 - \frac{z}{2}\right) R
\]

where \(z = p_1 p_2 = p_0 q \geq \sqrt{s} \; [v; 1]\) and \(Q_i\) is the fractional charge of the quark \(q_i\). \(p_1\) and \(p_2\) are the momenta of the two outgoing jets, and \(p_0\) and \(q\) are the momenta of the ingoing parton and virtual photon, respectively. Since \(Q^2 = q^2 = M_g^2\), the subtraction term is large and is therefore resummed by the DGLAP evolution equations for the virtual photon PDFs. After this subtraction, the finite term \(M_g (Q^2)_{MS}\), which remains in the matrix element for the NLO correction to the direct process \([12]\), has the same \(M_g\)-dependence as the subtraction term, \(i.e\). \(\ln M_g\) is multiplied with the same factor. As already mentioned, this yields the \(M_g\)-dependence before the evolution is turned on. In the usual non-diffractive dijet photoproduction these two \(M_g\)-dependences cancel, when the NLO correction to the direct part is added to the LO resolved cross section \([14]\). Then it is obvious that the approximate \(M_g\)-independence is destroyed, if the resolved cross section is multiplied by a suppression factor \(R\) to account for the factorization breaking in the experimental data. To remedy this deficiency, we propose to multiply the \(\ln M_g\)-dependent term in \(M (Q^2)_{MS}\) with the same suppression factor as the resolved cross section. This is done in the following way: We split \(M (Q^2)_{MS}\) into two terms using the scale \(p_T\) in such a way that the term containing the slicing parameter \(y_s\), which was used to separate the initial-state singular contribution, remains unsuppressed. In particular, we replace the finite term after the subtraction by

\[
M (Q^2; R)_{MS} = \frac{1}{2N_c} P_{q_i \gamma} (z) \ln \frac{M_g^2 z}{p_T^2 (1 - z)} + \frac{Q_i^2}{2} R
\]

\[
\frac{1}{2N_c} P_{q_i \gamma} (z) \ln \frac{p_T^2}{z Q^2 + y_s s}
\]

\[(3)\]
where \( R \) is the suppression factor. This expression coincides with the finite term after subtraction (see Ref. [5]) for \( R = 1 \), as it should, and leaves the second term in Eq. (3) unsuppressed. In Eq. (3) we have suppressed in addition to \( \ln (M_\gamma^2+p_T^2) \) also the \( z \)-dependent term \( \ln (z=(1-z)) \), which is specific to the \( \overline{\text{MS}} \) subtraction scheme as defined in [12]. The second term in Eq. (3) must be left in its original form, i.e. being unsuppressed, in order to achieve the cancellation of the slicing parameter \( (y_s) \) dependence of the complete NLO correction in the limit of very small \( Q^2 \) or equivalently very large \( s \). It is clear that the suppression of this part of the NLO correction to the direct cross section will change the full cross section only very little as long as we choose \( M_\gamma \neq p_T \). The first term in Eq. (3), which has the suppression factor \( R \), will be denoted by DIRIS in the following.

To study the left-over \( M_\gamma \)-dependence of the physical cross section, we have calculated the diffractive dijet cross section with the same kinematic constraints as in the H1 experiment [15]. Jets are defined by the CDF cone algorithm with jet radius equal to one and asymmetric cuts for the transverse momenta of the two jets required for infrared stable comparisons with the NLO calculations [16]. The original H1 analysis actually used a symmetric cut of 4 GeV on the transverse momenta of both jets [17]. The data have, however, been reanalyzed for asymmetric cuts [15].

For the NLO resolved virtual photon predictions, we have used the PDFs SaS1D [18] and transformed them from the DIS scheme to the \( \overline{\text{MS}} \) scheme as in Ref. [12]. If not stated otherwise, the renormalization and factorization scales at the pomeron and the photon vertex are equal and fixed to \( p_T = p_T_{\text{jet}} \). We include four flavors, i.e. \( n_f = 4 \) in the formula for \( \alpha_s \) and in the PDFs of the pomeron and the photon. With these assumptions we have calculated the same cross section as in our previous work [7]. First we investigated how the cross section \( d\sigma=dQ^2 \) depends on the factorization scheme of the PDFs for the virtual photon, i.e. \( d\sigma=dQ^2 \) is calculated for the choice SaS1D and SaS1M. Here \( d\sigma=dQ^2 \) is the full cross section (sum of direct and resolved) integrated over the momentum and rapidity ranges as in the H1 analysis. The results, shown in Fig. 2 of Ref. [5] demonstrate that the choice of the factorization scheme of the virtual photon PDFs has negligible influence on \( d\sigma=dQ^2 \) for all considered \( Q^2 \). The predictions agree reasonably well with the preliminary H1 data [15].

We now turn to the \( M_\gamma \)-dependence of the cross section with a suppression factor for DIRIS, which is the main part of this Report. To show this dependence for the two suppression mechanisms, (i) suppression of the resolved cross section only and (ii) additional suppression of the DIRIS term as defined in Eq. (3) in the NLO correction of the direct cross section, we consider \( d\sigma=dQ^2 \) for the lowest \( Q^2 \)-bin, \( Q^2 \leq 6 \) GeV\(^2\). In the left part of Fig. 1 this cross section is plotted as a function of \( \xi = M_\gamma + p_T \) in the range \( \xi \geq 0.25;4 \) for the cases (i) (light full curve) and (ii) (full curve). We see that the cross section for case (i) has an appreciable \( \xi \)-dependence in the considered \( \xi \) range of the order of 40%, which is caused by the suppression of the resolved contribution only. With the additional suppression of the DIRIS term in the direct NLO correction, the \( \xi \)-dependence of \( d\sigma=dQ^2 \) is reduced to approximately less than 20%, if we compare the maximal and the minimal value of \( d\sigma=dQ^2 \) in the considered \( \xi \) range. The remaining \( \xi \)-dependence is caused by the NLO corrections to the suppressed resolved cross section and the evolution of the virtual photon PDFs. How the compensation of the
$e p \rightarrow e^\prime + 2 \text{jets} + X + Y$

**FIGURE 1.** Left: Photon factorization scale dependence of resolved and direct contributions to $d\sigma = dQ^2$ together with their weighted sums for (i) suppression of the resolved cross section and for (ii) additional suppression of $\text{DIR}_{\text{IS}}$, using SaS1D virtual photon PDFs [18]. Right: $Q^2$-dependence of the dijet cross section for $M_\gamma = p_T/4$ (full) and $M_\gamma = 4p_T$ (dashed) and comparison with preliminary H1 data using SaS1D virtual photon PDFs [18].

$M_\gamma$-dependence between the suppressed resolved contribution and the suppressed direct NLO term works in detail is exhibited by the dotted and dashed-dotted curves in Fig. 4 (left). The suppressed resolved term increases and the suppressed direct NLO term decreases by approximately the same amount with increasing $\xi$. In addition we show also $d\sigma = dQ^2$ in the DIS theory, i.e. without subtraction of any $\ln Q^2$ terms (dashed line). Of course, this cross section must be independent of $\xi$. This prediction agrees very well with the experimental point, whereas the result for the subtracted and suppressed theory (full curve) lies slightly below. We notice, that for $M_\gamma = p_T$ the additional suppression of $\text{DIR}_{\text{IS}}$ has only a small effect. It increases $d\sigma = dQ^2$ by 5% only.

In order to get an idea about the $M_\gamma$ scale dependence of $d\sigma = dQ^2$ for the other $Q^2$ bins we have computed this cross section for two choices of $M_\gamma$, namely $M_\gamma = p_T/4$ and $M_\gamma = 4p_T$ corresponding to the lowest and highest $\xi$ in Fig. 4 (left). The result for the $d\sigma = dQ^2$ is shown on the right side of Fig. 4. We see that the $M_\gamma$-dependence in the considered range decreases with increasing $Q^2$. This is to be expected since the resolved contribution diminishes with increasing $Q^2$, so that the NLO corrections to the resolved cross section and the effect of the evolution of the photon PDF diminish as well.

**CONCLUSION**

In Summary, we described in this Report a new factorization scheme for diffractive production of jets in low-$Q^2$ deep inelastic scattering. By suppressing not only the resolved photon contribution, but also the unresummed logarithm as well as scheme-
dependent finite terms in the NLO direct initial state correction, factorization scheme and scale invariance is restored up to higher order effects, while at the same time the cut-off invariance required in phase space slicing methods is preserved.

For pedagogical reasons, we have chosen in this Report the kinematic region of finite, but low photon virtuality $Q^2$, which exposes and regularizes a logarithmic virtual photon initial state singularity. We do, however, not rely on the finiteness of $Q^2$, but rather separate suppressed and unsuppressed terms using the hard transverse momentum scale $p_T$, so that our scheme is equally valid for real photoproduction.

The scheme- and scale invariance has been demonstrated numerically using the kinematics of a recent H1 analysis, differential in $Q^2$ and parton momentum fraction in the pomeron $z_P$ (not shown). Very good stability with respect to scheme- and scale variations and good agreement with the experimental data has been found.

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**REFERENCES**

1. G. Ingelman and P. E. Schlein, Phys. Lett. B 152, 256 (1985).
2. J. C. Collins, Phys. Rev. D 57, 3051 (1998) [Erratum-ibid. D 61, 019902 (2000)].
3. T. Affolder et al. [CDF Collaboration], Phys. Rev. Lett. 84, 5043 (2000).
4. M. Klasen, Rev. Mod. Phys. 74, 1221 (2002).
5. M. Klasen and G. Kramer, DESY 05-095, LPSC 05-053, hep-ph/0506121, submitted to J. Phys. G.
6. M. Klasen and G. Kramer, contribution to DIS 2004, hep-ph/0401202, Eur. Phys. J. C 38, 93 (2004).
7. M. Klasen and G. Kramer, Phys. Rev. Lett. 93, 232002 (2004).
8. H1 Collaboration, Abstract 980, contributed to the 31st International Conference on High Energy Physics (ICHEP 2002), Amsterdam, July 2002.
9. S. Chekanov et al. [ZEUS Collaboration], Eur. Phys. J. C 38, 43 (2004).
10. A. D. Martin, M. G. Ryskin and G. Watt, Eur. Phys. J. C 37, 285 (2004).
11. M. Mozer and R. Renner for the H1 and ZEUS Collaborations, these proceedings.
12. M. Klasen, G. Kramer and B. Pötter, Eur. Phys. J. C 1, 261 (1998).
13. B. Pötter, Comput. Phys. Commun. 133, 105 (2000).
14. D. Bödeker, G. Kramer and S. G. Salesch, Z. Phys. C 63, 471 (1994).
15. S. Schätzel, hep-ex/0408049, to appear in the proceedings of the 12th International Workshop on Deep Inelastic Scattering (DIS 2004), Strbske Pleso, April 2004; H1 Collaboration, Abstract 6-0176, contributed to the 32nd International Conference on High Energy Physics (ICHEP 2004), Beijing, August 2004.
16. M. Klasen and G. Kramer, Phys. Lett. B 366, 385 (1996).
17. C. Adloff et al. [H1 Collaboration], Eur. Phys. J. C 20, 29 (2001).
18. G. A. Schuler and T. Sjöstrand, Phys. Lett. B 376, 193 (1996).