A fresh look at factorization breaking in diffractive photoproduction of dijets at HERA at next-to-leading order QCD

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Abstract We calculate the cross section of diffractive dijet photoproduction in ep scattering at next-to-leading order (NLO) of perturbative QCD (pQCD), which we supplement by a model of factorization breaking for the resolved-photon contribution. In this model, the suppression depends on the flavor and momentum fraction of the partons in the photon. We show that within experimental and theoretical uncertainties, the resulting approach provides a good description of the available HERA data in most of the bins. Hence, taken together with the observation that NLO pQCD explains well the data on diffractive production of dijets in DIS and open charm in DIS, our model of factorization breaking presents a viable alternative to the scheme based on the global suppression factor.

1 Introduction

One of the highlights of the physics results obtained at HERA was the measurement of inclusive diffraction \( \gamma^* p \rightarrow Xp \) in lepton–proton deep-inelastic scattering (DIS). Combined analyses of the H1 and ZEUS experiments have been published in Ref. [1]. Contrary to the expectations that the probability of large rapidity gap events in DIS should be very small [2], it was found that diffractive events in DIS constitute approximately 10–15% of the total cross section over a wide range of \( Q^2 \). Furthermore, the QCD collinear factorization theorem for hard inclusive diffraction [3] allowed one to treat diffractive DIS on the same footing as inclusive DIS. One can thus first introduce universal diffractive parton distribution functions (dPDFs) and then determine them by fitting to the measured diffractive structure function [4–6]. The universality of the resulting dPDFs is confirmed by good agreement between the perturbative QCD (pQCD) calculations and the data on diffractive production of dijets [7] and open charm [8] in DIS.

At the same time, in diffractive photoproduction of dijets in ep scattering, based on the well-known factorization breaking in diffractive dijet production in pp collisions at the Tevatron [9–11], collinear factorization is generally not expected to hold [12–14]. However, the pattern of this factorization breaking remains an open question [15]; for recent reviews see, e.g., Refs. [16–18]. To summarize, while the recent H1 [19,20] and ZEUS [21] data on diffractive dijet photoproduction are largely consistent with each other after the renormalization of the ZEUS data, the next-to-leading order (NLO) perturbative QCD calculations overestimate the data by approximately 40–50%. The theory and the data can be made consistent by introducing either a global suppression factor of 0.5 or a suppression factor of approximately 0.4 only for the resolved-photon contribution. The most recent H1 measurement of diffractive dijet photoproduction with a leading proton [22] is also consistent with the observation that NLO pQCD globally overestimates the data by the factor of 0.5.

Factorization breaking in diffractive dijet photoproduction is a result of soft inelastic photon interactions with the proton, which populate and thus partially destroy the final-state rapidity gap. This effect is usually described in the literature by a rapidity gap survival factor \( S^2 \leq 1 \). Since the magnitude of \( S^2 \) decreases with an increase of the interaction strength between the probe and the target, the pattern of the factorization breaking can be related to various components of the photon [17]. In the laboratory reference frame, the high-energy photon interacts with hadronic targets by fluctuating into various configurations (components) interacting with the target with different cross sections. These fluctuations contain both weakly interacting (the so-called point-like) components and the components interacting with large cross sections, which are of the order of

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the vector meson–proton cross sections. This general spacetime picture of photon–hadron interactions at high energies is usually realized in the framework of such approaches as the vector meson dominance (VMD) model and its generalizations [23,24] or the color dipole model [25,26]. It is also used in the language of collinear factorization, where the photon structure function and parton distribution functions (PDFs) are given by a sum of the resolved-photon contribution corresponding to the VMD part of the photon wave function and the point-like (inhomogeneous) term originating from the $\gamma \rightarrow q\bar{q}$ splitting; see, e.g., Ref. [27]. Note that the direct-photon contribution to diffractive dijet photoproduction corresponds to the configurations interacting with very small cross sections of the order of $1/E_T^2$ ($E_T$ is the transverse jet energy), which preserves factorization.

Let us recall that the hadron (VMD) part of the photon PDFs contributes only for small $x_\gamma$, whereas the point-like term gives the dominant contribution for large $x_\gamma$. Here, $x_\gamma$ is the light-cone momentum fraction of a parton in the photon. Based on the arguments presented above, it is then natural to expect $S_2^2 = 1$ for the direct-photon contribution localized near $x_\gamma = 1$, $S_2^2 \approx 0.34$ for the hadron-like component of the photon at small $x_\gamma$, and $S_2^2 \approx 0.53–0.75$ for the gluon and quark contributions at large $x_\gamma$ corresponding to small, but non-negligible factorization breaking due to the point-like component of the resolved photon [17,18] and factorization breaking in diffractive dijet photon production. This result reinforces the conclusion of Ref. [17].

Another important observation relevant to the possible pattern of factorization breaking is that the HERA data on diffractive dijet photoproduction in $ep$ scattering at HERA, while simultaneously, by construction, not conflicting with the good pQCD description of diffractive photoproduction of open charm in $ep$ scattering. Thus, next-to-leading order perturbative QCD coupled with the physically motivated assumption as regards the rapidity gap survival probability for the resolved-photon contribution and the effect of hadronization corrections provide a good description of all available HERA data on diffractive dijet photoproduction. This result reinforces the conclusion of Ref. [17].

2 New scenario for factorization breaking in diffractive photoproduction of dijets in $ep$

We performed next-to-leading order (NLO) pQCD calculations [18] of the cross sections of diffractive photoproduction of dijets in $ep$ scattering $ep \rightarrow e + 2\text{jets} + X' + Y$ using the kinematic conditions and cuts of the H1 [19,20] and ZEUS [21] data on diffractive dijet photoproduction in $ep$ scattering at HERA, while simultaneously, by construction, not conflicting with the good pQCD description of diffractive photoproduction of open charm in $ep$ scattering. Thus, next-to-leading order perturbative QCD coupled with the physically motivated assumption as regards the rapidity gap survival probability for the resolved-photon contribution and the effect of hadronization corrections provide a good description of all available HERA data on diffractive dijet photoproduction. This result reinforces the conclusion of Ref. [17].

Another important observation relevant to the possible pattern of factorization breaking is that the HERA data on diffractive photoproduction of open charm [31] agree with the NLO pQCD calculations [32,33], and hence no factorization breaking is required. This calls into question the pattern of factorization breaking in diffractive photoproduction of open charm [31] and ZEUS [21] data on diffractive dijet photoproduction in $ep$ scattering at HERA, while simultaneously, by construction, not conflicting with the good pQCD description of diffractive photoproduction of open charm in $ep$ scattering. Thus, next-to-leading order perturbative QCD coupled with the physically motivated assumption as regards the rapidity gap survival probability for the resolved-photon contribution and the effect of hadronization corrections provide a good description of all available HERA data on diffractive dijet photoproduction. This result reinforces the conclusion of Ref. [17].

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$$\sigma(ep \rightarrow e + 2\text{jets} + X' + Y)$$

$$= \sum_{i,j} \int dt \int dx_P \int dz_P \int dy \int dx_y$$

$$\times S_i^2(x_y) f_{i/\gamma}(y) f_{j/y}(x_y, \mu^2) f_{jj/p}^{D(4)}$$

$$\times (x_P, z_P, t, \mu^2) d\tilde{\sigma}_{jj}^{(n)}_{\rightarrow \text{jets}}, \quad (1)$$

where $X'$ denotes the pomeron (and possibly photon) remnant jet(s); $Y$ denotes either a proton or a low-mass proton excitation; $S_i^2(x_y)$ is the factor modelization factorization breaking; $f_{i/\gamma}(y)$ is the photon flux of the electron depending on the photon light-cone momentum fraction $y$; $f_{j/y}(x_y, \mu^2)$ is the PDF of parton $i$ in the photon depending on the momentum fraction $x_y$ and the factorization scale $\mu$; $f_{jj/p}^{D(4)}(x_P, z_P, t, \mu^2)$ is the diffractive PDF of the proton, which depends on $x_P$ (the momentum fraction carried by the diffractive exchange or "Pomeron") and $z_P$ (the momen-
Fig. 1 Diffractive production of dijets with invariant mass $M_{12}$ in direct (left) and resolved (right) photon–pomeron collisions, leading to the production of one or two additional remnant jets.

Fig. 2 Cross section of diffractive dijet photoproduction in ep scattering: comparison of the NLO pQCD predictions combined with the model of factorization breaking of Eq. (2) (red solid lines) to the H1 data with the low-$E_T^{jet}$ cut [19]; the theoretical uncertainty due to the variation of the normalization and factorization scales is shown by the red dotted lines. Also, the NLO pQCD results without the effect of factorization breaking are given by the blue dot-dashed lines labeled “NLO, $R = 1$”. Note that the pQCD predictions include the hadronization corrections.

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scheme [27] and the 2006 H1 proton diffractive PDFs (fit B) [5].

We explained in the Introduction that the space-time picture of high-energy photon–proton interactions suggests that in diffractive dijet photoproduction on the proton, QCD diffractive factorization holds for the direct-photon contribution and is broken for the resolved-photon contribution. Moreover, for the latter contribution, the factorization breaking is strongest at small \( x_{\gamma} \), small, but non-negligible, for large \( x_{\gamma} \), and depends on the parton flavor. In the framework of collinear QCD factorization, the decrease of factorization-breaking effects in the resolved-photon contribution with an increase of \( x_{\gamma} \) can be explained by the observation that based on the factorization of the collinear singularity, there should be a smooth transition from the resolved-photon contribution at large \( x_{\gamma} \) to the direct-photon contribution.

Therefore, we model the effect of factorization breaking by introducing the following suppression factor of \( S_{2i}(x_{\gamma}) \) for the resolved-photon contribution (i.e. for the photon PDFs) in Eq. (1):

\[
S_{2i}(x_{\gamma}) \rightarrow \begin{cases} 1, & i = c, \\ A_q x_{\gamma} + 0.34, & i = u, d, s, \\ A_g x_{\gamma} + 0.34, & i = g, \end{cases}
\]

where \( i \) is the parton flavor; \( A_q = 0.37–0.41 \) and \( A_g = 0.19–0.24 \). The given ranges of values take into account the possible effective dependence of \( S_{2i}(x_{\gamma}) \) on the hard resolution scale, where the first and the second values correspond to \( E_{T}^{\text{jet}} = 5 \) and 7.5 GeV, respectively. Thus, the factor of \( S_{2i}^{2}(x_{\gamma}) \) in Eq. (2) represents a linear interpolation between the domain of small \( x_{\gamma} \) dominated by the hadronic contribution to photon PDFs, where \( S_{2q}^{2}(x_{\gamma}) = 0.34 \), and the regime of large-\( x_{\gamma} \) dominated by the point-like contribution to photon PDFs, where \( S_{2q}^{2}(x_{\gamma}) = 0.71–0.75 \) for quarks and \( S_{2g}^{2}(x_{\gamma}) = 0.53–0.58 \) for gluons; see Ref. [17]. Note that the model of Eq. (2) assumes no factorization breaking in the charm quark channel according to the observation that NLO pQCD describes well diffractive photoproduction of open charm in \( ep \) scattering; see Sect. 1.

The comparison of the results of our calculations to the H1 and ZEUS data is shown in Figs. 2, 3 and 4. The kinematic
Fig. 4 The same as in Fig. 2, but for the ZEUS data [21]

cuts of the experimental analyses are summarized in Table 1, where $Q^2$ refers to the photon virtuality, $y$ its momentum fraction in the electron, $E_T^{jet}$ are the leading and sub-leading transverse jet energies, and $\eta^{jet}$ their rapidities. In Figs. 2, 3, and 4, the thick red solid lines correspond to the calculation, when the renormalization and factorization scale $\mu$ is identified with the transverse energy of jet 1, $\mu = E_T^{jet}$. The thin red dotted lines quantify the scale uncertainty of our NLO calculations and correspond to $\mu = E_T^{jet}$ (lower) and $\mu = E_T^{jet}/2$ (upper). For comparison, we also show the unsuppressed predictions (assuming no factorization breaking) by the blue dot-dashed lines labeled “NLO, $R=1$”. Note that our theoretical calculations have been multiplied by the hadronization corrections in each bin [19–21]. In the different panels, the values of the cross section are shown as functions of the following variables; see, e.g., Ref. [19]:

$$x_T^{jets} = \sum_{jets} (E_i - P_{i,z})/(E_X - P_{X,z})$$

is the hadron-level estimator of the parton momentum fraction in the photon, where the sum runs over the hadronic final states $i$ included in the jets and $X$ refers to the full diffractive final state; $x_T^{P} = \sum_{jets} (E_i + P_{i,z})/(E_X + P_{X,z})$ is the estimator of the “Pomeron” momentum fraction carried by a parton; $x_P = (E_X + P_{X,z})/(2E_P^{beam})$ is the measured “Pomeron” momentum fraction, where $E_P^{beam}$ is the proton beam energy; $E_T^{jet}$ is the transverse energy of jet 1; $M_X$ is the invariant mass of the diffractive final state (two jets plus diffractively produced remnants of the photon and the “Pomeron”); $M_{12}$ is the invariant mass of the dijet system; $(\eta^{hets}) = (\eta_1 + \eta_2)/2$ and $\Delta\eta^{hets} = |\eta_1 - \eta_2|$ are the average and the relative jet rapidities, and $W$ is the invariant photon–proton energy.

One can see from Figs. 2, 3, and 4 that within theoretical uncertainties, NLO perturbative QCD combined with the model of factorization breaking of Eq. (2) provides a good description of the data for most of the bins. The quality of the description of the data is similar to that of Ref. [18], where factorization breaking is realized either by the global or the resolved-only, flavor- and $x$-independent suppression factors.

An inspection of Figs. 2, 3, and 4 shows that NLO pQCD correctly reproduces the shape of almost all considered distributions and only fails to explain the normaliza-
ion in some bins receiving a significant contribution from the direct-photon contribution, which is unsuppressed in our factorization-breaking scheme. The most notable example is the distribution at high \( x_T^\text{jets} \) at low \( E_T^\text{jets} \). It was hypothesized in Ref. [17] that additional sizable hadronization corrections along with bin migration effects, which are not included in our analysis, might help to improve the agreement between theory and data at large \( x_T^\text{jets} \). This hypothesis is supported by very similar observations in inclusive photoproduction at low \( E_T^\text{jets} \) [30].

Integrating our results for \( d\sigma/dE_T^\text{jets} \) over \( E_T^\text{jets} \), we obtain the theoretical prediction for the integrated cross section \( \sigma_{\text{NLO}}^\text{tot} \). Table 2 gives our results for \( \sigma_{\text{NLO}}^\text{tot} \), the corresponding experimental cross sections \( \sigma_{\text{data}}^\text{tot} \), and the ratios

\[
R = \frac{\sigma_{\text{NLO}}^\text{tot}}{\sigma_{\text{data}}^\text{tot}}
\]

of the theoretical predictions to the measured values. In the presented values for \( R \), we have added in quadrature the experimental and theoretical uncertainties. One can see from the results shown in the table that within combined experimental and theoretical uncertainties, NLO pQCD with our factorization-breaking scheme gives a good description of the integrated cross section of diffractive dijet photoproduction in ep scattering measured at HERA.

Note that the central value of \( R \) for the high-\( E_T \) cut data is somewhat larger than that for the low-\( E_T \) cut, which can be explained by the fact that the unsuppressed charm quark contribution becomes more prominent due to the QCD evolution of the photon PDFs.

### 3 Conclusions

We calculated the cross sections of diffractive dijet photoproduction in ep scattering in HERA kinematics using NLO perturbative QCD and a scenario of factorization breaking, which assumes that only the resolved-photon contribution is suppressed. The suppression depended on the parton flavor and the light-cone momentum fraction of partons in the photon. It was absent for charm quarks, larger for gluons than for light quarks, and decreased with an increase of the parton momentum. This model for factorization breaking in diffractive QCD is based on the space-time picture of photon–hadron interactions and complies with the good pQCD description of diffractive photoproduction of open charm in ep scattering. We compared our results with the available H1 and ZEUS data and found that various measured distributions and the integrated cross sections can be reproduced by our calculations with good accuracy. This agreement allows us to advocate our model as a viable alternative to the purely phenomenological scheme based on a global suppression factor.

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**Table 1** Kinematic cuts applied in the most recent H1 [19,20] and ZEUS [21] analyses of diffractive dijet photoproduction

| \( Q^2 < 0.01 \text{ GeV}^2 \) | \( 0.3 < y < 0.65 \) | \( E_T^\text{jets} > 5 \text{ GeV} \) | \( E_T^\text{jets} > 4 \text{ GeV} \) | \( -1 < \eta^\text{jets(1)} < 2 \) | \( z_{\text{pr}} < 0.8 \) | \( x_{\text{pr}} < 0.03 \) | \( |t| < 1 \text{ GeV}^2 \) | \( M_Y < 1.6 \text{ GeV} \) |
|---|---|---|---|---|---|---|---|---|
| \( 1 \text{ pb} \) | \( 11 \text{ pb} \) | \( 295 \pm 6 \text{ (stat.)} \pm 58 \text{ (syst.) pb} \) | \( 375 \pm 157 \text{ pb} \) | \( 37 \pm 2 \text{ (stat.)} \pm 8 \text{ (syst.) pb} \) | \( 51 \pm 15 \text{ pb} \) | \( 37 \pm 2 \text{ (stat.)} \pm 8 \text{ (syst.) pb} \) | \( 51 \pm 15 \text{ pb} \) | \( 124 \pm 11 \text{ pb} \) |
| \( R = \frac{\sigma_{\text{NLO}}^\text{tot}}{\sigma_{\text{data}}^\text{tot}} \) |

**Table 2** The theoretical and experimental values of the total integrated cross sections of diffractive dijet photoproduction in ep scattering at HERA, \( \sigma_{\text{NLO}}^\text{tot} \) and \( \sigma_{\text{data}}^\text{tot} \), and their ratios \( R \); see Eq. (3)

| H1, low-\( E_T \) cut | H1, high-\( E_T \) cut | ZEUS |
|---|---|---|
| \( \sigma_{\text{data}}^\text{tot} = 295 \pm 6 \text{ (stat.)} \pm 58 \text{ (syst.) pb} \) | \( \sigma_{\text{data}}^\text{tot} = 37 \pm 2 \text{ (stat.)} \pm 8 \text{ (syst.) pb} \) | \( \sigma_{\text{data}}^\text{tot} = 124 \pm 11 \text{ pb} \) |
| \( \sigma_{\text{NLO}}^\text{tot} = 375 \pm 157 \text{ pb} \) | \( \sigma_{\text{NLO}}^\text{tot} = 51 \pm 15 \text{ pb} \) | \( \sigma_{\text{NLO}}^\text{tot} = 165 \pm 46 \text{ pb} \) |
| \( R = 1.27^{+0.46}_{-0.29} \) | \( R = 1.32^{+0.37}_{-0.31} \) | \( R = 1.33^{+0.29}_{-0.21} \) |
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