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FACTORIZATION BREAKING IN DIFFRACTIVE PHOTOPRODUCTION OF DIJETS

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We have calculated the diffractive dijet cross section in low-Q^2 ep scattering in the HERA regime. The results of the calculation in LO and NLO are compared to recent experimental data of the H1 collaboration. We find that in LO the calculated cross sections are in reasonable agreement with the experimental results. In NLO, however, some of the cross sections disagree, showing that factorization breaking occurs in that order. By suppressing the resolved contribution by a factor of approximately three, good agreement with the data is found.

1 Introduction

Diffractive γp interactions are characterized by an outgoing proton of high longitudinal momentum and/or a large rapidity gap, defined as a region of pseudo-rapidity, $\eta = -\ln\tan\theta/2$, devoid of particles. It is assumed that the large rapidity gap is due to the exchange of a pomeron, which carries the internal quantum numbers of the vacuum. Diffractive events that contain a hard scattering are referred to as hard diffraction. A necessary condition for a hard scattering is the occurrence of a hard scale, which may be the large momentum transfer Q^2 in inclusive deep-inelastic ep scattering or the high transverse momentum of jets or single hadrons produced in high-energy γp, ep, or $p\bar{p}$ collisions.

The central problem in hard diffraction is the question of QCD factorization, *i.e.* the question whether it is possible to explain the observed cross sections in hard diffractive processes by a convolution of diffractive parton distribution functions (PDFs) with parton-level cross sections.

The diffractive PDFs have been determined by the H1 collaboration from a recent high-precision inclusive measurement of the diffractive deep inelastic scattering (DIS) process $ep \to eXY$, where Y is a single proton or a low mass proton excitation [1]. The diffractive PDFs can serve as input for the calculation of any of the other diffractive hard scattering reactions. For diffractive DIS, QCD factorization has been proven by Collins [2]. This has the consequence that the evolution of the diffractive PDFs is predictable in the same way as the PDFs of the proton via the DGLAP evolution equations. Collins' proof is valid for all lepton-induced collisions. These include besides diffractive DIS also the diffractive direct photoproduction of jets. The proof fails for hadron-induced processes.

As is well known, the cross section for the photoproduction of jets is the sum of the direct contribution, where the photon couples directly to the quarks, and of the resolved contribution, where the photon first resolves into partons (quarks or gluons), which subsequently induce the hard scattering to produce the jets in the final state. So, the resolved part resembles hadron-induced production of jets as for example in $p\bar{p}$ collisions. Dijet production in single-diffractive collisions has been measured recently by the CDF collaboration at the Tevatron [3]. It was found that the dijet cross section was suppressed relative to the prediction based on older diffractive PDFs from the H1 collaboration [4] by one order of magnitude [3]. From this result we would conclude that the resolved contribution in diffractive photoproduction of jets should be reduced by a similar correction factor. This suppression factor (sometimes also called the rapidity gap survival probability) has been calculated using various eikonal models, based on multi-pomeron exchanges and s-channel unitarity [5]. The direct and the resolved parts of the cross section contribute with varying strength in different kinematic regions. In particular, the x_γ-distribution is very sensitively dependent on the way how these two parts of the cross section are superimposed. Near $x_\gamma \simeq 1$ the direct part dominates, whereas for $x_\gamma < 1$ the resolved part gives the main contribution. However, in this region also contributions from next-to-leading order (NLO) corrections of the direct cross section occur. Therefore, to decide whether the resolved part is suppressed as compared to the experimental data, a NLO analysis is needed. This is the aim of this contribution. For our calculations we rely on our work on dijet production in the inclusive (sum of diffractive and non-diffractive) reaction $\gamma + p \to \text{jets} + X$ [6], in which we have calculated the cross sections for inclusive one-jet and two-jet production up to NLO for both the direct and the resolved contribution.

Recently the H1 collaboration [7] have presented data for differential dijet cross sections in the low-$|t|$ diffractive photoproduction process $ep \to eXY$, in which the photon dissociation system X is separated from a leading low-mass baryonic system Y by a large rapidity gap. Using the same kinematic constraint as in these measurements we have calculated the same cross section as in the H1 analysis up to NLO. By comparing to the data we shall try to find out, whether or not a suppression of the resolved cross section is needed in order to find reasonable agreement between the data and the theoretical predictions.

2 Kinematic Variables, Diffractive Parton Distributions, and Cross Section Formula

The diffractive process $ep \to eXY$, in which the systems X and Y are separated by the largest rapidity gap in the final state, is sketched in Fig. 1 of [8]. The system X contains at least two jets, and the system Y is supposed to be a proton or another low-mass baryonic system. Let k and p denote the momenta of the incoming electron (or positron) and proton, respectively, and q the momentum of the virtual photon γ^*. Then the usual kinematic variables are

$$s = (k+p)^2,\ Q^2 = -q^2,\ \text{and}\ y = \frac{qp}{kp}. \tag{1}$$

We denote the four-momenta of the systems X and Y by p_X and p_Y. The H1 data [7] are described in terms of

$$t = (p - p_Y)^2, \ M_Y^2 = p_Y^2, \ \text{and} \ x_{I\!P} = \frac{q(p - p_Y)}{qp}, \tag{2}$$

where t is the squared four-momentum transfer of the incoming proton and the system Y, M_Y is the invariant mass of the system Y, and $x_{I\!P}$ is the momentum fraction of the proton beam transferred to the system X.

The exchange between the systems X and Y is supposed to be the pomeron $I\!P$, which couples to the proton and the system Y with four-momentum $p - p_Y$. The pomeron is resolved into partons (quarks or gluons) with four-momentum v. The virtual photon can resolve into partons with four-momentum u, which is equal to q for the direct process. With these two momenta u and v we define

$$x_\gamma = \frac{pu}{pq} \ \text{and} \ z_{I\!P} = \frac{qv}{q(p - p_Y)}. \tag{3}$$

x_γ is the longitudinal momentum fraction carried by the partons coming from the photon, and $z_{I\!P}$ is the corresponding quantity carried by the partons of the pomeron. For the direct process we have $x_\gamma = 1$. The regions of the kinematic variables, in which the cross section has been measured by the H1 collaboration [7] and calculated by us, are given in Tab. 1 of [8].

The upper limit of $x_{I\!P}$ is kept small in order for the pomeron exchange to be dominant. In the experimental analysis as well as in the NLO calculations, jets are defined with the inclusive k_T-cluster algorithm with a distance parameter $d = 1$ [9] in the laboratory frame. At least two jets are required with transverse energies $E_T^{\text{jet1}} > 5$ GeV and $E_T^{\text{jet2}} > 4$ GeV. They are the leading and subleading jets with $-1 < \eta_{\text{lab}}^{\text{jet1,2}} < 2$. We have $sy = W^2 = (q + p)^2 = (p_X + p_Y)^2$. $x_{I\!P}$ is reconstructed according to

$$x_{I\!P} = \frac{\sum_X (E + p_z)}{2E_p}, \tag{4}$$

where E_p is the proton beam energy and the sum runs over all particles (jets) in the X-system. The variables x_γ and $z_{I\!P}$ are determined only from the kinematic variables of the two hard leading jets with four-momenta p^{jet1} and p^{jet2}. So,

$$x_\gamma^{\text{jets}} = \frac{\sum_{\text{jets}} (E - p_z)}{2yE_e} \ \text{and} \ z_{I\!P}^{\text{jets}} = \frac{\sum_{\text{jets}} (E + p_z)}{2x_{I\!P} E_p}. \tag{5}$$

The sum over jets runs only over the variables of the two leading jets. These definitions for x_γ and $z_{I\!P}$ are not the same as the definitions given earlier, where also the remnant jets and any additional hard jets are taken into account in the final state.

The diffractive PDFs are obtained from an analysis of the diffractive process $ep \to eXY$, which is illustrated in Fig. 1 of [8], where now Q^2 is large and the state X consists of all possible final states, which are summed. The cross section for this diffractive DIS process depends in general on five independent variables (azimuthal angle dependence neglected): Q^2, x (or β), $x_{I\!P}$, M_Y, and t. These variables are defined as before, and $x = Q^2/(2pq) = Q^2/(Q^2 + W^2) = x_{I\!P}\beta$. The system Y is not measured, and the results are integrated over $-t < 1$ GeV^2 and $M_Y < 1.6$ GeV as in the photoproduction case.

The proof of Collins [2], that QCD factorization is applicable to diffractive DIS, has the consequence that the DIS cross section for $\gamma^* p \to XY$ can be written as a convolution of a partonic cross section $\sigma_a^{\gamma^*}$, which is calculable as an expansion in the strong coupling constant α_s, with diffractive PDFs f_a^D yielding the probability distribution for a parton a in the proton under the constraint that the proton undergoes a scattering with a particular value for the squared momentum transfer t and $x_{I\!P}$. For $f_a^D(x, Q^2; x_{I\!P}, t)$ an additional assumption is made, namely that it can be written as a product of two factors, $f_{I\!P/p}(x_{I\!P}, t)$ and $f_{a/I\!P}(\beta, Q^2)$,

$$f_a^D(x, Q^2; x_{I\!P}, t) = f_{I\!P/p}(x_{I\!P}, t) f_{a/I\!P}(\beta = x/x_{I\!P}, Q^2). \tag{6}$$

$f_{I\!P/p}(x_{I\!P}, t)$ is the pomeron flux factor. It gives the probability that a pomeron with variables $x_{I\!P}$ and t couples to the proton. Its shape is controlled by Regge asymptotics and is in principle measurable by soft processes under the condition that they can be fully described by single pomeron exchange. This Regge factorization formula, first introduced by Ingelman and Schlein [10], represents the resolved pomeron model, in which the pomeron is considered as a quasi-real particle with a partonic structure given by PDFs $f_{a/I\!P}(\beta, Q^2)$. β is the longitudinal momentum fraction of the pomeron carried by the emitted parton a in the pomeron. In [1] the pomeron flux factor is assumed to have the form

$$f_{I\!P/p}(x_{I\!P}, t) = x_{I\!P}^{1-2\alpha_{I\!P}(t)} \exp(B_{I\!P} t). \tag{7}$$

$\alpha_{I\!P}(t)$ is the pomeron trajectory, $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t$, assumed to be linear in t. The values of $B_{I\!P}, \alpha_{I\!P}(0)$ and $\alpha'_{I\!P}$ are taken from [1] and have the values $B_{I\!P} = 4.6$ GeV^{-2}, $\alpha_{I\!P}(0) = 1.17$, and $\alpha'_{I\!P} = 0.26$ GeV^{-2}. Usually $f_{I\!P/p}(x_{I\!P}, t)$ as written in Eq. (7) has in addition to the dependence on $x_{I\!P}$ and t a normalization factor N. This is included into the pomeron PDFs $f_{a/I\!P}$ and thus fixed from the diffractive DIS data [1]. The diffractive DIS cross section is measured in the kinematic range $6.5 \le Q^2 \le 120$ GeV^2, $0.01 \le \beta \le 0.9$, and $10^{-4} \le x_{I\!P} < 0.05$. The PDFs of the pomeron are parameterized by a particular form in terms of Chebychev polynomials as given in [1]. For these pomeron PDFs, we used a two-dimensional fit in the variables $z_{I\!P}$ and Q^2 and then inserted the interpolated result in the cross section formula.

The cross section for the reaction $e + p \to e + 2$ jets $+ X' + Y$ can then be calculated from the well known formulæ for jet production in low Q^2 ep collisions,

$$d\sigma^D(ep \to e + 2 \text{ jets} + X' + Y) = \sum_{a,b} \int_{t_{\text{cut}}}^{t_{\min}} dt \int_{x_{I\!P}^{\min}}^{x_{I\!P}^{\max}} dx_{I\!P} \int_0^1 dz_{I\!P} \int_{y_{\min}}^{y_{\max}} dy \int_0^1 dx_\gamma$$
$$f_{\gamma/e}(y) f_{a/\gamma}(x_\gamma, M_\gamma^2) f_{I\!P/p}(x_{I\!P}, t) f_{b/I\!P}(z_{I\!P}, M_{I\!P}^2)\ d\sigma^{(n)}(ab \to \text{jets}). \tag{8}$$

y, x_γ and $z_{I\!P}$ denote the longitudinal momentum fractions of the photon in the electron, the parton a in the photon, and the parton b in the pomeron. M_γ and $M_{I\!P}$ are the factorization scales at the respective vertices, and $d\sigma^{(n)}(ab \to$ jets) is the cross section for the production of an n-parton final state from two initial partons a and b. It is calculated in LO and NLO, as are the PDFs of the photon and the pomeron. For the resolved process, PDFs of the photon are needed, for which we choose the LO and NLO versions of GRV [11].

3 Results

Here we present the comparison of the theoretical predictions in LO and NLO with the experimental data from H1 [7]. In this paper, preliminary data on cross sections differential in $x_\gamma^{\rm jets}$ and $z_{I\!P}^{\rm jets}$ for the diffractive production of two jets in the kinematic regions specified in Tab. 1 of [8] are given. These two cross sections are the only differential cross sections, which are not normalized to unity in the measured kinematic range. All other differential cross sections, namely those differential in the variables $\log_{10} x_{I\!P}$, y, $E_T^{\rm jet1}$, $M_X^{\rm jets}$, $M_{12}^{\rm jets}$, $\overline{\eta}^{\rm jets}$, and $|\Delta\eta^{\rm jets}|$, are normalized cross sections. With these latter distributions, only the shape can be used to test a possible factorization breaking in the resolved component.

Before we confronted the calculated cross sections with the experimental data, we have corrected them for hadronization effects. The calculated cross sections are the cross sections for the production of QCD jets, which consist either of one parton or a recombination of two partons according to the k_T-cluster algorithm. The experimental cross sections are measured with hadron jets constructed with the same jet algorithm. Although the difference between the two kinds of jets is not large, in particular for jets with sufficiently large E_T's, we have corrected the originally calculated cross sections with a factor $C_{\rm had}$ for the transformation from QCD jets to hadron jets. The correction factors $C_{\rm had}$ for the differential cross sections in the kinematic variables of interest are shown in Fig. 2 of [8]. Here, $C_{\rm had}$ is the ratio of the respective cross sections for hadronic jets to partonic jets. As seen in Fig. 2 of [8], $C_{\rm had}$ is approximately equal to one with deviations less than 20%. The only exception is $C_{\rm had}$ for the $x_\gamma^{\rm jets}$ cross section with values that are appreciably different from one for $x_\gamma^{\rm jets} \geq 0.6$ [12].

The differential cross sections have been calculated in LO and NLO with varying scales, where the renormalization scale and both factorization scales are set equal and are $\mu = \xi E_T^{\rm jet1}$ with ξ in the range $0.5 \leq \xi \leq 2$. This way we have a reasonable estimate of the error for the theoretical cross sections and are not in danger to base our conclusions concerning factorization breaking only on one particular scale choice. The theoretical cross sections are presented in two versions in LO and NLO. In the first version no suppression factor R is applied. It corresponds to the LO or NLO prediction with no factorization breaking, labeled $R = 1$ in the figures. The second version is with a suppression factor $R = 0.34$ in the resolved cross section, labelled $R = 0.34$ in the figures. This particular value for R is motivated by the recent work of Kaidalov et al. [13]. These authors studied the ratio of diffractive to inclusive dijet photoproduction in the HERA regime with and without including unitarity effects, which are responsible for factorization breaking, as a function of x_γ. In this study they applied a very simplified dijet production model for this ratio. From the calculations of this ratio, with and without unitarity corrections, they obtained the suppression factor $R = 0.34$ for $x_\gamma \leq 0.3$ (see Fig. 6 in Ref. [13]), which they attribute to the resolved part of the photoproduction cross section. We use this value of the suppression factor and apply it to the total resolved part in

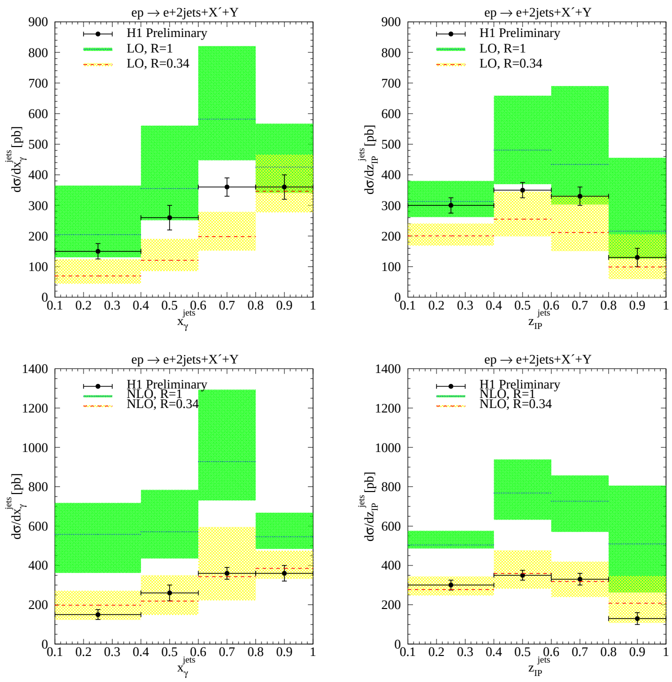

Figure 1. LO (upper) and NLO (lower) cross sections for diffractive dijet photoproduction as functions of $x_\gamma^{\rm jets}$ (left) and $z_{I\!P}^{\rm jets}$ (right), compared to preliminary H1 data. The shaded areas indicate a variation of scales by a factor of two around $E_T^{\rm jet1}$.

the LO calculation and to its NLO correction. The direct part is, in both cases, left unsuppressed ($R = 1$). Our LO (top) and NLO (bottom) results are shown in Fig. 1 for the differential cross sections in $x_\gamma^{\rm jets}$ (left) and $z_{I\!P}^{\rm jets}$ (right), which are not normalized to one. The normalized distributions in $x_\gamma^{\rm jets}$, $z_{I\!P}^{\rm jets}$, $\log_{10} x_{I\!P}$, y, $E_T^{\rm jet1}$, $M_X^{\rm jets}$, $M_{12}^{\rm jets}$, $\overline{\eta}^{\rm jets}$, and $|\Delta\eta^{\rm jets}|$ have been calculated also in LO and NLO. The results can be found in our more extended work [8].

For $d\sigma/dx_\gamma^{\rm jets}$ (Fig. 1, left), we have very different cross sections for $R = 1$ and $R = 0.34$ and for the scale choice $\xi = 1$. An exception is the highest $x_\gamma^{\rm jets}$-bin, where the difference is only 20%, since in this bin the direct contribution is dominant and the suppression factor is therefore less effective. In all the other bins, $d\sigma/dx_\gamma^{\rm jets}$ with $R = 0.34$ is reduced by this factor as expected. Except for the highest $x_\gamma^{\rm jets}$-bin, neither of the two LO calculations agrees with the data. The $R = 1$ cross section is too large and the $R = 0.34$ cross section is too small. Only when we consider the scale variation with $0.5 \leq \xi \leq 2$ as a realistic error estimate, we would conclude that the unsuppressed LO cross section ($R = 1$) is marginally consistent with the H1 data inside the experimental errors. At NLO, the conclusion is reversed: the suppressed cross section now agrees very well with the data, while the unsuppressed cross section drastically overestimates the data. For $d\sigma/dz_{I\!P}^{\rm jets}$ in Fig. 1 (right), the agreement of unsuppressed and suppressed cross sections with the data is equally marginal at LO, even within the respective error bands, while it is excellent for the suppressed NLO cross section.

4 Conclusions and Outlook

The recent measurement of diffractive dijet photoproduction combined with the analysis of diffractive inclusive DIS data in terms of diffractive PDFs offers the opportunity to test factorization in diffractive dijet photoproduction. For this purpose we have calculated several cross sections and normalized distributions for various kinematical variables in LO and NLO. Two of them are shown in this contribution and are compared with recent preliminary H1 measurements [7]. In LO we found that the measured distributions und unnormalized cross sections agree quite well with the theoretical results if, by a reasonable variation of scales, a theoretical error is taken into account. This means that in a LO comparison there is no evidence for a possible factorization breaking expected for the resolved contribution. However, it is well known that for dijet photoproduction NLO corrections are very important for the direct and in particular for the resolved contributions to the cross section. Indeed, the theoretical results at NLO disagree with the data for unnormalized cross sections like $d\sigma/dx_\gamma^{\rm jets}$ and $d\sigma/dz_{I\!P}^{\rm jets}$. Agreement between data and theoretical results is found, however, if the resolved contribution is suppressed by a factor $R = 0.34$. Since NLO results are more trustworthy than any LO cross section calculations, we consider our findings a strong indication that factorization breaking occurs in diffractive dijet photoproduction with a rate of suppression expected from theoretical models.

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