Evidence for Factorization Breaking in Diffractive Low- Q^2 Dijet Production

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We calculate diffractive dijet production in deep-inelastic scattering at next-to-leading order of perturbative QCD, including contributions from direct and resolved photons, and compare our predictions to preliminary data from the H1 Collaboration at DESY HERA. In contrast to recent experimental claims, evidence for factorization breaking is found only for resolved, and not direct, photon contributions. No evidence is found for large normalization uncertainties in diffractive parton densities. The results confirm theoretical expectations for the (non)cancellation of soft singularities in diffractive scattering as well as previous results for (almost) real photoproduction.

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At current high-energy colliders such as the DESY ep collider HERA and the Fermilab Tevatron, diffractive processes are known to constitute an important fraction of all scattering events. These events are defined experimentally by the presence of a forward-going hadronic system Y with four-momentum p_Y , low mass M_Y (typically a proton that has remained intact), small four-momentum transfer $t = (p - p_Y)^2$, and small longitudinal momentum transfer $x_{IP} = q(p - p_Y)/(qp)$ from the incoming proton with four-momentum p to the central hadronic system X (see Fig. 1). The presence of a hard scale, such as the squared photon virtuality $Q^2 = -q^2$ in deep-inelastic scattering (DIS) or large transverse jet momenta $p_{T,\text{jet}1,2}$ in the photon-proton center-of-momentum frame, should then allow for calculations of partonic cross sections for the central system X using perturbative QCD.

The question of whether diffractive cross sections are factorizable, like inclusive cross sections, into universal, diffractive parton densities f_i^D and partonic cross sections σ_{γ^*i} ,

$$\frac{d^2\sigma}{dx_{IP}dt} = \int_x^{x_{IP}} d\xi f_i^D(\xi, Q^2, x_{IP}, t) \sigma_{\gamma^*i}(x, Q^2, \xi), \quad (1)$$

is at the heart of the current debate in diffractive physics and may even affect the prospects for the discovery of new particles such as the Higgs boson at the LHC [1,2].

For DIS processes, factorization has indeed been proven to hold [3], and diffractive parton densities have been extracted from HERA data at low and intermediate Q^2 [4–6]. However, factorization breaks down for processes with two initial-state hadrons, where not all singularities from soft gluon exchange cancel [3] and initial-state rescattering effects become important [7]. At the

Tevatron, this leads to a suppression of the expected dijet rate by about a factor of 10 [8].

Processes with (almost) real photons are unique in the respect that they involve direct interactions of the photon with partons from the proton as well as resolved photon contributions leading to parton-parton interactions (for a recent review, see [9]). As in the case of DIS, factorization should hold for direct photoproduction, whereas it is expected to fail for the hadronlike resolved processes. A two-channel eikonal model using vector-meson dominated photon fluctuations predicts a suppression by about a factor of 3 for resolved photoproduction at HERA [10]. This suppression factor has recently been applied to diffractive dijet production [11,12] and compared to preliminary data from H1 [13] and ZEUS [14]. While at leading

FIG. 1. Diffractive scattering process $ep \rightarrow eXY$, where the hadronic systems X and Y are separated by the largest rapidity gap in the final state.

order (LO) of perturbative QCD no suppression of the resolved contribution seems necessary, next-to-leading order (NLO) corrections, calculated previously for inclusive direct [15] and resolved [16] dijet photoproduction, increase the cross sections significantly [11,12] and require indeed a suppression factor, showing that factorization breaking occurs at this order for *resolved* photoproduction.

Although a suppression factor is clearly not required theoretically for *direct* photoproduction, the H1 [13] and ZEUS [14] Collaborations have recently shown their data to be consistent with a *global* suppression of about a factor of 2 for direct *and* resolved NLO QCD predictions, claiming evidence for factorization breaking also in *direct* photoproduction [13] and citing uncertainties from diffractive parton densities [14]. These claims were based on the observation that the measured distributions in the observed photon momentum fraction x_γ^{obs} and in the kinematically related variable y were better described by a global than by a resolved-only suppression factor. However, these variables are known to be subject to large hadronization corrections at small p_T^* [17]. In fact, a global suppression factor underestimates the data at large p_T^* , where direct photoproduction dominates [13].

Obviously, these contradicting theoretical and experimental interpretations require clarification from an independent physical analysis. A particularly suitable physical process is low- Q^2 electroproduction of dijets, i.e., the transition region of (almost) real photoproduction to DIS. Resolved processes are known to continue to be important at low, but finite Q^2 , where the perturbative quark-antiquark splitting induces large higher order QCD corrections that have to be resummed due to the presence of a large mass logarithm. Consequently, any possible suppression for resolved photons should show up only at low, but not high, Q^2 , whereas a global suppression should be visible for *all* Q^2 .

A consistent factorization scheme for virtual photoproduction has been defined and the full (direct and resolved) NLO corrections for inclusive dijet production have been calculated in [18]. In this Letter, we therefore adapt our *inclusive* NLO calculation to *diffractive* dijet production at low Q^2 and compare our predictions with the corresponding data from H1 [19] in order to study the turn-on of factorization breaking as the photon virtuality decreases from the DIS to the photoproduction region. For this purpose, integrations over the additional diffractive variables t and x_{IP} and the kinematics corresponding to the H1 experiment have been implemented in the NLO Monte Carlo program JETVIP [20]. In particular, we use an electron and proton beam energy of 27.5 and 820 GeV, respectively, as well as the following kinematical ranges: $4 < Q^2 < 80 \text{ GeV}^2$, electron momentum transfer $0.1 < y < 0.7$, $x_{IP} < 0.05$, $|t| < 1 \text{ GeV}^2$, $M_Y < 1.6 \text{ GeV}$, $p_{T,\text{jets}}^* > 5(4) \text{ GeV}$, and jet rapidities $-3 < \eta_{\text{jets}}^* < 0$.

Jets are defined by the Collider Detector at Fermilab (CDF) cone algorithm with jet radius $R = 1$.

While the original H1 analysis used a symmetric cut of 4 GeV on the transverse momentum of both jets [24], asymmetric cuts are required for infrared-stable comparisons to NLO calculations [25]. The data have therefore been reanalyzed for asymmetric cuts [19], using the LO Monte Carlo program RAPGAP [26], and compared to a NLO calculation for diffractive dijet production in DIS [27]. In the extraction of the diffractive parton densities, the usual Regge factorization formula [29]

$$f_i^D(\xi, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) f_{i/IP}(\xi/x_{IP}, Q^2) \quad (2)$$

has been employed. For our LO and NLO resolved virtual photon predictions, we have used the parton densities SaSID [30] at the fixed factorization scale 40 GeV^2 and transformed them from the DISy to the modified minimal subtraction ($\overline{\text{MS}}$) scheme [18].

We now turn to our numerical results. The dependence of the diffractive dijet cross section at HERA on the squared photon virtuality Q^2 is shown in Fig. 2, where the preliminary H1 data [19] are compared with our theoretical predictions for DIS at LO (dot-dashed lines) and NLO (dotted lines) as well as NLO predictions including resolved virtual photon contributions with (solid lines) and without (dashed lines) a suppression factor of

FIG. 2. Dependence of the diffractive dijet cross section at HERA on the squared photon virtuality Q^2 . Preliminary H1 data [19] are compared with theoretical predictions for DIS at LO (dot-dashed lines) and NLO (dotted lines) and NLO predictions including resolved virtual photon contributions with (solid lines) and without (dashed lines) a suppression factor of $R = 0.34$.

FIG. 3. Dependence of the diffractive dijet cross section at HERA on the parton momentum fraction in the pomeron z_{IP}^{jets} for different ranges of $Q^2 + p_T^{*2}$. Preliminary H1 data [19] are compared with various theoretical predictions (see Fig. 2).

$R = 0.34$. The LO and NLO DIS results agree with those obtained in [27], and the latter describe the data well in the high- Q^2 region, where direct contributions should be sufficient. As expected, the resolved virtual photon contributions increase the theoretical predictions. They improve the description of the data at low Q^2 , but only if they are suppressed by the same factor of $R = 0.34$ observed previously for (almost) real photoproduction [11,12]. Note that the absolute normalization is now fixed for all Q^2 in a single experiment, showing that neither factorization breaking in the direct contributions nor large uncertainties from diffractive parton densities are present. In particular, a common suppression factor of 2 for the direct *and* resolved contributions would underestimate the data at all Q^2 . Furthermore, the presence of the large scale Q^2 in addition to the relatively small scale p_T^* leads to negligible hadronization corrections [19].

Further evidence for the turn-on of factorization breaking in the transition of high- to low- Q^2 diffractive dijet production can be derived from Fig. 3, where the dependence of the cross section on the longitudinal momentum fraction of the partons in the pomeron z_{IP} is shown for different ranges of $Q^2 + p_T^{*2}$. Concentrating on the low- z_{IP} regions, we find that the NLO DIS predictions underestimate the data and need to be supplemented at low $Q^2 + p_T^{*2}$ by resolved virtual photon contributions, which must again be suppressed by a factor of $R = 0.34$ in order for the predictions not to overestimate the data. As expected, the resolved contributions become less im-

portant at high $Q^2 + p_T^{*2}$, where the direct and total NLO calculations become very similar and describe the data almost equally well. The LO DIS prediction underestimates the data everywhere except at high Q^2 and z_{IP} , where consequently all NLO predictions overestimate the data. In this region, the agreement at NLO improves considerably, if hadronization corrections are taken into account [19].

In summary, we have presented a NLO analysis of diffractive dijet production in low- Q^2 DIS. Contributions from direct and resolved photons have been superimposed and compared with recent preliminary data from the H1 Collaboration at HERA. In contrast to experimental claims, evidence for factorization breaking is found only for resolved, and not direct, photon contributions, and no evidence is found for large normalization uncertainties in the diffractive parton densities. The results confirm theoretical expectations for factorization and its breaking in photon-hadron and hadron-hadron scattering as well as previous results for almost real photoproduction.

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