Factorisation issues in diffraction

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The high centre-of-mass energies of the HERA *ep* collider and of the Tevatron collider allow us to study the diffractive interactions in the presence of a hard scale and to describe them in terms of perturbative QCD. In QCD, the diffractive exchange is described in terms of partons, and the factorisation theorem states that the cross section for hard interactions can be expressed as convolution of universal diffractive parton distribution functions and process-dependent coefficients, perturbatively calculable. The recent experimental data from the H1 and ZEUS Collaborations at HERA are presented for diffractive dijet and D^* meson production, in both deep-inelastic scattering (DIS) and the photoproduction regimes and are compared to next-to-leading order QCD predictions using diffractive parton distributions. While good agreement is found for dijets in DIS and for D^* production in both DIS and photoproduction, the dijet photoproduction data are overestimated by NLO predictions at lower transverse momentum of the jets, indicating the breaking of QCD factorisation.

1. Introduction

Significant progress has been achieved over the last decade in understanding of diffractive phenomena at high energies in the light of measurements of hard diffractive processes at HERA. These processes, schematically represented in Figure 1, are identified experimentally by the presence of a final proton, tagged in the detectors at small angle, or by a large gap in rapidity between the system X of the outgoing hadrons and the proton remnant Y. In QCD, the probability to have no parton emission filling this rapidity gap is exponentially suppressed. The origin of these events is then due to a colourless exchange, referred to as Pomeron.

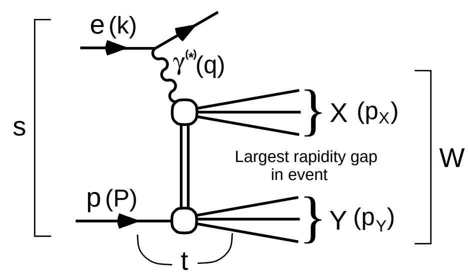

Figure 1. Illustration of the generic diffractive process $ep \to eXY$. The systems X and Y are separated by the largest gap in the rapidity distribution of the final state hadrons.

The variables used to describe the kinematics of inclusive diffractive events are the photon virtuality Q^2, the squared momentum transfer at the proton vertex $t = (P - p_Y)^2$, the fraction of longitudinal momentum transfer from the incoming proton to the system X, $x_{I\!P} = q(P - p_Y)/qP$ and the fraction of the exchanged momentum participating in the scattering with the photon, $\beta = x_{Bj}/x_{I\!P}$, where $x_{Bj} = Q^2/(2P \cdot q)$ is the Bjorken variable.

The central problem in hard diffraction is the question of the validity of *QCD factorisation.* In diffractive deep-inelastic scattering (DIS), the presence of a hard scale as, for example, the photon virtuality Q^2, the large transverse jet momentum in the photon-proton centre-of-mass frame or the heavy-quark mass, ensures the validity of the QCD factorisation theorem. It allows the cross sections to be calculated as convolution of the the partonic cross sections $\sigma^{\gamma^* i}$ and the universal diffractive parton densities functions (DPDFs) $f_i^D(x_{I\!P}, t, x, Q^2)$, which can be interpreted as the parton probability distribution in the proton conditional on the observation of a diffractive proton in the final state with a given t and $x_{I\!P}$:

$$\sigma^D(\gamma^* p \to Xp) \propto \sum_i f_i^D(x_{I\!P}, t, x, Q^2) \otimes \sigma^{\gamma^* i}(x, Q^2)$$

For diffractive DIS the QCD factorisation [1–4] has been proven by Collins [4], while it is expected to break down for hard processes in diffractive hadron-hadron scattering, due to rescattering of hadronic remnants (see e.g. [1]). These interactions occur in both the initial and final state and destroy the rapidity gap. A 'gap survival probability' factor must therefore be included in diffractive hadron-hadron scattering cross section calculations based on DPDFs. Factorisation breaking has been observed in $p\bar{p}$ collisions at the Tevatron: predictions using the DPDFs determined at HERA (as described in Section 3) overestimate the diffractive dijet cross sections measured by CDF by up to an order of magnitude [5]. All diffractive processes at the LHC are affected by rescattering of hadronic remnants, with survival probabilities estimated to be no more than a few percent [6]. Understanding of the detailed physics of gap destruction is thus vital to the preparations for diffractive studies at the LHC.

QCD factorisation can be further tested at HERA in diffractive photoproduction ($Q^2 \sim 0$) of dijets or D^* mesons. In these processes the validity of pQCD is ensured by the hard scale provided by the jet transverse energy or by the mass of c-quark. Processes in which the photon participates directly in the hard scattering are expected to be similar to the deep-inelastic scattering of highly virtual photons ('point-like' or 'direct' photon, see Figure 2a). In contrast, processes in which the photon is resolved into partons which participate in the hard scattering ('resolved' photon, see Figure 2b) resemble hadron-hadron scattering. In resolved photoproduction rescattering of the photon remnant may lead to breaking of QCD factorisation. A suppression by about a factor of three for resolved photoproduction at HERA is predicted [7]. In QCD, the direct and the resolved processes are unambiguously distinguished only in leading order (LO). In next-to-leading order (NLO) these two processes are related, and the separation depends on the factorisation scheme and scale. Experimentally, a rough separation of the direct and the resolved processes can be made via the x_γ variable, an estimator of the fraction of the photon energy participating in the hard scattering.

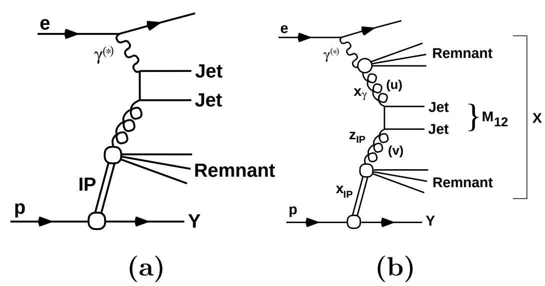

Figure 2. Leading order diagrams for diffractive dijet production at HERA. (a) direct (point-like) processes, (b) resolved (hadron-like) photon process.

In addition, it is important to test the conjecture of *Regge (proton vertex) factorisation*, which assumes that the DPDF can be expressed as a product of the Pomeron flux and the Pomeron structure function [8]:

$$f_i^D(x_{I\!P}, t, x, Q^2) = f_{I\!P/p}(x_{I\!P}, t) f_i^{I\!P}(\beta = \frac{x}{x_{I\!P}}, Q^2) \, .$$

In this report both the hard QCD and the Regge factorisation hypothesis are confronted with the recent HERA data.

2. Test of Regge factorisation in inclusive diffraction

One of the basic predictions of the Regge model is a specific asymptotic behavior of the total, elastic and diffractive cross sections with energy, which is controlled by the value of the intercept of the universal Pomeron trajectory, $\alpha_{I\!P}(t)$ at $t = 0$. If Regge factorisation holds, the Pomeron flux, parameterised as $f_{I\!P/p}(x_{I\!P}, t) \propto x_{I\!P}^{1-2\alpha_{I\!P}(t)} e^{bt}$, should not depend on β and Q^2.

Figure 3 shows the Q^2 dependence of the diffractive structure function $x_{I\!P} F_2^{D(3)}$ (defined in section 3) for fixed β and $x_{I\!P}$, measured by ZEUS [9]. It can be seen that for a fixed bin of β, the shape of the Q^2 distribution shows a dependence on the value of $x_{I\!P}$. This observation contradicts the assumption of Regge factorisation.

On the other hand, no indication of Regge factorisation breaking is observed using H1 data [10].

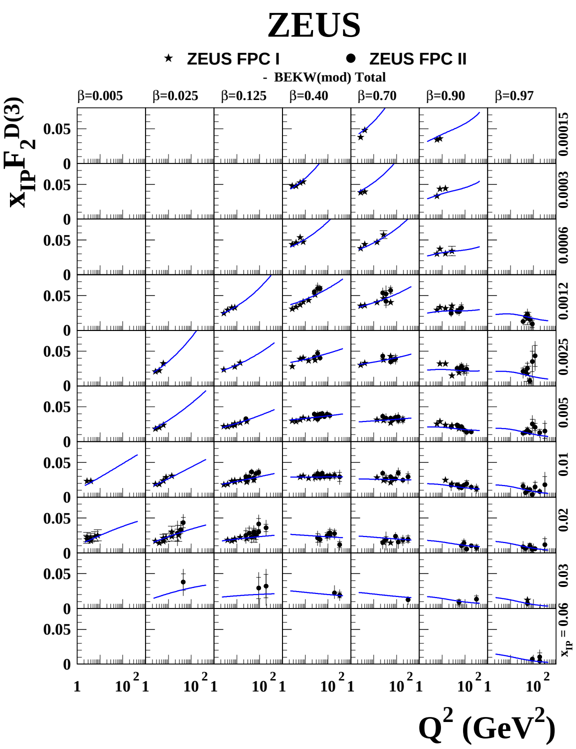

Figure 3. The diffractive structure function of the proton, $x_{I\!P}F_2^{D(3)}$, as a function of Q^2 for different regions of β and $x_{I\!P}$ from the ZEUS data [9].

3. Partonic structure of the diffractive exchange

Diffractive PDFs have been determined at HERA from high-precision measurements of the inclusive diffractive DIS processes [5,9,11–14]. In analogy with non-diffractive DIS scattering, the cross section for neutral current events is proportional to the diffractive structure function $F_2^{D(4)}(Q^2, x_{I\!P}, \beta, t)$, neglecting the longitudinal contribution:

$$\frac{d^4\sigma(ep \to eXp)}{dQ^2 dx_{I\!P} d\beta dt} = \frac{4\pi\alpha^2}{\beta Q^4}(1 - y + \frac{y^2}{2}) \cdot F_2^{D(4)}(Q^2, x_{I\!P}, \beta, t),$$

where $y = Q^2/(s \cdot x_{Bj})$ is the inelasticity variable. Assuming factorisation of the proton vertex, the diffractive structure function is written as the product of the Pomeron flux factor $f_{I\!P/p}(x_{I\!P}, t)$ and the Pomeron structure function $F_2^{I\!P}(\beta, Q^2)$

$$F_2^{D(4)}(Q^2, x_{I\!P}, \beta, t) = f_{I\!P/p}(x_{I\!P}, t) \times F_2^{I\!P}(\beta, Q^2)$$

This assumption is a useful approximation. As discussed in section 2, a violation of Regge factorisation is observed in ZEUS data [9]. The fits to inclusive diffractive cross sections, described below, are however insensitive to this mild breaking.

When the scattered proton is not detected, the t-integrated diffractive structure function $F_2^{D(3)}$ is obtained via:

$$\frac{d^3\sigma(ep \to eXp)}{dQ^2 dx_{I\!P} d\beta} = \frac{4\pi\alpha^2}{\beta Q^4}(1 - y + \frac{y^2}{2}) \cdot F_2^{D(3)}(Q^2, x_{I\!P}, \beta)$$

By analogy to the proton structure function F_2, the partonic distributions of the diffractive exchange are extracted from the Q^2 evolution of diffractive structure function F_2^D. The gluon and singlet quark density are parameterised as a function of z, the Pomeron momentum fraction carried by the parton entering the hard interaction, at starting scale of $Q_0^2 = 2$ GeV^2. They are evolved in Q^2 using the DGLAP equations and are fitted to the data [5].

The diffractive quark and gluon densities at low to moderate z are well constrained from the inclusive cross sections alone. However, the sensitivity to the gluon density from the inclusive process is lost at large z, which is among the most important regions for LHC studies. The lack of a constraint on the high z gluon density is reflected e.g. in two different solutions of the DGLAP QCD fit to H1 data, 'H1 2006 fit A' and 'H1 2006 fit B', which differ only in the parameterisations of the gluon density at the starting scale (see Fig.10). Other available sets of parameterisations of DPDFs, which are also used in the comparisons in this report, are 'MRW' [15], obtained from the fit to H1 data from [5], and 'ZEUS LPS+charm fit' from the combined fit to ZEUS leading proton spectrometer and $F_2^{D,charm}$ data [11].

Production of hadronic final states in diffractive interactions, e.g. open charm and dijet production, are directly sensitive to the diffractive gluon density via the boson-gluon fusion process $\gamma^* g \to q\bar{q}$. These measurements not only help to test the existing parameterisations, but also provide an additional constraint on the gluon density, in particular, at large z.

4. Diffractive D^* meson production in DIS and Photoproduction

The diffractive production of open charm has been studied by the H1 and ZEUS Collaborations [16–18]. The charm quark was tagged by the reconstruction of $D^*(2010)$ mesons in the DIS and photoproduction regimes. The H1 Collaboration used also the method based on the measurement of the displacement of tracks from the primary vertex.

The measurements are compared with NLO QCD predictions using the DPDFs extracted from the fits to the diffractive DIS cross sections from H1 and ZEUS. The calculations are performed using HVQDIS [19] for DIS and FMNR [20] for photoproduction. If QCD factorisation is valid, these calculations should be able to predict the production rates of open charm production in shape and normalisation.

In Figure 4 the cross sections are shown as functions of $x_{I\!P}$, β, $\eta(D^*)$ and $p_T(D^*)$ in DIS. As seen from the figure, the NLO QCD calculations provide a good description of the measurements within the experimental and theoretical uncertainties. In Figure 5 results of the measurements of diffractive D^* meson production in photoproduction are shown. As in the DIS case, there

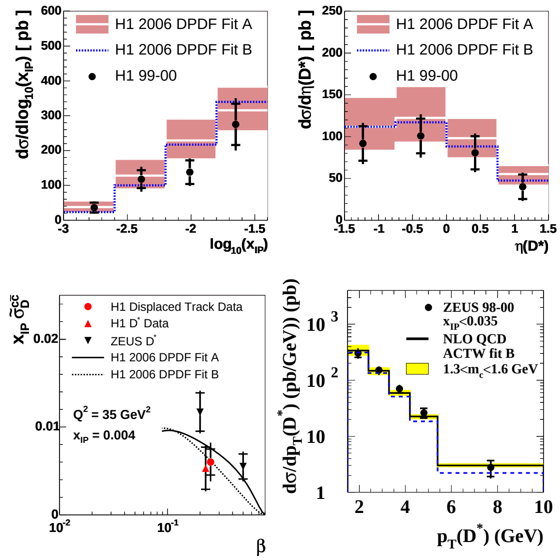

Figure 4. Differential cross sections for diffractive D^* meson production in DIS [16,17].

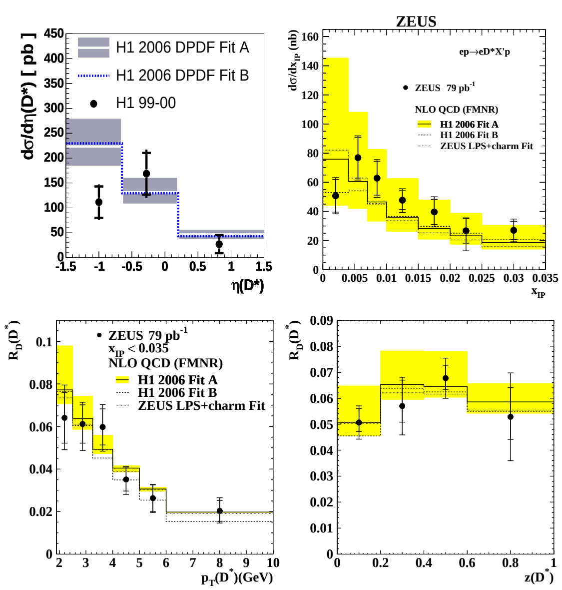

Figure 5. Differential cross sections for diffractive D^* meson photoproduction (upper plots) as well as the ratios of diffractive to inclusive D^* production (lower plots) [16,18].

is fair agreement between the measurements and the calculations. The two lower plots of Figure 5 show the ratio of diffractive to inclusive D^* production cross sections. The average value of this ratio is $R_D = 5.7 \pm 0.5\%$. This number is in good agreement with the values obtained from the NLO QCD calculations using the H1 2006 fit B (5.7%) or the ZEUS LPS+charm fit (5.8%).

Thus, the NLO calculations provide a satisfactory description of diffractive D^* meson data, both in DIS and photoproduction, supporting the validity of QCD factorisation.

5. Diffractive jet production in DIS

Diffractive jet production in DIS has been studied by both the H1 and ZEUS Collaborations [21–23]. The kinematic range of the photon virtuality is $4 < Q^2 < 80$ GeV^2 for the H1 and $5 < Q^2 < 100$ GeV^2 for the ZEUS analyses. Diffractive events are selected by requiring a large rapidity gap, and the jets are identified using the longitudinally invariant inclusive k_T clustering algorithm in the photon-proton rest frame. The transverse energies for the two must energetic jets are required to be $E_{T,1}^{jet} > 5$ GeV and $E_{T,2}^{jet} > 4$ GeV, respectively.

The experimental results are compared to the NLO predictions obtained with the DISENT [24] and NLOJET++ [25] codes using different sets of DPDFs described in section 3.

The cross sections measured by H1 and ZEUS are shown in Figures 6 and 7, respectively. In general, the shapes of the measured cross sections are described by the NLO calculations within the theoretical uncertainties (shown as bands), except at high value of $z_{I\!P}$, an estimator of the fraction of the momentum of the diffractive exchange carried by the parton participating in the hard scattering. These results support the validity of QCD factorisation for diffractive dijet production in DIS within uncertainties.

The diffractive dijet data are sensitive to the choice of diffractive PDFs used in NLO QCD calculations. Best agreements are obtained by the predictions using the DPDFs from the H1 2006 fit B and MRW 2006, the latter DPDFs have a somewhat lower gluon component. This is also

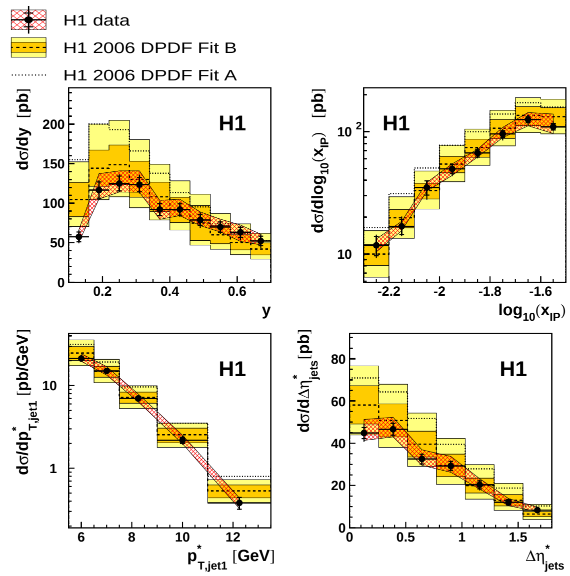

Figure 6. Differential cross sections of diffractive dijet production in DIS measured by H1 [21]. NLO predictions for several parameterisations of DPDFs are compared to the measurements.

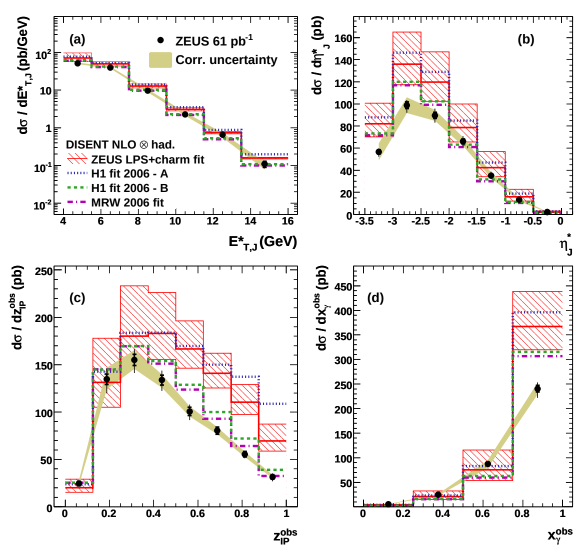

Figure 7. Differential cross sections of diffractive dijet production in DIS measured by ZEUS [23]. NLO predictions for several parameterisations of DPDFs are compared to the measurements.

demonstrated in Figure 8, where the cross section is shown a function of $z_{I\!P}$ and is compared separately with calculations using the H1 2006 fit A and the H1 2006 fit B. In [22] the diffrac-

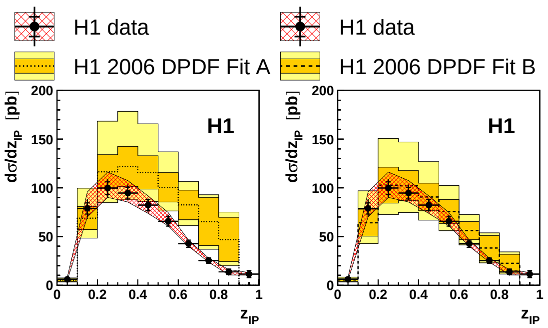

Figure 8. Differential cross sections of diffractive production of dijets in DIS as measured by H1 as function of $z_{I\!P}$ [21]. NLO predictions using DPDFs from the H1 2006 fit A and the H1 2006 fit B are compared to the measurements. The shaded bands show the uncertainty resulting from a variation of the renormalisation scale.

tive dijet cross sections have been used together with the inclusive diffractive cross sections [5] in a combined NLO QCD fit. The result of the combined fit, referred to as 'H1 2007 Jets DPDF', is compared to the diffractive dijet data in Figure 9. This DPDF is able to describe well both the dijet and inclusive diffractive DIS data. The diffractive gluon and singlet quark distributions from the H1 2007 Jets DPDF are shown in Figure 10 together with the respective distributions from the H1 2006 fit A and the H1 2006 fit B [5]. The gluon and quark components are determined with good accuracy over the whole phase space, in particular in the range $0.05 < z_{I\!P} < 0.9$.

6. Diffractive jet photoproduction

The diffractive photoproduction of dijets was analysed by both the H1 and ZEUS Collaborations [21,26,27]. The jet kinematic range of the H1 measurements is identical to the DIS measurements, i.e. $E_{T,1}^{jet} > 5$ GeV and $E_{T,2}^{jet} > 4$ GeV,

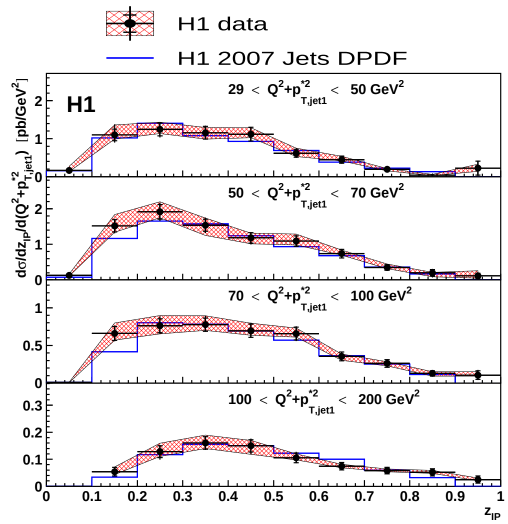

Figure 9. Cross sections for diffractive dijet production, doubly differential in $z_{I\!P}$ and $Q^2+p_{T,jet}^{*2}$. The solid line shows the NLO QCD predictions based on the H1 2007 Jets DPDF [21].

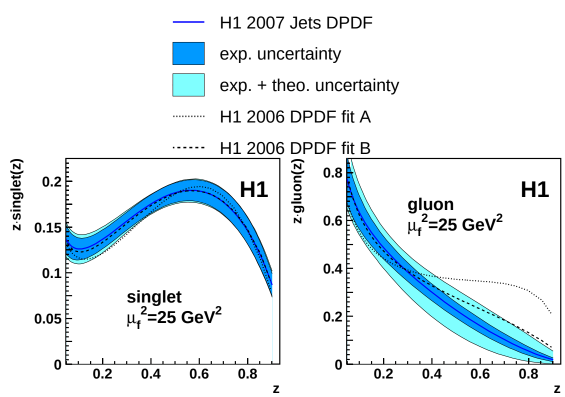

Figure 10. The diffractive quark and gluon densities for the factorisation scale $\mu_f = 5$ GeV [21]. The solid line indicates the H1 2007 Jets DPDF, surrounded by bands indicating the experimental and theoretical uncertainties added in quadrature. The dotted and dashed lines show the parton densities corresponding to the H1 2006 fit A and H1 2006 fit B, respectively.

while the ZEUS analysis required higher jet energies: $E_{T,1}^{jet} > 7.5$ GeV and $E_{T,2}^{jet} > 6.5$ GeV. Jets are identified using the inclusive k_T clustering algorithm in the laboratory frame.

The cross sections as function of $z_{I\!P}$ and x_γ as measured by H1 are shown in Figure 11. The

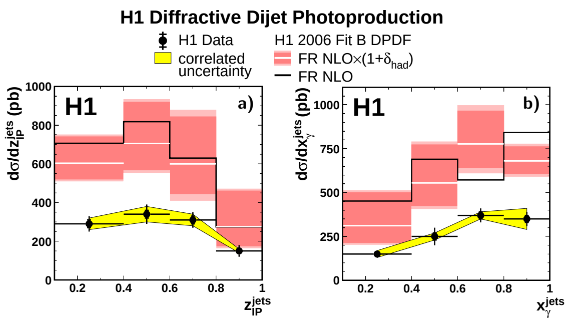

Figure 11. Differential cross sections for the diffractive photoproduction of dijets as function of $z_{I\!P}^{jets}$ and x_γ^{jets} measured by H1 [22]. The NLO predictions of the Frixione et al. program, interfaced to the H1 2006 Fit B DPDFs, are also shown. The shaded bands show the uncertainty resulting from a variation of the renormalisation scale.

cross sections measured as function of x_γ by ZEUS are presented in Figure 12. The measurements are compared with NLO QCD predictions using several parameterisations of DPDFs and photon PDFs. Two different QCD calculations have been used, by Frixione and Ridolfi [28] and by Klasen and Kramer [29]. Both calculations lead to identical results. The NLO predictions have large uncertainties due to different DPDFs and due to the uncertainties in the renormalisation and factorisation scales. Their predictions are generally able to describe the shape of the distributions. The NLO calculations are $\sim$ 10–20% higher but still compatible with the ZEUS data (Figure 12). However, in order to describe the H1 measurements, the NLO QCD predictions need to be downscaled by a global factor of 0.5, as seen from Figure 11. Both experiments observe that the approach of only suppressing the

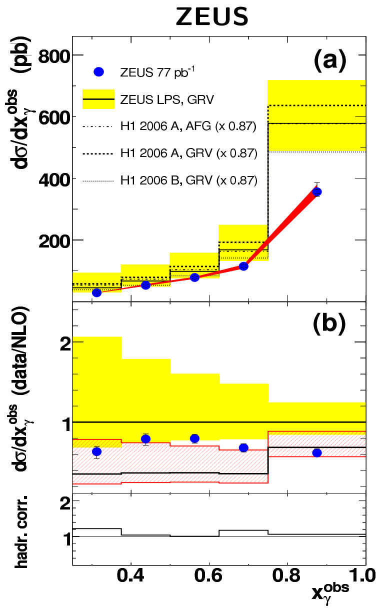

Figure 12. Differential cross sections as a function of x_γ compared with NLO QCD predictions using the DPDFs from the ZEUS LPS+charm fit, the H1 2006 fit A and the H1 2006 fit B [26]. The lower plot shows the ratio of data and NLO predictions using the ZEUS LPS+charm fit. The histogram indicates the theory expectation with the resolved photon component scaled down by a factor of 0.34. The shaded and hatched bands show the theoretical uncertainty.

resolved photon part of the cross section ($x_\gamma \lesssim 0.8$) is clearly disfavored by the data in contradiction with the theoretical expectation of [7]. This can be seen from the lower plot of Figure 12, where the NLO expectations are shown with the predicted resolved photon component scaled down by a factor of 0.34, according to [7].

The different conclusions of both experiments on the size of the suppression factor initiated detailed investigations. As a possible reason for this apparent contradiction the difference in the kinematic region (E_T^{jet} range) of both measurements was suggested. In this case the suppression may depend on E_T^{jet}. Indeed, the double ratio of data cross sections to NLO predictions for diffractive photoproduction and DIS as a function of transverse momentum E_T of the leading jet as measured by H1 (upper plot of Figure 13) and the ratio of the ZEUS data cross sections to the NLO predictions (lower plot of Figure 13), indicate a rise with increasing E_T^{jet}.

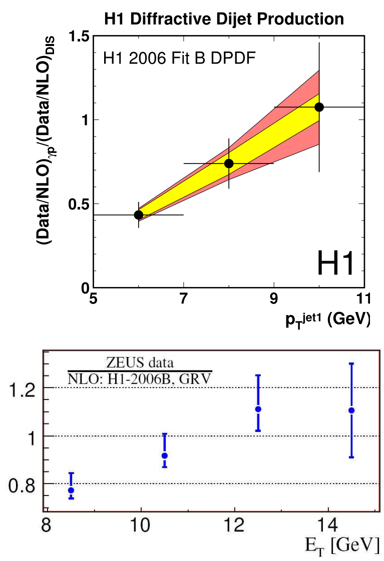

Figure 13. (Upper plot) Double ratio of cross sections for data to NLO predictions for photoproduction and DIS as a function of transverse momentum of the leading jet measured by H1 (plot derived from [22]); (lower plot) ratio of cross sections of data to NLO predictions for the diffractive photoproduction of dijets vs E_T of the leading jet as measured by ZEUS [30].

A detailed study of this issue was performed in the new H1 analysis of dijets in photoproduction [27], in which two E_T^{jet} cut schemes were applied. The first scheme is identical to [21] with $E_{T,1} > 5$ GeV, to crosscheck the result of the previous analysis. The second scheme applies cuts similar to the ones used by ZEUS [26], in particular $E_{T,1}^{jet} > 7.5$ GeV, to check for a possible dependence of the suppression of the cross section on the E_T of the jets. In Figure 14 the results are compared to NLO calculations using three H1

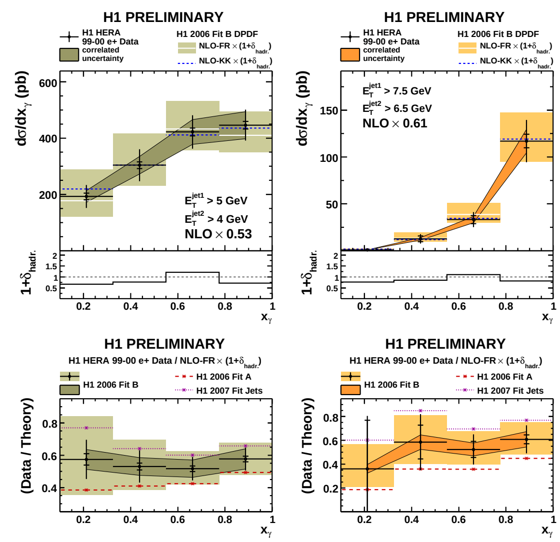

Figure 14. Differential cross sections for the diffractive photoproduction of dijets as a function of x_γ for the lower E_T cut scenario (left side plot) and higher E_T cut scenario (right side plot), as measured by H1 [27] and compared with NLO calculations.

DPDF fits: H1 2006 fit A, H1 2006 fit B and H1 2007 Jets. The best agreement of the shapes of measured cross sections was obtained with NLO predictions using H1 2006 fit B scaled by a factor of $0.53 \pm 0.01(\text{stat.}) \pm 0.10(\text{syst.}) \pm 0.14(\text{scale unc.})$ for the low E_T cut scenario, and by a factor of $0.61 \pm 0.03(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.16(\text{scale unc.})$ for the high E_T cut scenario. With the higher E_T^{jet} cut the H1 data requires less suppression, i.e. it is closer to the ZEUS result obtained in this E_T range (with suppression factor of ~ 0.8).

The data show no evidence for a suppression as a function of x_γ. In the H1 analysis [27] the comparison is made with NLO predictions for which only resolved part was suppressed by a factor of 0.3 [7]. Also with this suppression scheme the measured distributions can be reasonably well described, both for the lower and the higher E_T cut scenario. However, this leads to a much worse description of the x_γ distribution, in particular the NLO prediction clearly underestimates the data at lower x_γ and overestimates them at $x_\gamma > 0.8$. This result is in qualitative agreement with the theoretical analysis of [29]. Thus, the suppression of the resolved component only is not favoured by data.

7. Dijet production with leading neutrons

Factorisation breaking is expected not only in the diffractive region, where the momentum fraction transferred to the exchanged particle in the t channel $x_{I\!P} \ll 1$, but also for events with larger values of $x_{I\!P}$, where Regge exchanges other than the Pomeron occur at the proton vertex. It is expected also for events with a transition $p \to n$, dominated by pion exchange (see diagram in Figure 15). Dijet photoproduction with a leading neutron $\gamma p \to jet + jet + n + X$ has been investigated to test factorisation breaking [31]. In these events soft rescattering is expected between the photon remnant and the neutron reducing the normalisation of the cross section.

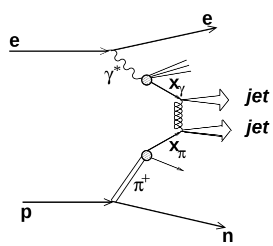

Figure 15. Generic Feynman diagram for the production of two jets in the one-pion exchange model.

The NLO QCD calculations [31] for dijet production with a final state forward neutron are compared with the measured cross sections in both the DIS and photoproduction regimes [32]. In this analysis jets are identified using the cone algorithm and are selected by requiring $E^{jet}_{T,1(2)} > 7$ (6) GeV. In the pion exchange model, the cross section for leading neutron production is the product of the non-perturbative pion flux factor, describing the splitting function of a proton into a pion and a neutron, and the parton distribution function of the pion. In [31] the pion flux normalisation factor for the dijet photoproduction cross section was determined from the measurement of the DIS dijet cross section, where no absorptive interactions is expected. Figure 16 shows the cross sections for neutron-tagged dijet production in DIS and in photoproduction as a function of jet pseudorapidity. There is good agreement between the NLO calculation and the measured cross sections in the DIS regime. On the other hand, the NLO calculation can describe the photoproduction measurement only after suppressing the resolved photon contribution by a factor of 0.48, or after suppressing both the direct and resolved components by 0.64.

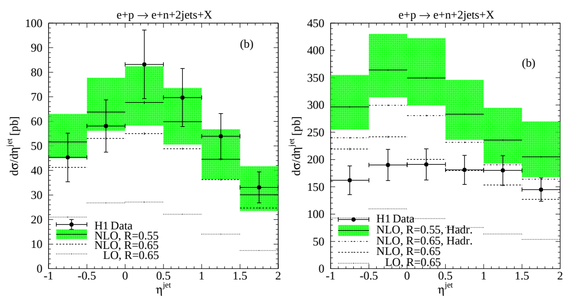

Figure 16. Differential cross sections for dijet production with a leading neutron in DIS (left) and photoproduction (right). The H1 measurement [32] is compared to perturbative QCD predictions in LO and NLO [31].

8. Conclusions

Diffractive processes have been extensively studied in ep interactions at HERA, and the validity of the QCD factorisation theorem has been investigated. NLO predictions using the diffractive PDFs measured in inclusive diffraction successfully describe diffractive dijet and charm production in DIS, as well as charm photoproduction. In diffractive dijet photoproduction the situation is much less clear. The dijet photoproduction data are overestimated by NLO predictions at lower transverse momentum of the jets, indicating the breaking of QCD factorisation. Contrary to the theoretical expectations, no suppression is observed for the resolved component of the photon with respect to the direct component, while there is an indication of the dependence of the suppression factor on the transverse momenta of the jets. Similar suppression is also observed for dijet photoproduction with leading neutrons.

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