Diffractive Final States and Factorisation at HERA

W. Słomiński[a] *and Alice Valkárová*[b]
[a]M. Smoluchowski Institute of Physics, Jagellonian University, Kraków,
[b]Institute of Particle and Nuclear Physics, Faculty of Mathematics and Physics, Charles University, Praha

Abstract
The recent experimental data from the H1 and ZEUS collaborations at HERA collider for diffractive dijet production and open charm production in deep inelastic scattering and photoproduction are presented and compared to next-to-leading order (NLO) QCD predictions. While good agreement is found for dijets in DIS and open charm production (D^*) in both DIS and photoproduction, the dijet photoproduction data for jets with low transverse energy E_{T} of the leading jet are clearly overestimated by NLO predictions. The indication of the dependence of the suppression factor on E_{T} was found. Within large errors the same amount of suppression was observed in both direct and resolved enhanced regions.

1 Factorisation and diffractive parton distribution functions

Diffractive electron-proton interactions studied with the HERA collider allow us to investigate the proton diffractive structure. In this type of interactions the proton remains intact or dissociates into a low-mass state, while the photon dissociates into a hadronic state X, $\gamma^* p \to X p'$. The final proton p' and the hadronic state X are separated by a large rapidity gap (LRG). [1] The diffractive exchange (Pomeron), with the vacuum quantum numbers, carries away a fraction $x_{I\!P}$ of the initial proton longitudinal momentum and has virtuality $t = (p - p')^2$. The Regge phenomenology tells us that for small $|t|$ the diffractive cross section drops exponentially with t which allows us to integrate over t to cope with experimental setup when the final proton is not tagged.

The actual beam particles are electrons or positrons which emit photons in a wide range of virtualities Q^2. In general, the cross sections depend on both the proton and the photon structure.

For a highly virtual photon, *i.e.* the one we can consider point-like, the factorisation theorem holds [2], stating that the cross section is given in terms of the universal diffractive parton distributions (DPDFs) and hard partonic cross sections. A generic formula reads

$$\frac{d\sigma^{\gamma^* p}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \sum_{k=g,q,\bar{q}} f_k^{\mathrm{D}(3)}\left(x_{I\!P}, Q^2\right) \otimes \hat{\sigma}^{\gamma^* k}\,, \tag{1}$$

where $\otimes$ denotes the convolution and DPDFs $f_k^{\mathrm{D}(3)}\left(x_{I\!P}, z, Q^2\right)$ are integrated over t. In the leading log (LO) approximation Eq. (1) simplifies to

$$\frac{d\sigma^{\gamma^* p}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \sum_{q} e_q^2\, f_q^{\mathrm{D}(3)}\left(x_{I\!P}, \beta, Q^2\right)\,, \tag{2}$$

[1]For the definition of kinematics and variables see *e.g.* G. Watt's talk [1].

yielding the parton-model interpretation of β being fractional momentum of the quark struck by γ^*.

The factorisation (1) holds for the inclusive as well as non-inclusive processes provided Q^2 is high enough for the photon to remain point-like and for the higher twist corrections to be neglected. Applied to the inclusive diffractive DIS it allows us to extract the proton DPDFs from the data. Both H1 and ZEUS collaborations performed such fits, assuming the Regge factorisation for DPDFs [3],

$$f_k^{\mathrm{D}(3)}\left(x_{I\!P}, z, Q^2\right) = f_{I\!P}(x_{I\!P}) f_k^{I\!P}\left(z, Q^2\right) \tag{3}$$

with the Pomeron flux $f_{I\!P}(x_{I\!P})$ taken from the Regge phenomenology. In actual fits a small contribution from a secondary Reggeon was also taken into account — for details see [4–7].

A more elaborate approach not assuming Regge factorisation and taking into account higher twists and perturbative Pomeron contributions is discussed in [1, 8].

With DPDFs at hand, we can study some semi-inclusive processes. The topics summarized in the following include dijet and open charm (D^*) production in both DIS and photoproduction (PHP) regimes. As already stated, if factorisation is not spoiled by higher twist contributions, it should work equally well for the above mentioned processes in the DIS regime. Thus one can extract the DPDFs from inclusive data only and use them to predict the dijet and D^* production cross sections. Comparison to the data provides us with the information on the quality of the fit and pQCD calculations. Another approach is to use inclusive as well as dijet and/or charm production data to extract DPDFs. The reason for using the semi-inclusive data is that the inclusive DIS is known to be mainly sensitive to the quark content of the proton, *cf.* (2). Gluons enter the cross section only via scaling violations and higher order QCD corrections, resulting in a quite high uncertainty in the extracted f_g [6]. Both dijet and charm production are directly sensitive to f_g and can be used to better establish the diffractive gluon distribution. A combined fit using inclusive and dijet data is discussed in detail in [7, 9–11], while the one using inclusive and D^* production data is presented in [5].

The photoproduction regime is qualitatively different. Here the photon is (nearly) real and reveals its hadronic structure. The γp interaction has components analogous to the hadron-hadron scattering, at LO ascribed to the 'resolved' photon. In this case there is no theoretical reason for the factorisation and experimentally it is known to be badly broken in the $p\bar{p}$ diffractive dijet production [12]. This factorisation breaking is phenomenologically understood in terms of the rescattering (screening) effects [13, 14], which lead to a suppression of the cross section calculated assuming that both proton and photon PDFs factorise.

In order to investigate the amount of this suppression the NLO QCD calculations using factorisation assumption are confronted with the experimental results. In general the observed suppression is much smaller than in the $p\bar{p}$ case, which qualitatively agrees with theoretical expectations [13, 14]. For a small suppression (up to ca. 50%, as observed at HERA) the accuracy of theoretical predictions becomes an important factor. The actual uncertainties can easily reach the order of the measured effect.

The uncertainty inherent in the perturbative QCD calculations, is the amount of higher order contributions. A common method to qualify it, is to look at the renormalisation/factorisation scale dependence (there should be none in the complete result). As shown in the figures below this scale dependence is strong, telling us that the higher order corrections are important[2]. The only way to resolve this issue is to go to higher pQCD orders (NNLO,...). There are, however, other uncertainties which are not shown in the plots. Let us discuss them briefly.

The fits to the inclusive DIS data are performed using the Fixed Flavour Number Scheme (FFNS) with three massless quarks and heavy charm and bottom treated as massive particles, not partons. On the contrary, the NLO calculations of the dijet production cross section take all flavours massless, as in the Variable Flavour Number Scheme. The both flavour schemes differ in the heavy quarks treatment and in the amount of gluons.

Gluon content of the Pomeron is poorly established by a fit to the inclusive DIS data only and both dijet and open charm production are very sensitive to gluons. In photoproduction about 80% of the cross section comes from γg subprocesses [15]. This ambiguity is, of course, smaller in the case of combined fits [5, 9].

All the above mentioned uncertainties, present in the assumed model of Regge factorisation and non-perturbative Pomeron, should be kept in mind when looking at experimental data compared to the NLO QCD predictions.

For a discussion on theoretical aspects of diffractive dijet photoproduction see the contribution of M. Klasen and G. Kramer to these proceedings.

2 Diffractive Dijet Production

Diffractive dijet production in DIS was analysed by both H1 and ZEUS collaborations in [9, 16, 17] and presented in [10, 11, 15, 18–20]. The data was taken during the HERA running periods 1996/97 and 1999/00. The kinematic range of the photon virtuality was $4 < Q^2 < 80\ \mathrm{GeV}^2$ (H1) and $5 < Q^2 < 100\ \mathrm{GeV}^2$ (ZEUS). The photon-proton CMS energy W was above $100\ \mathrm{GeV}$. Diffractive events were selected with the help of criteria of large rapidity gap (LRG) and the jets were identified using the longitudinally invariant inclusive k_T cluster algorithm [21] in the Breit frame. The transverse energies for leading and subleading jets were required to be $E^*_{\mathrm{T}1} > 5\ \mathrm{GeV}$ ($E^*_{\mathrm{T}1} > 5.5$ GeV in [9]) and $E^*_{\mathrm{T}2} > 4\ \mathrm{GeV}$.

The experimental results are compared to the NLO predictions obtained with the DISENT [22] and NLOJET++ [23] codes using several DPDFs. The cross sections vs. $x_{I\!P}$ and $E^*_{\mathrm{T}1}$ depicted in Figure 1, show that the NLO predictions agree within errors with the data. We can conclude that the QCD factorisation for diffractive dijets holds as expected. Note, however, that the ZEUS data tend to lie about (10–20)% below the NLO predictions.

The diffractive photoproduction (DPHP) of dijets was analysed by both H1 [16] and ZEUS [24] collaborations. The H1 experiment analysed the data with tagged electron in the running period 1996/97. The kinematic region was taken the same as for the DIS dijets (except $Q^2 < 0.01\ \mathrm{GeV}^2$) with the purpose to study the double ratio of photoproduction/DIS cross sections. The ZEUS analysis of dijets in DPHP covers somewhat different kinematic region, main difference being higher transverse energies of leading and subleading jets satisfying $E_{\mathrm{T}1} > 7.5\ \mathrm{GeV}$, $E_{\mathrm{T}2} > 6.5\ \mathrm{GeV}$. In both experiments the jets were identified using

[2] Note that very small or no scale dependence is not a proof that the result is correct.

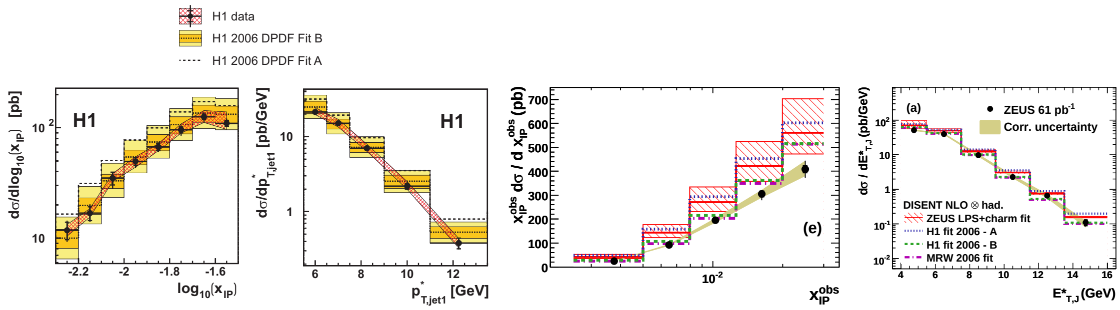

Fig. 1: Differential cross section for the diffractive production of dijets vs. $x_{I\!P}$ and E^*_{T1} as measured by H1 [9] (two left plots) and ZEUS [17] (two right plots). NLO predictions for several DPDFs parametrizations are also shown. The shaded bands show the uncertainty resulting from the variation of renormalization scale by factors 1/2 and 2.

the inclusive $k_{\rm T}$ cluster algorithm in the laboratory frame. For detailed discussion of the results see [10, 11, 15, 18, 19].

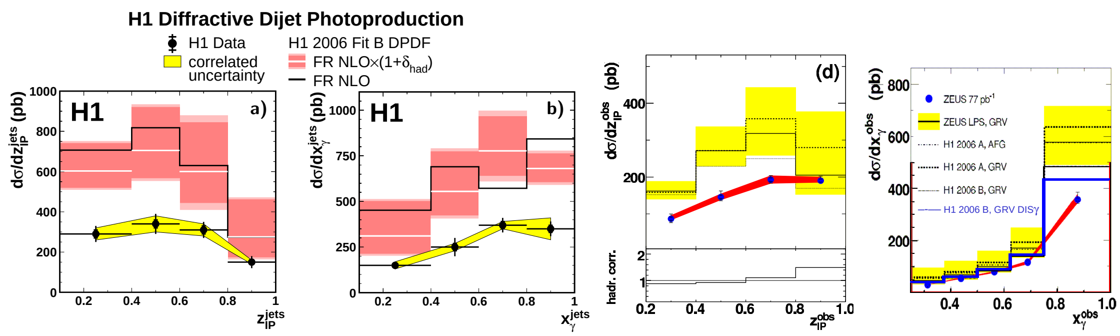

Fig. 2: Differential cross section for the diffractive photoproduction of dijets vs. $z_{I\!P}$ and x_γ as measured by H1 [16] (two left plots) and ZEUS [24] (two right plots). NLO predictions for several DPDFs parametrizations are also shown. The shaded bands show the uncertainty resulting from the variation of renormalization scale by factors 1/2 and 2.

The cross sections vs. $z_{I\!P}$ and x_γ are shown in Figure 2. The NLO QCD predictions were obtained using several DPDFs and photon PDFs parametrisations, and with two independent computer codes, one by Frixione and Ridolfi [25] and the other by Klasen and Kramer [26]. It was checked that both codes give the same results.

The H1 experiment observes a global suppression of NLO QCD predictions by factor 0.5. The ZEUS data are compatible with no suppression — the level of agreement with the NLO predictions is similar to the DIS case. However, 10–20% suppression is not excluded. Both experiments observe that the approach when only resolved photon part of the cross section is suppressed ($x_\gamma \lesssim 0.8$) is clearly disfavoured by data in contradiction with theoretical expectation of [14].

The difference between kinematic regions of both experiments lead us to a hypothesis that the suppression may depend on the $E_{\rm T}$ range of the jets [27]. Indeed, the cross section double ratio of data and NLO prediction for the diffractive PHP and DIS as a function of transverse momentum E_{T} of the leading jet measured by H1, and the ratio of the ZEUS data cross section over the NLO predictions, indicate the rise with increasing E_{T}, as shown in Figure 3[3].

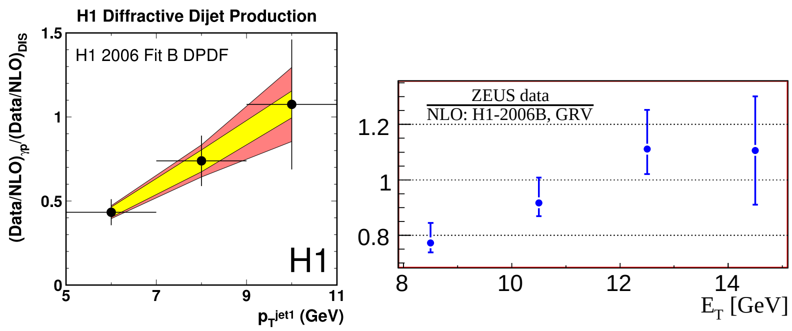

Fig. 3: Cross section double ratio of data to NLO prediction for photoproduction and DIS as a function of transverse momentum of the leading jet measured by H1 (left plot) and cross section ratio of data and NLO for the diffractive photoproduction of dijets vs. E_{T} of the leading jet as measured by ZEUS (right plot).

A detailed study of this issue was performed in the new H1 analysis of dijets in photoproduction [28]. The study was performed in two cut schemes. The first one identical to [16] with $E_{\mathrm{T}1} > 5$ GeV, to crosscheck results of previous analysis. The second one with all cuts as close as possible to the cuts used by ZEUS [24], $E_{\mathrm{T}1} > 7.5$ GeV, to check for a possible dependence of suppression on E_{T} of the jets. The results were compared to NLO calculations using three H1 DPDFs — fits A,B and Jets. The best agreement of the shapes of measured cross sections was obtained with NLO predictions using fit B and scaled by factor 0.53 for low E_{T} cut scenario, and by factor 0.61 for high E_{T} cut scenario [28].

This measurement of the suppression factor together with the ZEUS results of 0.8–1 factor seem to support the idea of the E_{T}-dependent suppression.

As in the previous analyses no dependence of suppression on measured x_γ was observed, indicating that there is no evidence for the suppression of the resolved part only.

3 Open charm production in diffraction

Another semi-inclusive process analysed at HERA is the diffractive production of open charm observed in the reactions with D^* mesons production. Both DIS and PHP regimes have been studied and discussed during the workshop [18–20, 29, 30].

If QCD factorisation is fulfilled, NLO QCD calculations based on DPDFs measured in inclusive processes should be able to predict the production rates of such processes in shape and normalization.

The data from the HERA running period 1998–2000 were analysed by both H1 [31] and ZEUS [32] collaborations. The charm quark was tagged by the reconstruction of $D^{*\pm}(2010)$ meson in diffractive DIS and PHP regimes. H1 used also another method — based on the measurement of the displacement of tracks from primary vertex — to identify the D^* production in the sample of DIS events only.

[3] left plot derived from [16], thanks to S.Schaetzel

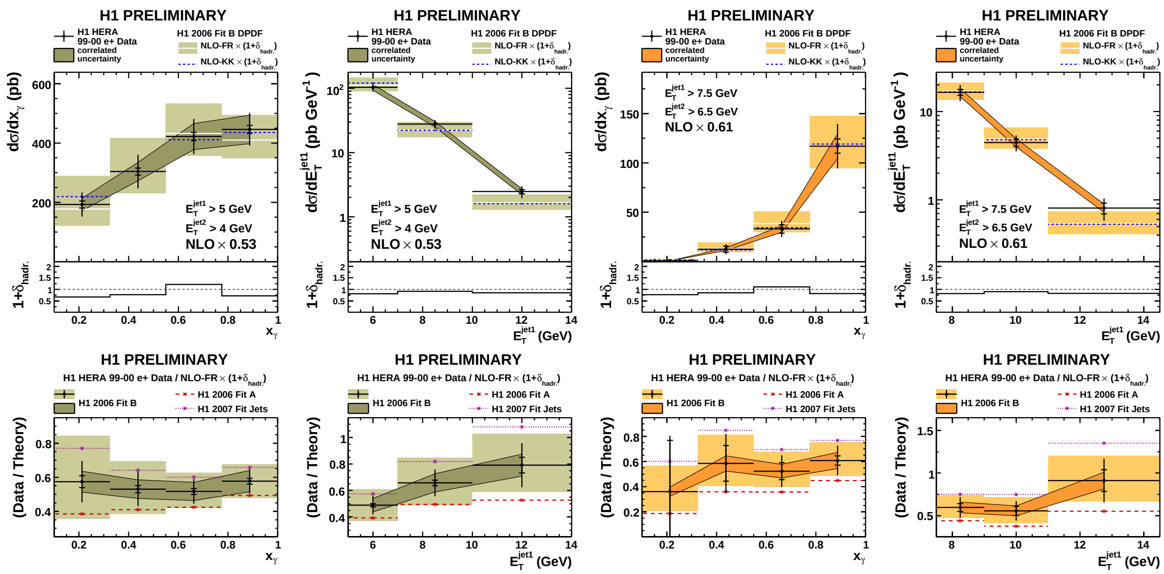

Fig. 4: Differential cross section for the diffractive photoproduction of dijets as a function of x_γ and E_{T1} for the lower E_{T} cut scenario (two left plots) and for the higher E_{T} cut scenario (two right plots), compared to NLO scaled calculations (upper plots). The lower plots show the corresponding ratios of the data to NLO calculated cross sections.

The measurements were compared to the NLO QCD predictions using DPDFs from H1 and ZEUS fits. The calculations were performed using HVQDIS [33] for DIS and FMNR [34] for PHP. In Figure 5 the H1 results for the cross sections vs. $x_{I\!P}$ and $z_{I\!P}$ are shown. The recent ZEUS results for the diffractive $D^{*\pm}(2010)$ photoproduction are presented in Figure 6.

Within large errors a good agreement is observed, which supports the validity of QCD factorisation in both diffractive DIS and PHP. In particular no sizable suppression of the open charm photoproduction is seen, in contrast to the diffractive dijet case. A plausible explanation of this difference is that the resolved photon contribution to the D^* production is ca. 10% as compared to about 50% for the dijet diffractive PHP.

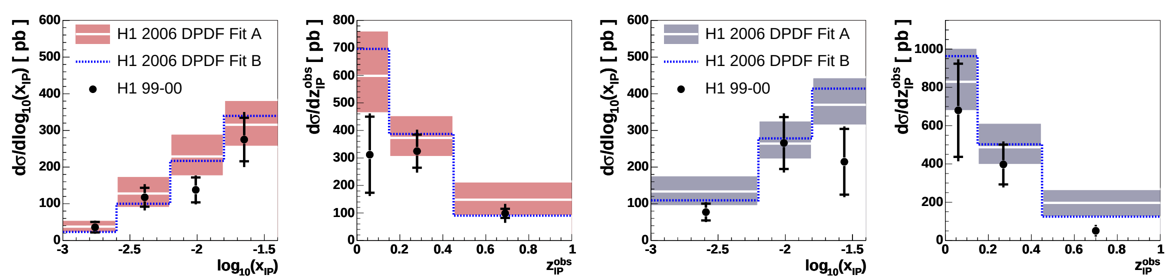

Fig. 5: Differential cross sections for diffractive D^* meson production as a function of $x_{I\!P}$ and $z_{I\!P}$ in DIS (two left plots) and photoproduction (two right plots).

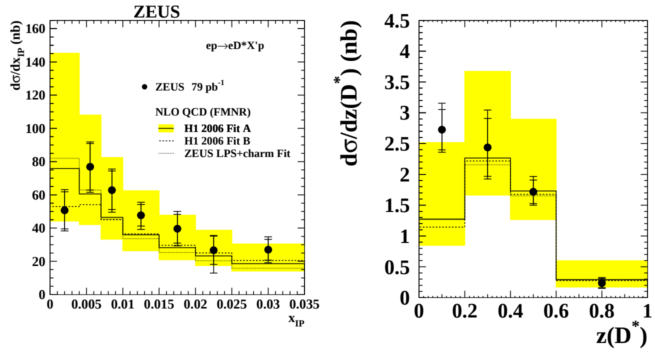

Fig. 6: Differential cross section for the diffractive photoproduction of $D^{*\pm}(2010)$ as a function of $x_{I\!P}$ and $z(D^{*})$ compared to NLO predictions.

4 Summary

The factorisation issues were analyzed by H1 and ZEUS experiments studying the production of dijets and open charm in diffractive DIS and photoproduction. The factorisation was found to hold in the case of D^{*} production and dijet production in DIS. In dijet photoproduction factorisation breaking was observed. The indication was found that the suppression of the dijet photoproduction depends on the transverse momentum E_{T} of the leading jet. On the other hand, no dependence on measured x_{γ} was observed indicating the same order of suppression in the direct and resolved enhanced regions.

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