Rescattering and gap survival probability at HERA

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Abstract
Diffractive dijet photoproduction and leading neutron data measured with the H1 and ZEUS detectors at HERA are presented. These data allow to study rescattering and gap survival probability in ep interactions.

1 Introduction

The role of rescattering and gap survival probability in ep interactions at HERA has been studied by the H1 and ZEUS Collaborations looking at diffractive dijet photoproduction and leading neutron production.

Diffractive ep events, $ep \rightarrow eXp$, are characterized by the presence in the final state of a fast forward proton, scattered at a very small angle having lost only a small fraction of the incoming proton energy, and a large rapidity gap (LRG) with no particle flow between the scattered proton and the hadronic system X from the dissociated photon. This event topology is ascribed to the absence of colour flow between the proton and the system X, due to the exchange of an object with vacuum quantum numbers, historically called pomeron. Both characteristics have been used at HERA to select diffractive events, either by measuring the fast scattered proton with detectors placed along the proton beamline at distances between 20 and 90 m from the interaction point, or by searching for LRG in the central detectors. The diffractive samples for the dijet photoproduction analyses presented here were selected by both Collaborations using the LRG method.

Leading neutron events, $ep \rightarrow eXn$, are characterized by the presence in the final state of a fast forward neutron carrying a relevant fraction of the incoming proton beam energy. This neutron escapes along the beamline and is detected by both Collaborations by means of forward neutron calorimeters placed at about 100 m from the interaction point.

2 QCD factorization in diffraction

According to the quantum chromodynamics (QCD) factorization theorem [1], the cross section for diffractive processes in deep inelastic scattering (DIS) can be expressed as a convolution of partonic hard scattering cross sections, which are calculable in perturbative QCD (pQCD), and universal diffractive parton density functions (DPDFs) of the proton, which are analogous to the usual proton PDFs under the condition that the proton stays intact in the interaction.

At HERA, various sets of DPDFs [2] have been determined from QCD fits to inclusive diffractive cross section measurements in DIS. It was found that most of the momentum of the diffractive exchange is carried by gluons.

The DPDFs extracted from inclusive data have been used for calculating next-to-leading order (NLO) predictions of semi-inclusive DIS diffractive final states, in particular dijet and open

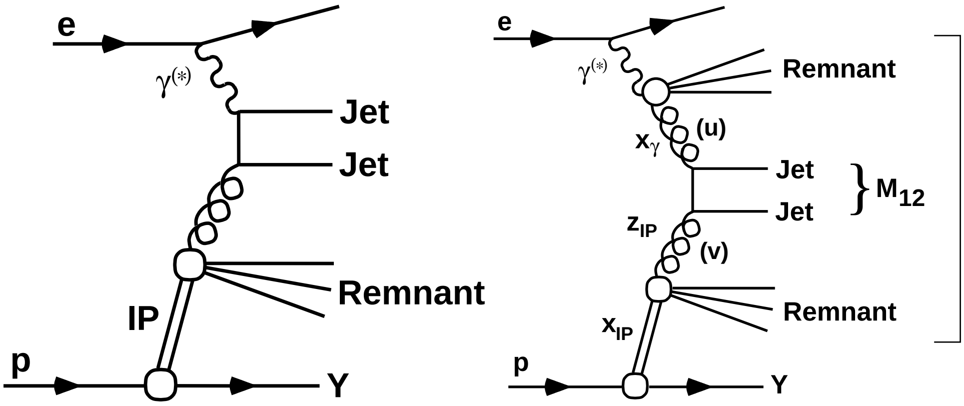

Fig. 1: Left panel: Direct-photon diagram for diffractive dijet photoproduction. Right panel: Resolved-photon diagram for the same process.

charm production, for which the presence of hard scales ensures that the partonic cross sections are perturbative calculable. Both H1 and ZEUS data on the DIS diffractive production of open charm [3] and dijets [4, 5] agree with NLO predictions within the uncertainties, which represents an experimental proof of the validity of QCD factorization in diffractive DIS. This also allowed to include dijet data in the QCD fits to better constrain the DPDFs, in particular the gluon one [5].

QCD factorization is not expected to hold in diffractive hadron-hadron interactions. Actually, QCD calculations with HERA DPDFs as input overestimate the cross section for single diffractive dijet production in $p\bar{p}$ collisions at the Tevatron by approximately a factor 10 [6]. This violation of factorization has been understood in terms of secondary interactions and rescattering between spectator partons, which may fill the rapidity gap, leading to a breakdown of hard-scattering factorization and causing a suppression of the diffractive cross section. Models including rescattering corrections via multi-pomeron exchanges are able to describe the suppression observed [7], which is often quantified by a 'rapidity gap survival probability'. This is also of great interest for the forthcoming LHC data analyses.

The increasing role of rescattering in the transition from DIS to hadron-hadron interactions can be studied at HERA by comparing processes in DIS and in photoproduction (PHP), since in photoproduction the quasi-real photon, with virtuality $Q^2 \sim 0$, can develop a hadronic structure.

At leading order (LO) two types of processes contribute to PHP events (see Fig. 1), direct- and resolved-photon processes. When the photon participates directly in the hard scattering as a point-like probe the processes are expected to be similar to the DIS ones and diffractive QCD factorization is expected to hold as in DIS. In contrast, processes in which the photon is first resolved into partons which then engage in the hard scattering resemble hadron-hadron interactions. In this latter case, the additional photon remnant opens up the possibility of secondary remnant-remnant interactions and diffractive QCD factorization is not expected to hold.

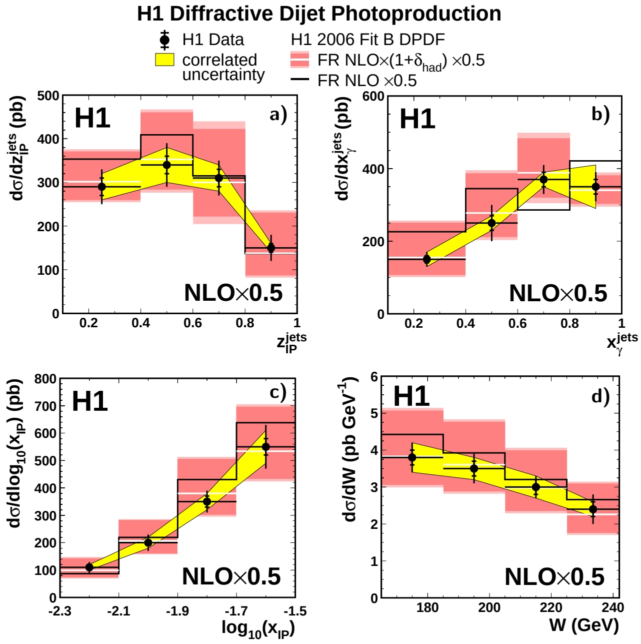

Fig. 2: Differential cross sections for the diffractive photoproduction of dijets. H1 data are compared to NLO calculations by Frixione et al.

3 Diffractive dijets in photoproduction: gap survival probability and its E_T dependence

Diffractive photoproduction of dijets has been studied by the H1 and ZEUS Collaborations as an interesting process to test the QCD factorization hypothesis and measure a possible rapidity gap survival probability in ep interactions. A reasonably high transverse energy, E_T, of the jets provides the hard scale, ensuring the applicability of pQCD at the small photon virtualities considered. The variable x_γ, which is the fraction of the photon momentum entering in the hard scattering, is used to separate direct- and resolved-photon events, where the latter have $x_\gamma < 1$.

A first sample of H1 diffractive data [8] has been analyzed in the kinematic region $Q^2 < 0.01$ GeV^2, $x_{I\!P} < 0.03$, where $x_{I\!P}$ is the fraction of the proton momentum carried by the pomeron, $E_T^{jet1} > 5$ GeV and $E_T^{jet2} > 4$ GeV. Since the data were selected with the LRG method, where the diffractive proton is not measured, the sample includes events in which the proton dissociates into low mass states, up to $M_Y < 1.6$ GeV, that escape detection going into the beampipe. Figure 2 shows a few differential distributions measured with this sample. The H1 data, corrected to the hadron level, are compared with NLO calculations obtained assuming factorization with a program by Frixione et al. [9]. H1 2006 Fit B DPDFs have been used as input and one can see that the NLO predictions, also corrected to the hadron level, agree with the data if scaled by a factor 0.5. Two conclusions can be drawn: NLO calculations overestimate the measured cross sections by a factor ~2 both in the direct and in the resolved region, in contrast to the expectation the only resolved-photon processes should be suppressed; as expected the suppression in ep events is much smaller than in $p\bar{p}$ interactions.

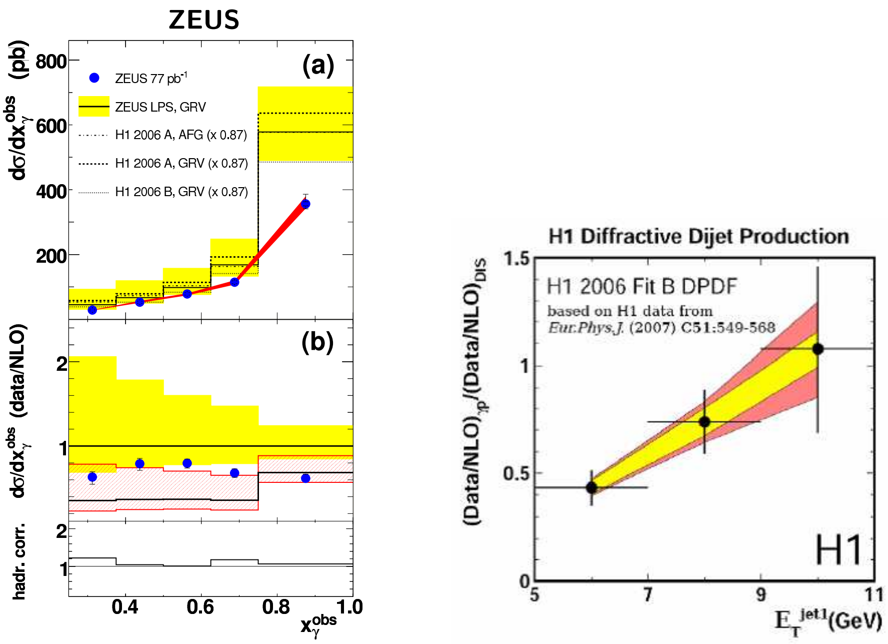

Fig. 3: Left panel: a) Differential cross section in x_γ for the diffractive photoproduction of dijets; b) ratio of data to NLO prediction. ZEUS data are compared to NLO calculations by Klasen and Kramer. Right panel: Cross section double ratio of H1 data to NLO predictions for PHP and DIS as function of x_γ.

In Fig. 3, left panel, the ZEUS measurement [10] of the differential cross section in x_γ and the ratio of data to NLO calculation are shown. NLO predictions have been obtained assuming factorization with a program by Klasen and Kramer [11]. The ZEUS data were selected in the kinematic region $Q^2 < 1$ GeV^2, $x_{I\!P} < 0.025$, $E_T^{jet1} > 7.5$ GeV and $E_T^{jet2} > 6.5$ GeV. Cross sections were corrected to the hadron level and the contribution due to proton dissociative events ($16 \pm 4\%$) was subtracted. A correction for the proton dissociative contribution was also applied when using the H1 DPDFs, since these are extracted from inclusive diffractive samples including proton dissociation with $M_Y < 1.6$ GeV. As in the H1 analysis presented above, data do not show any difference between the resolved and the direct photon region. However, the ZEUS data show a very weak, if any, suppression, which mainly originates from the lower E_T^{jet1} region. NLO calculations tend to overestimate the measured cross sections but within the large theoretical uncertainties the data are still compatible with QCD factorization.

The discrepancy between H1 and ZEUS has been attributed to the different E_T regions of the two analyses. Indeed, both H1 and ZEUS data have a harder E_T distribution than in NLO. The possible E_T dependence of the suppression can be better seen in the double ratio shown in Fig. 3, right panel, obtained by dividing the ratio of measured to predicted cross section in photoproduction by the corresponding ratio in DIS. In this double ratio many experimental errors and also theoretical scale errors cancel to a large extend. The plot gives a clear signal that the rapidity gap survival probability might increase with E_T.

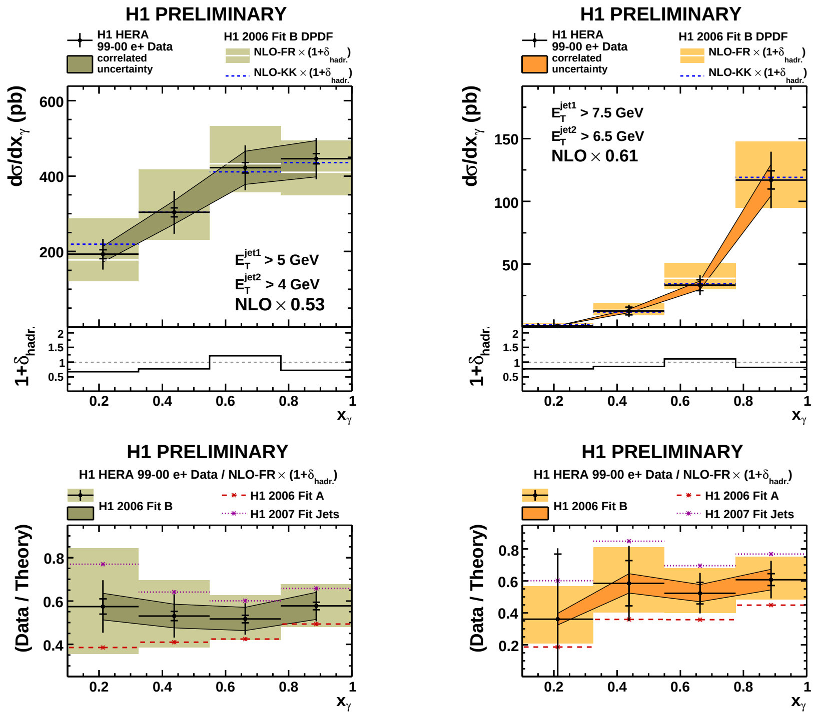

Fig. 4: Differential cross section in x_γ for the diffractive photoproduction of dijets and ratio of H1 data to NLO predictions. Left panel: 'Low E_T' sample. Right panel: 'High E_T' sample.

To better study the E_T dependence, a more recent H1 analysis [12] has been performed, based on a three times higher integrated luminosity with respect to the previous one. This allowed selecting two samples with different E_T cuts: for the first sample (Low E_T one) all the cuts were the same as in the previous H1 analysis, in particular $E_T^{jet1} > 5$ GeV and $E_T^{jet2} > 4$ GeV, to be able to cross check the results; instead, the second sample (High E_T one) covered a kinematical region similar to that of the ZEUS analysis, with $E_T^{jet1} > 7.5$ GeV and $E_T^{jet2} > 6.5$ GeV. Two independent NLO calculations have been compared to the measurements, that by Frixione et al. and that by Klasen and Kramer, using three sets of DPDFs, H1 2006 Fit A and Fit B and H1 2007 Fit Jets. Figure 4, left panel, shows the x_γ distribution and the ratio of data to theory expectation for the 'Low E_T' sample, while Fig. 4, right panel, shows the same plots for the 'High E_T' sample.

In both cases, data confirm that there is no sign of a dependence in x_γ of the rapidity gap survival probability, as already observed in the previous H1 and ZEUS analyses. The survival probabilities measured with the 'Low E_T' sample are in the range 0.43-0.65, depending on the DPDFs but always compatible within uncertainties, and also compatible with the one of the previous H1 analysis. The survival probabilities measured with the 'High E_T' sample are in the range 0.44-0.79, that is slightly higher than in the 'Low E_T' case and closer to the ZEUS results, confirming a possible E_T dependence of the suppression.

H1 data have also been compared to NLO calculations assuming factorization breaking and suppression of the resolved component only. The result is a much worse agreement in the x_γ distribution. Awaiting for more theoretical work, the experimental data seem to prefer an unexpected global suppression.

4 Leading neutron production: rescattering and absorption

The measurement of leading neutron (LN) production at HERA is particularly interesting for studying rescattering effects in ep collisions. Although the production mechanism of leading neutrons is not completely understood, exchange models give a reasonable description of the data. In this picture, the incoming proton emits a virtual particle which scatters on the photon emitted from the beam electron. In particular, one-pion exchange is a significant contributor to LN production for large values of x_L [13], where x_L is the fraction of the beam proton energy carried by the leading neutron. In exchange models, neutron absorption can occur through rescattering [15-18], which can thus be studied measuring neutron yields and distributions.

Figure 5, left panel, shows the measurement with the ZEUS data [14] of the ratio of the normalized cross section for LN photoproduction as a function of x_L to the same distribution in DIS. The ratio is below 1 at low x_L values and rises with increasing x_L. As shown by the comparison with the theoretical curves, data are consistent with a π-exchange model by D'Alesio and Pirner, which includes absorption via a geometrical picture [16]. In this picture, if the size of the $n - \pi$ system is small compared to the size of the photon, besides the π also the neutron can scatter on the photon, escaping then detection, which can be seen as neutron absorption. Since the size of the virtual photon is inversely related to Q^2, more absorption is expected in photoproduction than in DIS. Moreover, since parametrizations of the pion flux in general show that the mean value of the $n - \pi$ separation increases with x_L, less absorption is expected at high x_L than at low x_L. Both behaviours are confirmed by the data. Figure 5 also shows that the data are reasonably consistent with a Regge-based model with multi-pomeron exchanges [15].

The presence of a forward neutron tracker, a scintillator hodoscope installed in the calorimeter at a depth of one interaction length, allowed the measurement of neutron transverse momenta in the range $p_T \leq 0.69\ x_L$ GeV. The p_T^2 distributions in the different x_L bins are all compatible with a single exponential distribution. In Fig. 5a, right panel, is shown the measurement of the exponential slopes b in DIS, while in Fig. 5b is presented the difference of the exponential slopes for photoproduction and DIS. Data are compared to a π-exchange model with enhanced neutron absorption based on multi-pomeron exchanges, which also accounts for the migration of neutrons in (x_L, p_T^2) after rescattering [18]. Including secondary exchanges (ρ, a_2) allows the model to give a good description of the b slopes. Finally, since the size of the $n - \pi$ system is inversely proportional to the neutron p_T, rescattering removes neutrons with large p_T. Thus rescattering results in a depletion of high p_T neutrons in photoproduction relative to DIS.

A possible suppression has also been looked for by H1 in a sample of photoproduction dijet events with a leading neutron [19]. Jets were selected with transverse energies $E_T^{jet1} > 7$ GeV and $E_T^{jet2} > 6$ GeV. No suppression has been observed since NLO calculations by Klasen and Kramer [20], which assume factorization, agree with the data if corrections to the hadron level are introduced. A more recent analysis by Klasen and Kramer [21] concludes instead for the

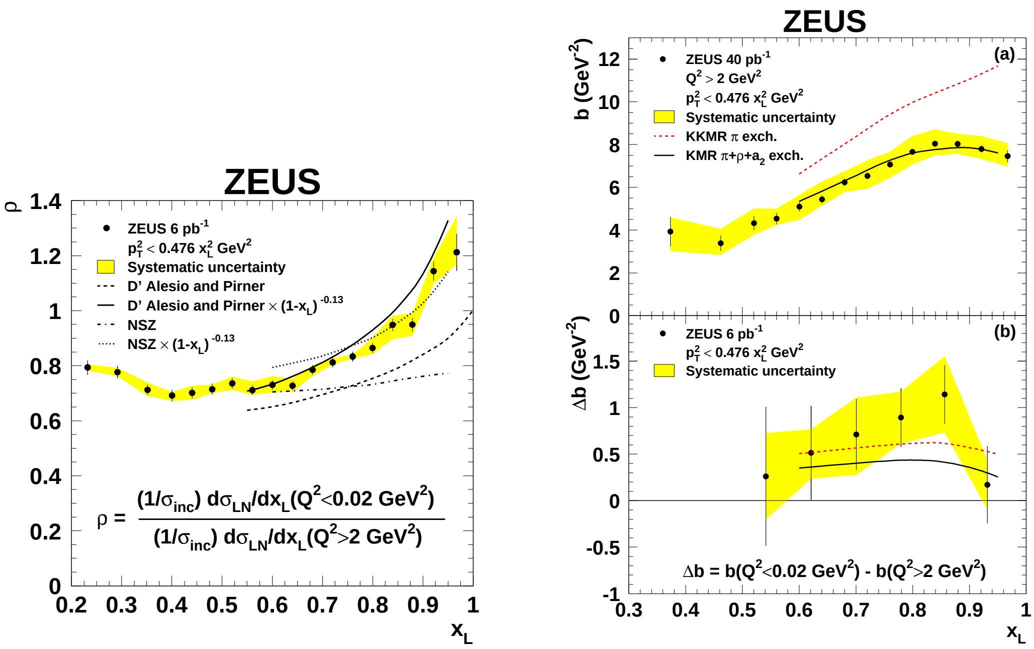

Fig. 5: Left panel: Ratio of the normalized x_L distributions for PHP and DIS. Right panel: a) Exponential slopes b for DIS; b) difference of the exponential slopes b for PHP and DIS.

observation of factorization breaking.

5 Summary and conclusions

Diffractive dijet photoproduction has been studied at HERA to test possible QCD factorization breaking, expected for resolved-photon processes only, as in $p\bar{p}$ collisions at the Tevatron. Rapidity gap survival probabilities have been measured in the range 0.4-0.9, higher than in $p\bar{p}$. Both H1 and ZEUS data, in contrast to the expectation, prefer a global suppression for direct and resolved components of the photon, with a possible E_T dependence of the suppression factor.

Leading neutron data show the effects of rescattering through the neutron absorption observed at low x_L and high p_T in photoproduction with respect to DIS. π-exchange models with enhanced absorptive corrections, including migration and secondary exchanges, are able to describe the data. Absorptive effects may equally be described in terms of gap survival probability. It is worth to note that the HERA data can be used to get reliable predictions for the gap survival probability in pp interactions [22], which is a crucial input to calculations of diffractive processes at the LHC.

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