Inclusive Diffraction at HERA

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The high centre-of-mass energies of the HERA *ep* 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. In this report the recent experimental data from the H1 and ZEUS Collaborations at HERA of inclusive processes and hadronic final states in diffractive interactions are presented. The data are used to investigate the factorisation properties and study the partonic structure of colour singlet exchange.

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I. 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. The origin of these events is due to a colourless exchange, referred to as Pomeron.

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, $\beta = x/x_{I\!P}$, where $x = Q^2/(2P \cdot q)$ 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 [1–4]. 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 $x_{I\!P}$ [4]:

$$\sigma^D(\gamma^* p \to Xp) \propto \sum_i f_i^D(x_{I\!P}, t, x, Q^2) \otimes \sigma^{\gamma^* i}(x, Q^2). \quad (1)$$

In addition, it is important to test the conjecture of *Regge (proton vertex) factorisation*, which as-

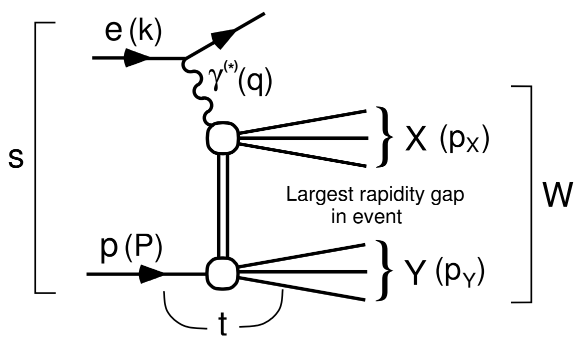

FIG. 1: Illustration of the generic diffractive process $ep \to eXY$. The systems X and Y are separated by the largest gap in the rapidity distribution of the final state hadrons.

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sumes that the DPDF can be expressed as a product of the Pomeron flux, $f_{I\!P/p}$, and the Pomeron structure function, $f_i^{I\!P}$ [5]:

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

In analogy with inclusive DIS scattering, the cross section for neutral current diffractive events is proportional to the diffractive reduced cross section $\sigma_r^{D(4)}(Q^2, x_{I\!P}, \beta, t)$:

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

where $y = Q^2/(s \cdot x)$ is the inelasticity variable. When the scattered proton is not detected, the t-integrated diffractive structure function $F_2^{D(3)}$ is obtained via:

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

The reduced cross section depends at moderate scales, Q^2, on two diffractive structure functions F_2^D and F_L^D according to

$$\sigma_r^D = F_2^D - \frac{y^2}{1 + (1 - y)^2} F_L^D. \quad (5)$$

For y not too close to unity, $\sigma_r^D = F_2^D$ holds to very good approximation.

The β and Q^2 dependences of σ_r^D may be subjected to a perturbative QCD analysis based on the DGLAP equations in order to obtain DPDFs. DPDFs have been determined at HERA from high-precision measurements of the inclusive diffractive DIS processes [6–11]. Whilst F_2^D directly measures the quark density, the gluon density is only indirectly constrained, via the scaling violations $\partial F_2^D/\partial \ln Q^2$.

The QCD factorisation is valid in diffractive DIS [4], however it is expected to break down for hard processes in diffractive hadron-hadron scattering, due to rescattering of hadronic remnants (see e.g. [1, 12]). 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 overestimate the diffractive dijet cross sections measured by CDF by up to an order of magnitude [6]. All diffractive processes at the LHC are affected by rescattering of hadronic remnants, with survival probabilities estimated to be only a few percent [13]. 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 DIS of highly virtual photons ('point-like' or 'direct' photon, figure 2a). In contrast, processes in which the photon is resolved into partons which participate in the hard scattering ('resolved' photon, 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 [14].

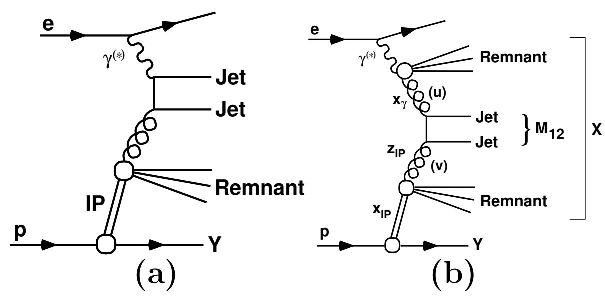

FIG. 2: Leading order diagrams for diffractive dijet production at HERA. (a) direct (point-like) processes, (b) resolved (hadron-like) photon process.

II. MEASUREMENT METHODS AND COMPARISONS

Experimentally, diffractive ep scattering is characterised by the presence of a leading proton in the final state, retaining most of the initial state proton energy, and by a lack of hadronic activity in the direction of outgoing proton. Because of this the system X is cleanly separated and its mass M_X may be measured in the central detector components. These signatures have been exploited at HERA to select diffractive events by tagging the outgoing proton in the H1 Forward Proton Spectrometer or the ZEUS Leading Proton Spectrometer ('LPS method' [8, 11, 15]) or by requiring the presence of a large gap in the rapidity distribution of hadronic final state particles in the forward region ('LRG method' [6, 11, 16]). In 'Mx method' the inclusive DIS sample is decomposed into diffractive and non-diffractive contributions based on their characteristic dependences on M_X [7, 16]. Whilst the LRG and M_X-based techniques yield better statistics than the LPS method, they suffer from systematic uncertainties associated with an admixture of proton dissociation to low mass states, which is irreducible due to the limited forward detector acceptance.

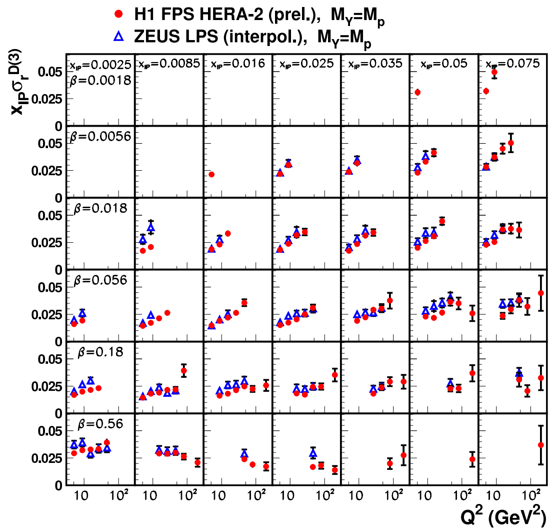

FIG. 3: The diffractive reduced cross section $x_{I\!P}\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P})$ for $|t| < 1$ GeV^2, shown as function of Q^2 in bins of β and $x_{I\!P}$. The H1 FPS data are compared to ZEUS LPS results interpolated to H1 Q^2, $x_{I\!P}$ and β values using a parameterisation of 'H1 2006 DPDF FitB'.

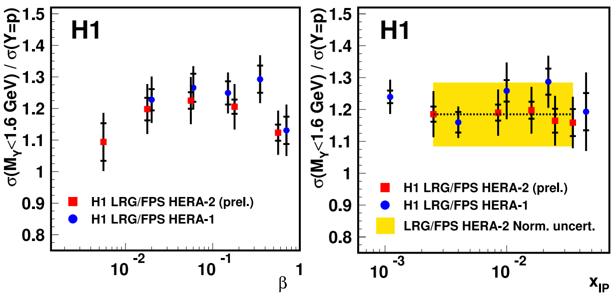

FIG. 4: The ratio of the diffractive cross sections for $M_Y < 1.6$ GeV and $|t| < 1$ GeV^2 to that for $Y = p$ and $|t| < 1$ GeV^2, obtained from $\sigma_r^{D(3)}$ measurements using the H1 LRG data [6] and the H1 FPS data [8, 15].

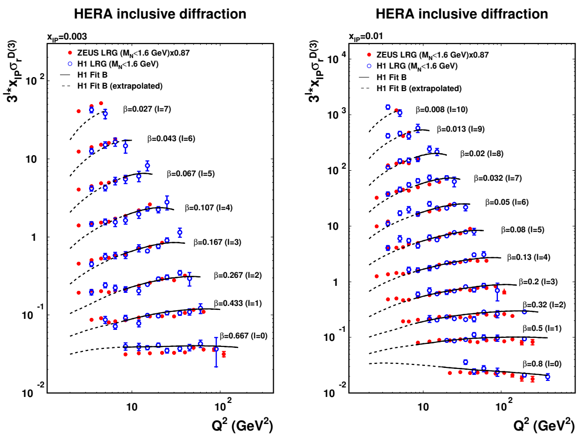

FIG. 5: H1 and ZEUS measurements of the diffractive reduced cross section at two example $x_{I\!P}$ values [17]. The ZEUS data are scaled by a factor of 0.87 to match the H1 normalisation. The data are compared with the results of the H1 2006 Fit B DPDF based parameterisation [6] for $Q^2 \geq 8.5$ GeV^2 and with its DGLAP based extrapolation to lower Q^2.

The H1 collaboration recently released a preliminary proton-tagged measurement using its full available FPS sample at HERA-II [15]. The integrated luminosity is 156 pb^{-1}, a factor of 20 higher than in previous H1 measurements. The new data tend to lie slightly above the recently published final ZEUS LPS data from HERA-I [11], but are within the combined normalisation uncertainty of around 10% (figure 3).

The comparison of the data obtained with the LRG and the LPS methods is presented in figure 4. Here the ratio is shown of the diffractive cross sections for $M_Y < 1.6$ GeV and $|t| < 1$ GeV^2 to that for $Y = p$ and $|t| < 1$ GeV^2, obtained from $\sigma_r^{D(3)}$ measurements using the H1 LRG data [6] and the H1 FPS data [8, 15]. This ratio defines a size of proton dissociation contribution to the LRG sample. The ratio, which is an estimator of proton dissociation contribution to LRG, is order of 18% for H1 measurements, and is almost independent of the kinematic variables Q^2, β and $x_{I\!P}$. This result supports the validity of proton vertex factorisation, so that the diffractive PDFs extracted from the LRG measurements are applicable to LPS data if corrected for the contribution of proton dissociation.

The compatibility between the H1 and ZEUS measurements is further tested using the LRG data. The recently published ZEUS data [11] are based on an integrated luminosity of 62 pb^{-1} and thus have substantially improved statistical precision compared with the older H1 published results [6]. The normalisation differences between the two experiments are 13%, which is a little beyond one standard deviation in the combined normalisation uncertainty. After correcting for this factor, very good agreement is observed between the shapes of the H1 and ZEUS cross sections throughout most of the phase space studied, as shown in figure 5. A more detailed comparison between different diffractive cross section measurements by H1 and ZEUS and a first attempt to combine the results of the two experiments can be found in [17].

III. SOFT PHYSICS AT THE PROTON VERTEX

The LRG and LPS measurements [6, 8, 11] demonstrate that the diffractive DIS data are consistent with a proton vertex factorisation to good approximation. The dependences on variables which describe the scattered proton ($x_{I\!P}$, t) factorise from those describing the hard partonic interaction (Q^2, β). As an example, the slope parameter b, extracted in [11] by fitting the t distribution to the form $\mathrm{d}\sigma/\mathrm{d}t \propto e^{bt}$, is shown as a function of Q^2, $x_{I\!P}$ and M_X in figure 6a. There are no significant variations from the average value of $b \simeq 7$ GeV^{-2} anywhere in the studied range. It is interesting to note, that the measured value of b is significantly larger than

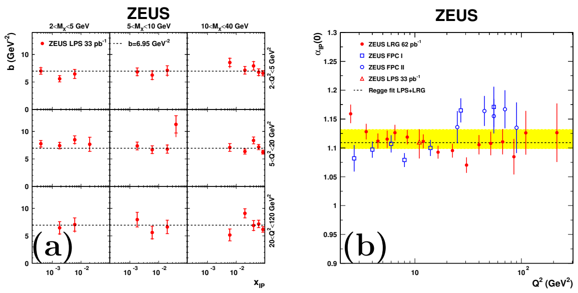

FIG. 6: a) Measurements of the exponential t slope from ZEUS LPS data, shown as a function of Q^2, $x_{I\!P}$ and M_X. b) ZEUS extractions of the effective pomeron intercept describing the $x_{I\!P}$ dependence of diffractive DIS data at different Q^2 values [11].

that from 'hard' exclusive vector meson production ($ep \to eVp$) [18]. Assuming that b is related to the radius of interaction region, this observation indicates that in diffractive DIS the virtual photon probes spatial extent which is considerably larger than the proton radius and characterises the the non-perturbative exchanges similar to the Pomeron of soft hadronic physics [19, 20].

Figure 6b shows the Q^2 dependence of the effective Pomeron intercept $\alpha_{I\!P}(0)$, which is extracted from the $x_{I\!P}$ dependence of the data [11]. No significant dependence on Q^2 is observed, again compatible with proton vertex factorisation. These results are consistent with the H1 value of $\alpha_{I\!P}(0) = 1.118 \pm 0.008$ (exp.) $^{+0.029}_{-0.010}$ (model) [6]. Both collaborations have also extracted a value for the slope of the effective Pomeron trajectory, the recently published ZEUS value being $\alpha'_{I\!P} = -0.01 \pm 0.06$ (stat.) ± 0.06 (syst.) GeV^{-2} [11].

The intercept of the effective Pomeron trajectory is consistent within errors with the 'soft Pomeron' results from fits to total cross sections and soft diffractive data [21]. Although larger effective intercepts have been measured in hard vector meson production [18], no deviations with either Q^2 or β have yet been observed in inclusive diffractive DIS. The measured slope of the effective trajectory is smaller than the value 0.25 GeV^{-2} obtained from the soft diffractive processes [22, 23], though it is compatible with results from the soft exclusive photoproduction of ρ^0 mesons at HERA [24, 25].

IV. EXTRACTION OF DIFFRACTIVE PARTON DENSITY FUNCTIONS (DPDFS)

The high statistics ZEUS LRG and LPS data [11] have recently been fitted to extract DPDFs [26]. The method and DPDF parameterisation are similar to an earlier H1 analysis [6]. 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 Q_0^2. They are evolved in Q^2 using the DGLAP equations and are fitted to the data. The heavy flavour treatment follows the general mass variable flavour number scheme [27]. In figure 7, the resulting DPDFs are compared with results from both ZEUS and H1 using a fixed flavour number scheme. The agreement between the experiments is reasonable when the uncertainty on the H1 DPDFs is also taken into account and the conclusion that the dominant feature is a gluon density with a relatively hard z dependence is confirmed. The error bands shown in figure 7 represent experimental uncertainties only. 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 lower at large z, which is among the most important regions for LHC studies. Indeed, in the large z region, where the dominant parton splitting is $q \to qg$, the sensitivity of $\partial F_2^D / \partial \ln Q^2$ to the gluon density becomes poor and different DPDF parameterisations lead to large variations [6, 26]. Improved large z constraints have been obtained by including dijet data in the QCD fits [26, 28].

The comparison of quark and gluon contributions shows that up to 70% of the diffractive exchange's momentum is carried by gluons. It is consistent with a common QCD radiation pattern far from the valence region.

V. FACTORISATION TESTS IN DIFFRACTIVE DIS

According to the factorisation theorem (see Section I) which was proved for diffractive DIS [4], the diffractive parton densities extracted from σ_r^D are applicable to the prediction of a wide range of other observables in diffractive DIS. There have been many tests of this diffractive hard scattering factorisation over the years, the most precise and detailed arising from jet [28–31] and heavy flavour [32–34] cross section measurements. These processes are dominated by the boson-gluon fusion process $\gamma^* g \to q\bar{q}$ (figure 2a), and thus are directly sensitive to the diffractive gluon density, in contrast to inclusive diffractive DIS measurements. The factorisation works well at moderate values of z, as demonstrated for the example of diffractive charm quark production in figure 8. However, the situation changes at large $z \gtrsim 0.4$ where the gluon density from σ_r^D has a large uncertainty and dijet data give the best constraints.

At low x and Q^2, the longitudinal diffractive structure function, F_L^D, is closely related to the diffractive gluon density and thus gives a complementary test of diffractive factorisation and the role of gluons to those provided by jet and charm cross sections. Measurements of F_L^D became possible following the reduced proton beam energy runs at the end of HERA operation. According to equation 5, F_L^D and F_2^D may then be separated through the $y = Q^2/(s\,\beta\,x_{I\!P})$ dependence as s varies at fixed Q^2, β and $x_{I\!P}$.

The H1 collaboration recently released preliminary F_L^D results [35]. Figure 9 shows that the F_L^D value integrated over β is non-zero at the 3σ level. The measured ratio of longitudinal to transverse photon induced cross sections in diffraction is similar to that in inclusive DIS

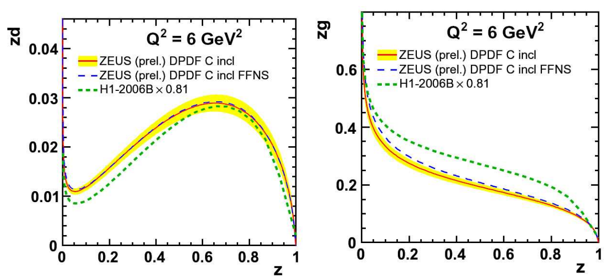

FIG. 7: ZEUS down quark (one sixth of the total quark + antiquark) and gluon densities as a function of generalised momentum fraction z at $Q^2 = 6$ GeV^2 [26]. Two heavy flavour schemes are shown, as well as H1 results [6] corrected for proton dissociation with a factor of 0.81.

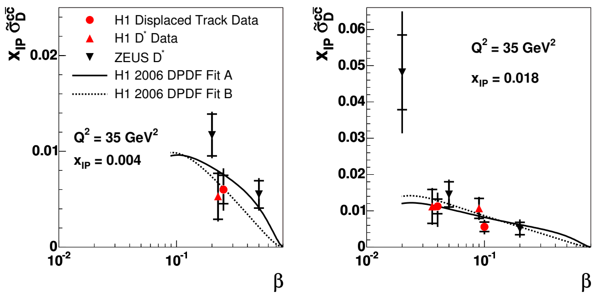

FIG. 8: Comparison of measurements of diffractive open charm production [34] with predictions based on DPDFs extracted from σ_r^D data [6].

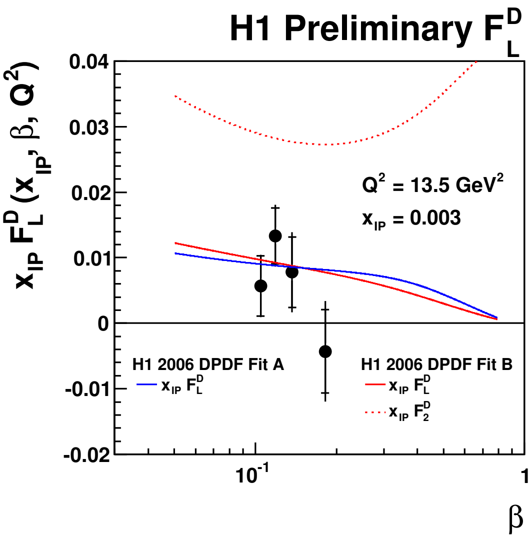

FIG. 9: The measurement of the longitudinal diffractive structure function F_L^D [35], compared with DPDF based predictions.

measurements [36, 37], though the errors in the diffractive case are large. The measured F_L^D is in agreement with predictions based on DPDFs extracted from σ_r^D.

VI. FACTORISATION TESTS WITH DIFFRACTIVE JET PHOTOPRODUCTION

In diffractive hadronic collisions the QCD factorisation is expected to breaks down [1, 12]. The predictions based on DPDFs from diffractive DIS at HERA overestimate the diffractive jet production cross section $p\bar{p}$ by almost an order of magnitude [6]. This factorisation breaking is generally attributed to absorptive corrections, corresponding to the destruction of the outgoing proton coherence and the rapidity gap due to multiple interactions within a single event. These effects are associated with the presence of a proton remnant, in contrast to the point-like photon coupling in diffractive DIS. The understanding of the rapidity gap survival probability at high energies is extremely important for diffractive studies at the LHC [38, 39].

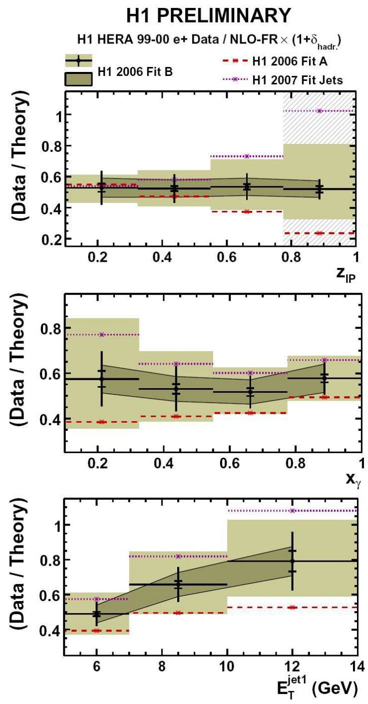

FIG. 10: Ratios of diffractive dijet photoproduction cross sections measured by H1 to NLO QCD calculations as a function of E_T^{jet1}, $z_{I\!P}$ and x_γ. [40].

The questions of DPDF applicability and rapidity gap survival is further investigated in hard diffractive photoproduction at HERA. As the photon is almost real (virtuality $Q^2 \sim 0$) it can develop a partonic structure via $\gamma \to q\bar{q}$ fluctuations. In a leading order (LO) picture, there are thus two classes of hard photoproduction: ‘resolved’ interactions (figure 2b), where the photon interacts via its partonic structure and only a fraction x_γ of its four-momentum participates in the hard subprocess and ‘direct’ interactions (figure 2a), where the photon behaves as a point-like particle. and $x_\gamma = 1$. Resolved photoproduction interactions resemble hadron-hadron scattering to a large extent and are therefore expected to exhibit gap destruction effects. The gap survival probability has been estimated to be 0.34 for resolved processes [14] and is expected to be unity for direct photon interactions. In QCD, the direct and the resolved processes are unambiguously distinguished only in LO. In next-to-leading order (NLO) these two processes are related, and the separation depends on the factorisation scheme and scale.

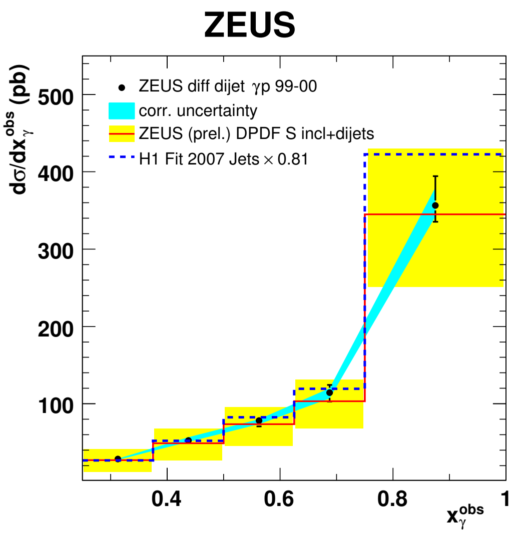

FIG. 11: ZEUS diffractive dijet photoproduction data [43], compared with DPDF based predictions.

Figure 10 shows ratios of H1 measurements of diffractive dijet photoproduction cross sections [40] to NLO QCD calculation [41, 42] which neglects absorptive effects. Results are presented differentially in the leading jet transverse energy E_T^{jet1} and in hadron level estimators of $z_{I\!P}$ and x_γ, obtained as described in [31]. For most of the measured points, the ratios are significantly below unity.

Figure 11 shows a recent ZEUS measurement [43] as a function of x_γ compared with predictions based on H1 [28] and ZEUS [26] DPDFs extracted by fitting σ_r^D and diffractive dijet electroproduction data. In contrast to the H1 result, the ZEUS data are compatible with NLO predictions. A possible reason for this contradiction between the two experiments could be an observed dependence of the data-to-theory ratio on the jet transverse energy (figure 10c) [31, 40, 43]. The ZEUS measurement is made for $E_t^{jet1} > 7.5$ GeV, whereas H1 measure for $E_t^{jet1} > 5$ GeV. Intriguingly, the ratios of data to theory measured by both collaborations have at most a weak dependence on x_γ, in contrast to theoretical expectations [14, 44]. A better understanding of observed effects require more detailed investigations.

VII. CONCLUSIONS

Diffractive processes have been extensively studied in ep interactions at HERA, and the validity of the QCD factorisation theorem has been investigated. Recent H1 and ZEUS semi-inclusive diffractive DIS data are in fair agreement within their normalisation uncertainties.

The measurements of inclusive diffraction and the hadronic final state in diffractive DIS can be described within a consistent picture. The results support QCD factorisation with diffractive parton densities which are evolved according to the DGLAP equations and are dominated by the gluon contribution. The data exhibit proton vertex factorisation to good approximation. NLO predictions using the diffractive PDFs measured in inclusive diffraction successfully describe diffractive dijet and charm production in DIS. In diffractive dijet photoproduction the situation is less clear. The ZEUS dijet photoproduction data are compatible with NLO predictions, while the H1 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. There is an indication of the dependence of the suppression factor on the transverse momenta of the jets.

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