Future Diffraction at HERA

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Future prospects of hard diffraction at HERA a reviewed. A selection of processes which can be calculated in pQCD is given, with emphasis on the separation of soft and hard diffraction. The main focus will be put on the energy dependence of diffractive processes and signatures for the hard pQCD pomeron. Problems in the experimental detection of these processes and the expected significance of future measurements at HERA are discussed.

I. INTRODUCTION

In a deep inelastic diffractive process $ep \to e'p'X$, where p' represents the scattered proton or a low mass final state, and X stands for the diffractive hadronic state, the cross section can be written as [1]:

$$\frac{d^4\sigma(ep \to e'Xp')}{dy\,dQ^2\,dx_{I\!P}\,dt} = \frac{4\pi\alpha^2}{yQ^4}\left(\left(1 - y + \frac{y^2}{2}\right) F_2^{D(4)}(x,Q^2;x_{I\!P},t) - \frac{y^2}{2} F_L^{D(4)}(x,Q^2;x_{I\!P},t)\right) \tag{1}$$

with $y = (q.p)/(e.p)$, $Q^2 = -q^2 = (e-e')^2$, $x_{I\!P} = (q.I\!P)/(q.p) = 1 - (q.p')/(q.p)$ and $t = (p-p')^2$, where e (e') are the four vectors of the incoming (scattered) electron, the Bjorken x variable $x = Q^2/(y \cdot s)$ with the total center of mass energy $s = (e+p)^2$, p (p') are the four vectors of the incoming (scattered) proton, $q = e - e'$ is the four vector of the exchanged photon and $I\!P = p - p'$ corresponds to the four vector of the pomeron, which here only serves as a generic name. These variables are defined independently of the underlying picture of diffraction. In analogy to Bjorken-x, one can define $\beta = x/x_{I\!P}$. In terms of experimental accessible quantities, these variables can be expressed as:

$$x_{I\!P} = \frac{Q^2 + M_X^2}{Q^2 + W^2} \tag{2}$$

$$\beta = \frac{Q^2}{Q^2 + M_X^2} \tag{3}$$

with M_X being the invariant mass of the diffractive ($\gamma^* I\!P$) system and W the mass of the $\gamma^* p$ system.

In the following I shall concentrate on the question of the mechanism responsible for diffraction. In section 2, I shall briefly describe different approaches to deep inelastic diffraction and their expected significance. The question of the energy dependence of diffraction will be addressed. In section 3, I shall discuss a personal selection of main open questions in diffraction and in section 4, I will concentrate on the most promising processes suited for a separation of soft and hard pQCD contributions to diffractive scattering at HERA. Main emphasis will be put on processes that can be calculated in pQCD and on the pQCD description of the pomeron.

II. PRESENT KNOWLEDGE OF DEEP INELASTIC DIFFRACTION AT HERA

Three different approaches to deep inelastic diffractive scattering are mainly discussed in the literature:

1. **Resolved pomeron a la Ingelman and Schlein and diffractive parton densities**

   In the model of Ingelman-Schlein [2] $F_2^{D(4)}$ can be written as the product of the probability, $f_{p\,I\!P}$, to find a pomeron in the proton, and the structure function $F_2^{I\!P}$ of the pomeron:

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

   In analogy to the quark - parton - model of the proton, β can be interpreted as the fraction of the pomeron momentum carried by the struck quark and $F_2^{I\!P}(\beta,Q^2)$ can be described in terms of momentum weighted quark density functions in the pomeron.

Eq.(4) is a special case of the more general definition of diffractive parton densities [3,4]:

$$F_2^{D(4)}(\beta, Q^2; x_{I\!P}, t) = \sum_i e_i^2 \cdot f^D(\beta, Q^2; x_{I\!P}, t) \tag{5}$$

where the sum runs over all partons with charge e_i. Here no Regge type factorization of $F_2^{D(4)}$ into a flux, $f_{p\,I\!P}(x_{I\!P}, t)$, and $F_2^{I\!P}$ is assumed. The diffractive parton densities can be subjected to the same DGLAP evolution equations as used in non - diffractive deep inelastic scattering [5].

2. **pQCD calculation of diffraction via two gluon exchange**

   The pQCD calculation of $ep \to e' q\bar{q}p'$ was mainly intended to describe exclusive (or lossless) high p_T di-jet production, and in the model of [6] estimates on the total inclusive diffractive cross section are given. The calculation of diffractive di-jet production can be performed in pQCD for large photon virtualities Q^2 and high p_T of the $q(\bar{q})$ jets [6–11] or for heavy quarks [12,13].

   Since the processes discussed here are mediated by two gluon exchange, different assumptions on the nature of the exchanged gluons can be made: in [7,8] the gluons are non perturbative, in [6] they are a hybrid of non perturbative and perturbative ones and in [9,10] they are taken from a NLO parameterization of the proton structure function [14,15]. The cross section is essentially proportional to the gluon density squared of the proton: $\sigma \sim \left[x_{I\!P} G_p\left(x_{I\!P}, \mu^2\right)\right]^2$ at the scale $\mu^2 = p_T^2/(1-\beta)$. In the case of heavy quarks the cross section is finite for all p_T, and the scale is taken to be $\mu^2 = (p_T^2 + m_f^2)/(1-\beta)$ [12,13], where m_f is the mass of the heavy quark. Since the gluon density depends on the scale μ^2 which is set by the details of the interaction, this type of processes violates Regge type factorization.

   Due to the different gluon densities, different $x_{I\!P}$ dependencies of the cross sections are expected and are further discussed in [9,10], where also numerical estimates are presented.

3. **Semi-classical approach to diffraction and Soft Color Interactions**

   Buchmüller et al. [16–20] attempt to describe $\gamma^* + p \to q + \bar{q} + p'$ and $\gamma^* + p \to q + \bar{q} + g + p'$ in a semi - classical approach where the partons interact with the color field of the proton. The cross section of the first process turns out to be of similar structure as in the pQCD calculation of [10] and is proportional to a constant, which can be interpreted in the semi-classical approach as the gluon density squared of the proton. The $q\bar{q}g$ process is described with a usual boson gluon fusion subprocess involving an effective diffractive gluon density [19]. In [21] it is shown that this semi-classical approach is exactly equivalent to the approach using diffractive parton density functions of quarks and gluons convoluted with the proper partonic scattering amplitude. Therefore the semi-classical approach will not be discussed separately in the following.

   In the Soft Color Interaction (SCI) approach events with large rapidity gaps are produced by color reorientation of the colored partons originating from the hard interaction process [22–26], before fragmentation. Also here no pomeron is explicitly introduced. All parameters in this model are determined by non-diffractive deep inelastic scattering, except the probability for soft color reorientation R_{SCI}.

From a phenomenological point of view the first approach (resolved pomeron and diffractive parton densities) is the most advanced. A QCD analysis of the inclusive structure function $F_2^{D(3)}$ has been performed by the H1 collaboration [27] to describe the Q^2 evolution including an estimate of the intercept of the pomeron trajectory $\alpha_{I\!P}(0)$ and the parton distribution functions of the pomeron. Here $F_2^{D(3)}$ was described including a contribution from sub-leading trajectories, giving a good description of the data. At the present level of accuracy, $\alpha_{I\!P}(0)$ is consistent with having no dependence on Q^2 [27,28]. for $Q^2 > 1$ GeV^2.

It has been shown by J. Collins [5] that the QCD factorization theorem also holds for hard diffraction, saying that

$$F_2^D = \sum_i C_{2i} \otimes f_i^D + \text{non-leading power of Q} \tag{6}$$

where $\otimes$ indicates the convolution of the diffractive parton density, f_i^D, with the hard scattering coefficient C_{2i} and the sum is running over all partons i. Therefore standard DGLAP evolution equations are also applicable to F_2^D. These diffractive parton density functions can then be used to model the hadronic final state, in close analogy to standard non-diffractive deep inelastic scattering. Therefore the full machinery of Monte Carlo techniques used in deep inelastic scattering can be also applied to here [29]. This approach is very successful in the description of hadronic final state properties (see for example [29–31]). However one has to note that if the diffractive cross section can be factorized into a diffractive parton density and a hard scattering process. This implies that a softer part is left, which can be identified with a pomeron remnant. This remnant does not participate in the hard interaction and has smaller p_T than the partons of the hard interaction.

The proof of factorization given in [5] does not imply Regge factorization, meaning that $\alpha_{I\!P}(0)$ found in deep inelastic diffractive scattering needs not to be the same as the one observed in hadron-hadron collisions and indeed measurements of $\alpha_{I\!P}(0)$ show that in deep inelastic diffraction $\alpha_{I\!P}(0) \sim 1.2$ [27,28], which is larger than $\alpha_{I\!P}(0) = 1.08$ obtained from the total cross section in hadron-hadron and photon-hadron collisions.

From a theoretical point of view the second approach (pQCD calculation of diffraction via two gluon exchange) is more attractive, since here diffraction is related to the gluon density squared of the proton, and no free parameters are left, except the gluon density. Such calculations based on the gluon density squared predict a larger intercept of the pomeron trajectory $\alpha_{I\!P}(0)$ than expected from the soft pomeron. The intercept is essentially given by the rise of the gluon density at small values of x. Moreover since the gluon density depends also on the scale μ^2 of the hard subprocess, this calculation predicts a violation of the Regge type factorization of the cross section into a part which only depends on $x_{I\!P}$ and t and another part depending only on β and Q^2. Diffractive processes described by two gluon exchange are not covered by the factorization proof of [5], since all the partons in the system M_X participate in the hard interaction and the cross section is found to be of higher twist [10].

The pQCD calculations are quite complicated, and presently only the most simple diagrams have been fully calculated: $\gamma^* p \to q\bar{q}p$ both for light and heavy quarks and also the production of vector meson bound states. Even with only these processes included, an impressively good description of the hadronic energy flow and vector meson production could be achieved, as is shown in [29]. The contribution for $\gamma^* p \to qg\bar{q}p$ has been estimated in a specific region of the phase space, where the gluon has much smaller transverse momentum than the quarks [6,32,33]. A more complete calculation of this process is just being performed [34].

Within the present accuracy of diffractive measurements in deep inelastic scattering at HERA, all three very different approaches to hard diffraction (resolved pomeron model, pQCD calculation and soft color interactions) are able to describe the experimental data reasonably well.

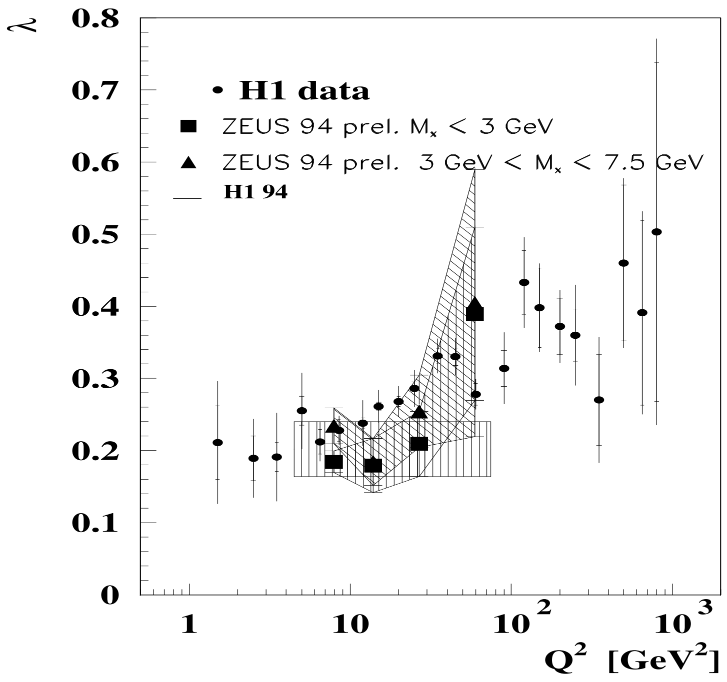

FIG. 1. The slope of $F2 \sim x^{-\lambda}$ [35] (full dots) as a function of Q^2 compared to $(\alpha_{I\!P}(0) - 1)$ (shaded areas) obtained from F_2^D [27,28]. The ZEUS data on diffraction have been corrected for finite t, as given in [28]: $\alpha_{I\!P}(0) = \bar{\alpha_{I\!P}} + 0.03$.

It is, however, important to understand the relation of the energy dependence of the inclusive structure function F_2 to that of the diffractive structure function F_2^D. The optical theorem relates the total cross section of $\gamma^* p$ to the forward scattering amplitude of elastic scattering and to the diffractive cross section. Writing the total cross section of

$\gamma^* p$ as $\sigma_{tot}(\gamma^* p) \sim x^{-\lambda}$ and the cross section for diffractive dissociation of $\gamma^* p$ as $\sigma_{diff}(\gamma^* p) \sim x_{I\!P}^{1-2\alpha_{I\!P}(t)}$ one can ask whether the relation $\lambda = (\alpha_{I\!P}(0) - 1)$ holds, which would indicate that the same mechanism (or the same pomeron) is responsible for the rise of the total inclusive γp cross section at small x and for hard diffractive scattering. In Fig. 1 the exponent λ as a function of Q^2 as obtained from F_2 [35] is plotted (full dots), together with $(\alpha_{I\!P}(0) - 1)$ obtained from the measurements of F_2^D [27,28] (shaded areas). There is remarkable agreement between the measurement from the total cross section and from diffraction, although the errors are still large. The important message is, that λ and $\alpha_{I\!P}(0) - 1$ is of the same magnitude and both are larger than the value obtained from hadron hadron collisions ($(\alpha_{I\!P}(0) - 1) = 0.08$). This suggests that the same mechanism responsible for the rise of F_2 at small x is also relevant in deep inelastic diffraction.

III. MAIN OPEN QUESTIONS

One of the main issues to be understood is still the question of the mechanism responsible for deep inelastic diffraction. If diffraction can be mainly described by the approach using diffractive parton densities, then a sort of soft pomeron remnant must be observable. This just follows directly from the factorization theorem in [5], because not all partons in the system M_X participate in the hard interaction. On the other hand, in the pQCD calculation of diffraction via two gluon exchange, all partons participate in the hard interaction resulting in the absence of a soft pomeron remnant. Are there ways to unambiguously identify a $I\!P$ remnant, or on the contrary is there a significant set of events which definitely has no $I\!P$ remnant and which can be described by the pQCD mechanisms outlined above? This point is directly related to the question of a separation of hard pQCD processes in diffraction (where *hard* means that all partons in the diffractive system M_X are perturbative) from the part where soft processes are also involved (identified by the presence of a soft $I\!P$ remnant).

Another issue is the energy dependence of diffraction: from the F_2^D measurements the pomeron intercept is found to be $\alpha_{I\!P} \simeq 1.2$, which is larger than the value found for the soft pomeron ($\alpha_{I\!P}^{soft} \simeq 1.08$). Thus the question arises, whether the pomeron in deep inelastic scattering is different from the one seen in hadron hadron collisions, and whether a superposition of a soft pomeron with a hard QCD pomeron (perturbative two gluon exchange) is already observed. But the energy dependence of the cross section alone is not sufficient to establish the existence of a hard pQCD pomeron (two gluon state). As in the case of the inclusive structure function F_2 there could be a mixture of soft and hard processes, resulting in an effective slope λ as measured. It is however suggestive, that the slope of the energy dependence as measured in the inclusive diffractive structure function F_2^D is similar to the one obtained from the inclusive structure function F_2, from vector-meson production at large Q^2 and from J/ψ production. Vector-meson production at large Q^2 can be consistently calculated in pQCD, at least for longitudinal polarized photons. Whereas in the soft pomeron regime shrinkage of the diffractive peak must be observed (given by $\alpha' = 0.25$), A. Levy [36] found evidence for no shrinkage in J/ψ production ($\alpha' \simeq 0$). If confirmed this would be one of the most important ingredients for a hard diffractive pQCD process.

Understanding of diffraction in terms of pQCD requires the separation of the soft from the hard diffractive regime. Several processes have been proposed as signatures for hard pQCD diffraction. The most promising processes for hard diffraction accessible by pQCD I shall address in the following sections.

IV. MOST PROMISING PROCESSES

In this section I shall discuss signatures for hard diffraction calculable in pQCD:

- exclusive di-jets at $Q^2 > 0$
- charm production
- light vector-mesons at small t and large Q^2 or heavy vector-mesons
- vector-mesons at large t
- rapidity gaps between jets
- deep virtual Compton scattering at small and large t

All these processes can be calculated completely in pQCD and they all have in common a specific energy dependence, which is different from the one expected from soft pomeron processes. Thus the observation and the measurement of these processes is a crucial test of pQCD calculations of diffraction, and it will help solving the question of the relative size and the interplay of soft and hard processes in diffraction.

A. Di-jets

The calculation of exclusive diffractive di-jet production $ep \to e' q\bar{q}p$ can be performed using pQCD for large photon virtualities Q^2 and high p_T of the $q(\bar{q})$ jets [6–11]. Since both quark and anti-quark participate in the hard interaction, they both receive the same transverse momentum in the $\gamma^* I\!P$ system leaving no remnant behind. This has to be contrasted to the approach using diffractive parton densities, where also a $q\bar{q}$ state can be produced in a QPM process, but there the quarks have vanishing transverse momentum (except from a small intrinsic p_T) in the $\gamma^* I\!P$ center of mass system and therefore one of the quarks serves as a pomeron remnant.

The experimental observation of exclusive (or lossless) diffractive di-jet production would give new and important information, since this process is of higher twist nature and it cannot be factorized into a diffractive parton density convoluted with the hard scattering matrix element. Thus it is not covered by the factorization proof of [5].

The most striking feature of the perturbative QCD calculation of diffractive $q\bar{q}$ final states is the ϕ dependence of jet production. Here ϕ is the angle between the lepton and the quark plane in the $\gamma^* p$ center of mass system. Since it is difficult to identify the quark jet at hadron level, the jet with the largest p_T can be used (the partons have the same p_T, but the reconstructed jets not necessarily because of the jet reconstruction). The azimuthal asymmetry obtained after jet reconstruction is shown in Fig. 2, where also a comparison with the azimuthal asymmetry expected from a diffractive BGF process with one gluon exchange (from a resolved pomeron) is given. Also at the hadron level the difference between the two approaches is clearly visible.

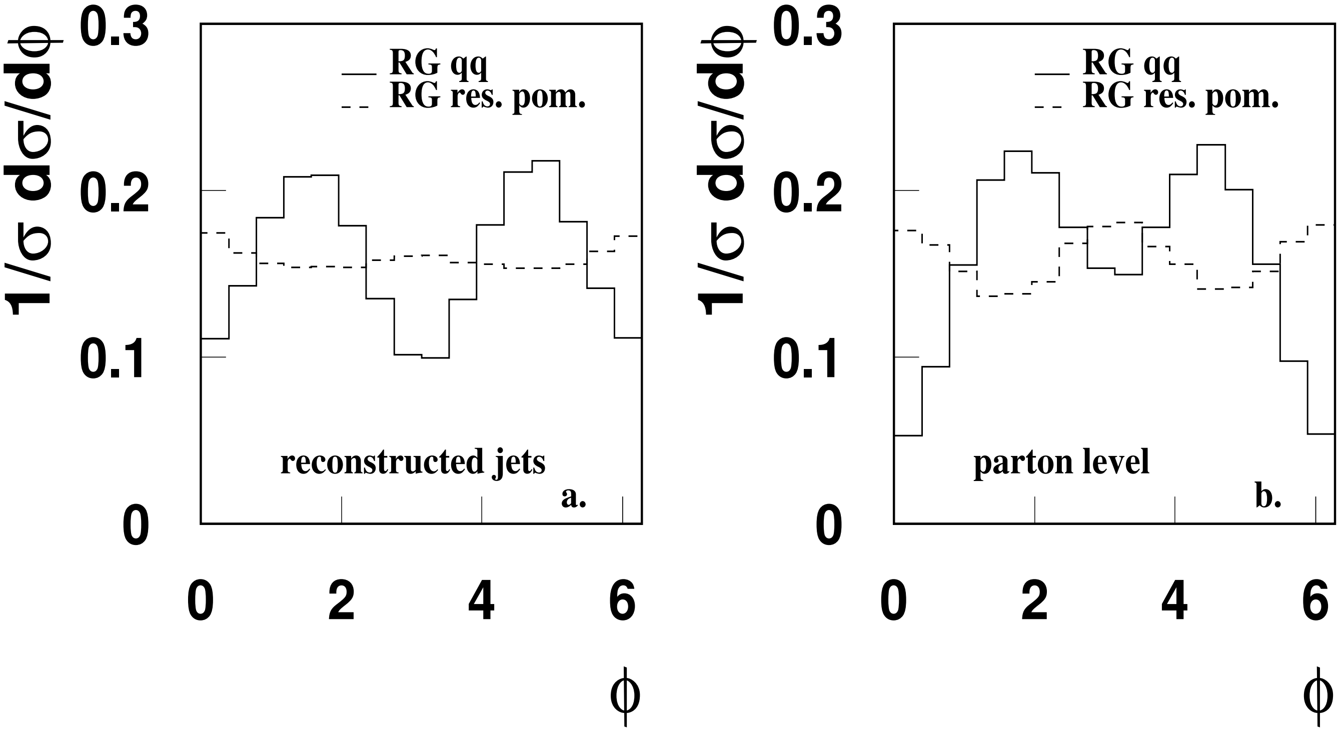

FIG. 2. *a.* The ϕ dependence of one jet with respect to the electron plane for high p_T di jet events in the region $0.1 < y < 0.7$, $5 < Q^2 < 80$ GeV^2 $x_{I\!P} < 0.05$ and $p_T^{jet} > 2$ GeV. The solid line shows the prediction from the two gluon exchange mechanism after jet reconstruction at the hadron level. The dashed line shows the ϕ dependence from a BGF type process in diffraction (one gluon exchange). In *b.* the ϕ dependence of the quark with the electron plane is shown for comparison. The predictions are obtained with the RAPGAP Monte Carlo [37].

In the kinematic region defined by $0.1 < y < 0.7$, $5 < Q^2 < 80$ GeV^2 $x_{I\!P} < 0.05$ and $p_T^{jet} > 2$, the cross section for $ep \to e'q\bar{q}p$ is (calculated with the RAPGAP Monte Carlo using the GRV parameterization for the gluon density) $\sigma^{q\bar{q}} = 46$ pb, calculated with the RAPGAP Monte Carlo using the GRV parameterization for the gluon density. This should be compared to the cross section of $\sigma^{res. I\!P} = 1138$ pb also obtained from RAPGAP, but within the resolved pomeron model using the parameterization of the diffractive parton densities by [27]. However the pQCD calculation of $ep \to e'q\bar{q}p$ is only valid in a region of relatively small values of M_X or equivalently medium values of $\beta > 0.1$. The difficulty of identifying exclusive di-jets is further discussed in [29].

In the region of large M_X the contribution from $q\bar{q}g$ states becomes important. Estimates of this cross section have been given in [6,32] in a region where the transverse momentum of the gluon is much smaller than that of the quarks. The final state configuration is then similar to the one obtained using boson gluon fusion convoluted with a diffractive gluon density. A full calculation where no ordering in transverse momentum of the final state partons is supposed, is just being performed [34]. With this calculation a detailed test of the pQCD prediction for hard diffraction can be made: the energy dependence of the cross section is still proportional to the gluon density squared, at a scale depending on the transverse momentum of the outgoing partons. Thus an energy dependence stronger than expected from soft pomeron exchange and a violation of Regge type factorization should be observed. Additional information of the underlying mechanism can be obtained from an analysis of the 3 jet final state configuration.

B. Charm - production

The calculation of a diffractive $q\bar{q}$ state can also be extended to heavy quark production [12,13], where the difficulty of identifying high p_T di-jets may be avoided by the observation of D^* mesons. Because of the heavy quark mass, no p_T^{cut} is necessary.

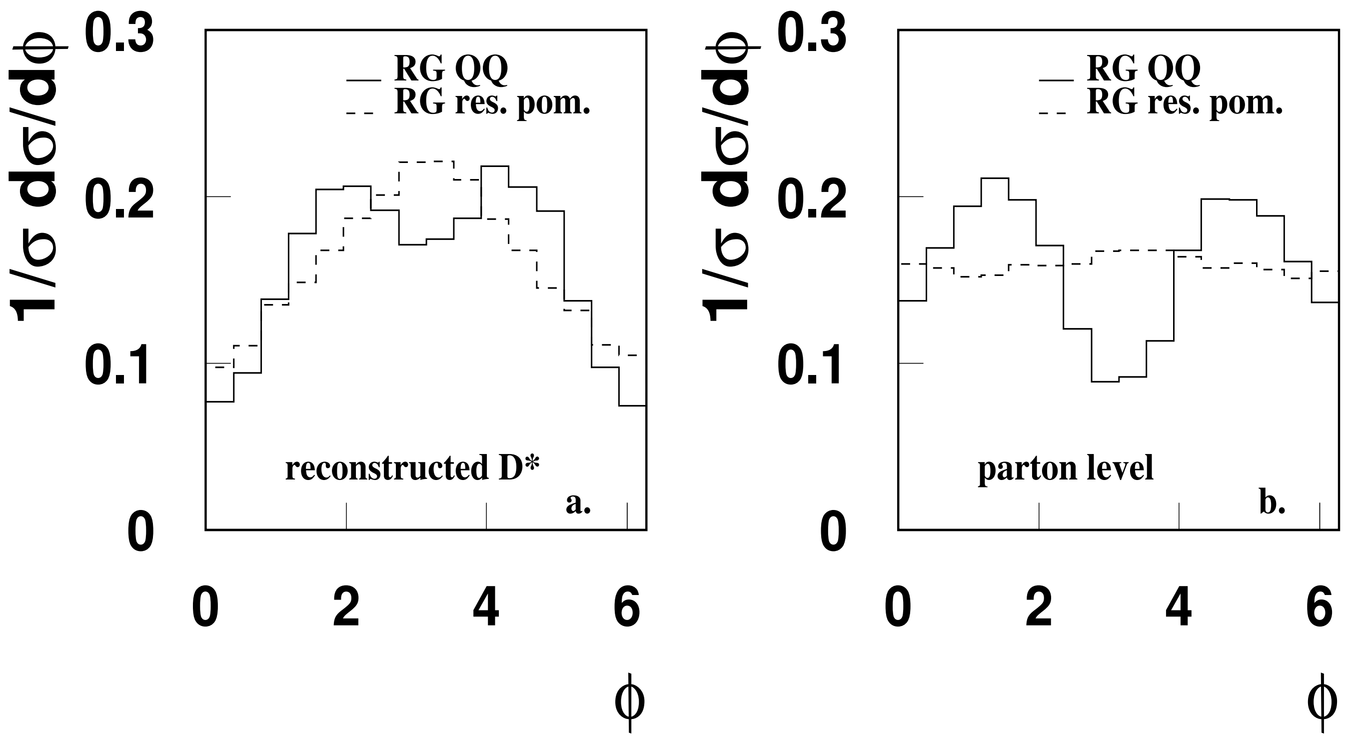

FIG. 3. a. The ϕ dependence of the D^* with respect to the electron plane in the kinematic region $0.06 < y < 0.6$, $2 < Q^2 < 100$ GeV^2 $x_{I\!P} < 0.05$, $p_{T\ lab}^{D^*} > 1$ GeV and $|\eta_{lab}^{D^*}| < 1.25$. The solid line shows the prediction from the two gluon exchange mechanism after hadronization. The dashed line shows the ϕ dependence from a BGF type process in diffraction (one gluon exchange). In b the ϕ dependence of the quark with respect the electron plane is shown, without the D^* acceptance cuts of a. The predictions arc obtained with the RAPGAP Monte Carlo [37].

In Fig. 3a the ϕ dependence is shown for D^* mesons produced by the two gluon exchange mechanism and compared to the prediction from a boson gluon fusion process using a diffractive gluon density in a kinematical region typical for the analyzes of the HERA experiments ($0.06 < y < 0.6$, $2 < Q^2 < 100$ GeV^2 $x_{I\!P} < 0.05$, $p_{T\ lab}^{D^*} > 1$ GeV and $|\eta_{lab}^{D^*}| < 1.25$) This process may thus also be used to differentiate between the two approaches. One should note that the different ϕ distribution observed here, as compared to the ones from the jets, is due to the cuts in the laboratory frame used by the experiments to identify the D^* meson. Without the $p_{T\ lab}^{D^*}$ cut, the ϕ distribution looks the same as for the jets. In Fig. 3b the ϕ dependence at parton level is shown without the D^* acceptance cuts.

Within the search regions of the H1 experiment ($0.06 < y < 0.6$, $10 < Q^2 < 100$ GeV^2, $x_{I\!P} < 0.05$, $p_T^{D^*} > 1$ GeV and $|\eta^{D^*}| < 1.25$) and the ZEUS experiment ($0.04 < y < 0.7$, $10 < Q^2 < 80$ GeV^2 $\eta_{max} < 2$, $p_T^{D^*} > 1$ GeV and $|\eta^{D^*}| < 1.5$), the cross sections calculated with RAPGAP for the two gluon exchange process $ep \to e'c\bar{c}p$ including charm fragmentation into D^* are: $\sigma = 68$ pb (for H1) and $\sigma = 75$ pb (for ZEUS), compared to the measurement of H1 and ZEUS [31]: $\sigma = 380 \pm^{150}_{120} \pm^{140}_{110}$ pb and $\sigma = 875 \pm 248 \pm^{395}_{199}$ pb obtained from a luminosity of $L = 2.5$ pb^{-1} and $L = 6.4$ pb^{-1}, respectively. The D^* cross section predicted from boson gluon fusion convoluted with the diffractive gluon density as obtained from a fit to F_2^D by H1 [27] is: $\sigma = 283.6$ pb for the H1 measurement and $\sigma = 509.1$ pb for ZEUS measurement. Given the large errors on the measurement, no firm conclusion on the underlying production mechanism can be drawn. [1]

Charm production in deep inelastic diffraction is one of the key processes for understanding diffraction in terms of pQCD. Besides the measurements of the total cross section for diffractive charm production, the energy (or $x_{I\!P}$) dependence will help to differentiate between different mechanisms. Moreover as shown in Fig. 3, the measurement of the ϕ dependence is one of the most interesting ones, since it allows to unambiguously distinguish the hard pQCD process involving 2 gluon exchange from standard boson gluon fusion processes. However, the cross section is rather small and a large increase in luminosity is needed for a precise measurement of diffractive charm production as a function of $x_{I\!P}$. It has been argued in [39], that a luminosity of $L \sim 750$pb^{-1} is needed for a reasonable measurement of the differential cross section $d\sigma^{D*}/dx_{I\!P}$.

C. Vector-meson production

The cross section for exclusive vector meson production (light vector-meson production at large Q^2 and heavy vector meson production even in the photo-production region) can be calculated in pQCD, via two gluon exchange, similar to the one discussed in the previous sections on high p_T jet and open charm production. Measurements (for an overview see [31]) of the energy dependence of the vector-meson production cross section are consistent with the pQCD calculations and show a much stronger rise with W than expected from soft pomeron processes. However only in photo-production of J/ψ mesons the energy dependence could be determined from HERA measurements alone with a reasonable precision. It has been shown in [40] that 10000 events are necessary for a determination of the energy slope with an error of $\Delta\alpha_{I\!P}(0) \sim 0.01$. In the 1995 data H1 has ~ 100 events for $2 < Q^2 < 8$, thus a factor of 100 in luminosity is needed to meet $\Delta\alpha_{I\!P}(0) \sim 0.01$.

Even more important for the proof of a pQCD process responsible for vector-meson production is the absence of shrinkage of the diffractive peak. In Regge theory the $I\!P$ trajectory is given by: $\alpha_{I\!P} = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$ with t being the momentum transfer from the proton and $\alpha'_{I\!P} = 0.25$ as determined from soft hadronic collisions. A confirmation of the reported evidence for no shrinkage in J/ψ production [36] would be a clear indication of hard pQCD processes in heavy vector-meson production. However, in the analysis [36] low energy experiments had to be included. To reduce the uncertainty in normalization and background subtraction a measurement of $\alpha'_{I\!P}$ needs to be done within a single experiment. This would require a luminosity of ~ 250 pb^{-1} for a determination of $\Delta\alpha'_{I\!P} \sim 0.12$ for ρ production in the range $20 < Q^2 < 25$ GeV^2, as shown in [40].

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[1] In the meantime new results on diffractive charm production have been presented at ICHEP 98 by the H1 experiment [38], with much smaller statistical error. The cross section for D^* production in the region $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$, $x_{I\!P} < 0.04$, $p_T^{D^*} > 2$ GeV and $|\eta^{D^*}| < 1.5$ is $\sigma = 154 \pm 40 \pm 35$ pb compared to a prediction from the two gluon exchange mechanism of $\sigma = 112$ pb obtained from the RAPGAP Monte Carlo program.

J/ψ production at large t can be calculated in pQCD, because two large scales are involved, the J/ψ mass at the photon vertex and the large $t > 1$ GeV^2 at the proton vertex. For $t \sim m^2_{J/\psi}$ this process can be calculated using the BFKL evolution equation. Measurements have been performed and are in agreement with the pQCD calculations. The t distribution becomes flatter at large t than expected from an exponential t distribution. The W dependence of the cross section would yield directly a measurement of the BFKL pomeron intercept. At present the statistics is too low for a precise measurement. Besides the energy dependence, a measurement of the t slope as a function of W should show again the characteristic pQCD feature of no shrinkage of the diffractive peak.

D. Rapidity gaps between jets

Similarly to J/ψ production at large t, the cross section for rapidity gaps between jets can be calculated in pQCD. Instead of the J/ψ mass and the large t value, here the perturbative scale is set by the transverse momenta of the jets. This process is mediated also by two gluon exchange. If the rapidity gap between the jets is large enough, a rise of the cross section, typical for BFKL, should be obtained. Measurements [41] show that a faction of $\sim 10\%$ of the jet events have a rapidity gap of $\Delta\eta > 3.5$. This fraction is a factor of 10 larger than in a similar search at $p\bar{p}$ collisions.

However one has to worry about the gap survival probability because of soft interactions between the remnants of the photon and the proton. The difference in the fraction of events with rapidity gaps between the jets as measured in $p\bar{p}$ collisions and in ep scattering might be understood in terms of color transparency as argued in [42]. Partons in a spatially small configuration can screen each other's color leading to color transparency and a small interaction cross section with no final state interaction. On the other hand large size configurations will have large cross sections and final state interactions. Hadron hadron interactions are of the latter type, having a large cross section. In resolved photon processes in photo-production the final state interactions will fill the gap between jets like in hadron hadron collisions, resulting in a smaller cross section for events with rapidity gaps between the jets. In contrary direct photon processes should yield a larger cross section, because no final state interaction will spoil the gap. It would be important to measure the fraction of events with large rapidity gap between the jets as a function of x_γ, the fraction of the photon momentum carried in the hard scattering process. Even more if the same measurement is performed in deep inelastic scattering ($Q^2 > 0$), where resolved photon processes are less important, a even higher fraction of events with rapidity gaps between the jets could be expected than observed in photo-production and $p\bar{p}$ scattering.

The limited detector acceptance also limits the size of the rapidity gap that can be observed in the experiments. Especially BFKL effects could contribute to large rapidity gap values. This very interesting process has experimental limitations coming from the jet requirement. A similar measurement, but not relying on jets has been proposed in [41,43].

E. Deep - Virtual Compton Scattering

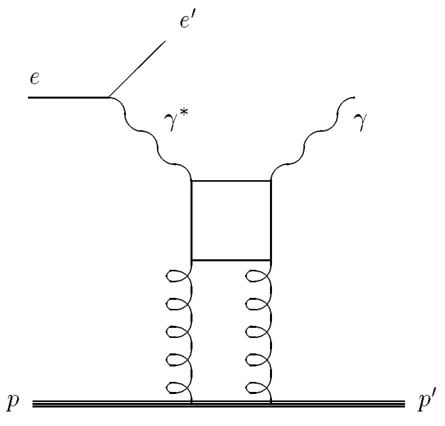

FIG. 4. Basic diagram for deep virtual compton scattering.

Deep virtual compton scattering ($\gamma^* p \to \gamma p'$) is another example of a diffractive process, which can be calculated in pQCD [44–46]. The virtual photon splits into a $q\bar{q}$ pair which then interacts via two gluon exchange with the proton, similarly to elastic vector-meson production, but instead of a vector-meson, a real photon appears in the final state (Fig 4). This process is again proportional to the gluon density squared of the proton. The main advantage of this process over vector-meson production is that it can be fully calculated in pQCD, whereas in the case of vector-meson production a main uncertainty comes from the poorly known wave-function of the vector-meson and possible relativistic corrections [47]. A more detailed calculation showed that diffractive virtual compton scattering is sensitive to the off diagonal gluon density, because a finite momentum transfer is needed to put the incoming virtual photon on mass shell [44–46]. At large Q^2 the energy dependence of this process is expected to be similar to the ones of vector-meson production, and much stronger than expected from soft pomeron exchange.

This process would then complete the measurement of vector-meson production at large energies: production of real photons, ρ, ω, ϕ and J/ψ. Very interesting would be the measurement of the t slope and whether and how it changes with the final state vector-meson. Again, if this process can be described in terms of pQCD, no shrinkage of the diffractive peak should be observed ($\alpha'_{I\!P} \sim 0$).

Going one step further, similar to heavy vector-meson production at large t, deep virtual compton scattering at large t can be studied. This would then also be similar to processes with rapidity gaps between jets where one jet is replaced by the real photon in the final state. Because of the appearance of the photon in the final state, no final state QCD interactions are present, which could spoil the gap, compared to the measurement with rapidity gaps between jets. The main advantage here is, that no jets, nor vector-meson reconstruction are required, and that the detection of a high energetic photon is much simpler, and it can even be detected at much smaller angles, leading to a larger rapidity region between the proton dissociative system and the photon. As argued in the previous sections, having the largest possible rapidity range would be promising for the search of new small x dynamics like BFKL.

V. SUMMARY AND OUTLOOK

The main problems to be understood in deep inelastic diffraction are the relatively large diffractive cross section and its energy dependence, which is stronger than expected from soft processes. The energy dependence might be understood in terms of pQCD calculations involving 2 gluon exchange processes. Such calculations are consistent with present HERA data, but a firm conclusion on the mechanism responsible for deep inelastic diffraction cannot be drawn yet.

A significant increase in luminosity is needed for precise measurements of the energy dependence and the t slope in various processes in order to study the contribution from two gluon exchange mechanisms. If these are established experimentally, it would be a major step forward in understanding diffraction in terms of fully calculable pQCD processes. Even more, this will improve our understanding of the structure of the proton significantly. Such a major increase in luminosity can be expected after the luminosity upgrade at HERA, which is planned for the year 2000.

Given the importance of understanding diffraction in terms of pQCD, one should not forget the attractive and unique possibility for future experiments measuring collisions between electrons from a possible linear collider with protons from HERA (500 GeV e $\times$ 820 GeV p). In such a scenario diffraction and the structure of the proton could be studied at values of $x_{I\!P}$ or x a order of magnitude smaller than presently accessible at HERA. This could open a completely new area in diffraction.

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