INCLUSIVE DIFFRACTION*

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Results are given on the measurements of the hard diffractive interactions at HERA ep collider. The structure of the diffractive exchange in terms of partons and the factorisation properties are discussed, in particular by comparing the QCD predictions for dijets and D^* with measurements both in the photo and electroproduction regimes.

1. Introduction

The high energies of the HERA ep collider and of the Tevatron $p\bar{p}$ collider allow us for the first time to study diffraction in terms of perturbative QCD (pQCD), i.e. in the presence of a hard scale, which is called hard diffraction. At HERA the diffractive interaction takes place between the hadronic behaviour of the exchanged virtual photon and the proton (see Fig. 1a), and between the two protons at Tevatron (see Fig. 1b). The possible hard scales are large Q^2, the negative of the four-momentum squared of the exchanged virtual photon, large transverse energy, E_T, in jet production, heavy-quark mass or large momentum transfer squared at the proton vertex, t. The hard scale presence of large Q^2 at HERA and large E_T at Tevatron, in particular, gives the possibility to probe the partonic structure of the diffractive exchange.

This article concentrates on the factorisation properties using a structure function approach giving insight into the understanding of the nature of diffraction in terms of partons. Before reviewing recent measurements,

*contribution to the proceedings of the ringberg workshop "new trends in hera physics 2005" a short discussion on the parton densities of the diffractive exchange and their relation to the diffractive cross section is given.

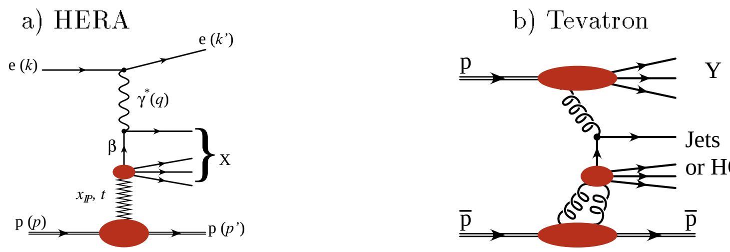

Figure 1. Basic diagrams for diffraction in presence of a hard scale at HERA and at Tevatron

Although it will not be covered here, the study of diffraction has several other topics of interest on top of the diffractive exchange measurement in terms of partons. It gives access to the partons correlation through the exclusive final state measurements (generalised parton distribution formalism). It allows to test the region of validity of the different asymptotic dynamical approaches of QCD that are DGLAP and BFKL from the measurement of vector meson or photon exclusive production at large values of $|t|$. Finally, the alternative approach of colour Dipole models allows us to study the transition between non-perturbative and perturbative regimes and to test the presence of a gluon density saturation in the proton.

2. Partonic Structure of Diffractive Exchanges and Factorisation Properties

The inclusive diffractive cross section at HERA, $ep \to eXp$, can be defined with the help of four kinematic variables conveniently chosen as Q^2, $x_{I\!P}$, β and t, where $x_{I\!P}$ and β are defined as

$$x_{I\!P} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2}, \qquad \beta \simeq \frac{Q^2}{Q^2 + M_X^2};$$

M_X being the invariant mass of the X system, and W the $\gamma^* - p$ center of mass energy. $x_{I\!P}$ can be interpreted as the fraction of the proton momentum carried by the exchanged Pomeron and β is the fraction of the exchanged momentum carried by the quark struck by the photon, or in other terms, the fraction of the exchanged momentum reaching the photon. These variables are related to the Bjorken x_{Bj} scaling variable by the relation $x_{Bj}= \beta \cdot x_{I\!P}$. The presence of the hard scale, Q^2, ensures that the virtual photon is point-like and that the photon probes the partonic structure of the diffractive exchange (Fig. 1a), in analogy with the inclusive DIS processes.

Factorisation Properties in hard Diffraction.
For hard QCD processes in general, like high-E_T jet production or DIS, the cross section can be factorized into two terms: the parton density and the hard parton-parton cross section. The cross section can be written as

$$\sigma = \sum_i f_i(\xi, \mu^2)\ \hat{\sigma}_{i\gamma}(\xi, \mu^2)$$

where i runs over all parton types, f_i is the parton density function for the i-th parton with longitudinal momentum fraction ξ, which is probed at the factorisation scale μ. $\hat{\sigma}_{i\gamma}$ denotes the cross section for the interaction of the i-th parton and the virtual photon. Such an expression, often referred to as the QCD factorisation theorem, is well supported by the data. If the theorem holds, only one parton per hadron is coupled to the hard scattering vertex.

The theorem is proven to be applicable at all orders in the strong force coupling constant α_s for the leading log Q^2 for hard inclusive diffraction [1] in ep collisions at large Q^2, namely

$$\frac{d\sigma(x, Q^2, x_{I\!P}, t)}{dx_{I\!P} dt} = \sum_i \int_x^{x_{I\!P}} dz\ \hat{\sigma}_{i\gamma}(z, Q^2, x_{I\!P})\ f_i^D(z, Q^2, x_{I\!P}, t)$$

where z is the longitudinal momentum fraction of the parton in the proton, $\hat{\sigma}_{i\gamma}$ is again the hard scattering parton-photon cross section for hard diffraction and f_i^D is the diffractive parton density for the i-th parton. f_i^D can be regarded as the parton density of the diffractive exchange occuring at a given $(x_{I\!P}, t)$. If such a theorem holds, f_i^D should be universal for all hard processes, e.g. inclusive diffraction, jet or heavy-quark production etc.

If the scattered proton is not detected in Roman Pots, the t variable is not measured with enough accuracy and is integrated over. In analogy with non-diffractive DIS scattering, the measured cross section is expressed, in the neutral current case, in the form of a three-fold diffractive structure function $F_2^{D(3)}(Q^2, x_{I\!P}, \beta)$ (neglecting the longitudinal contribution and Z

exchange),

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

where y is the usual scaling variable, with $y \simeq W^2/s$.

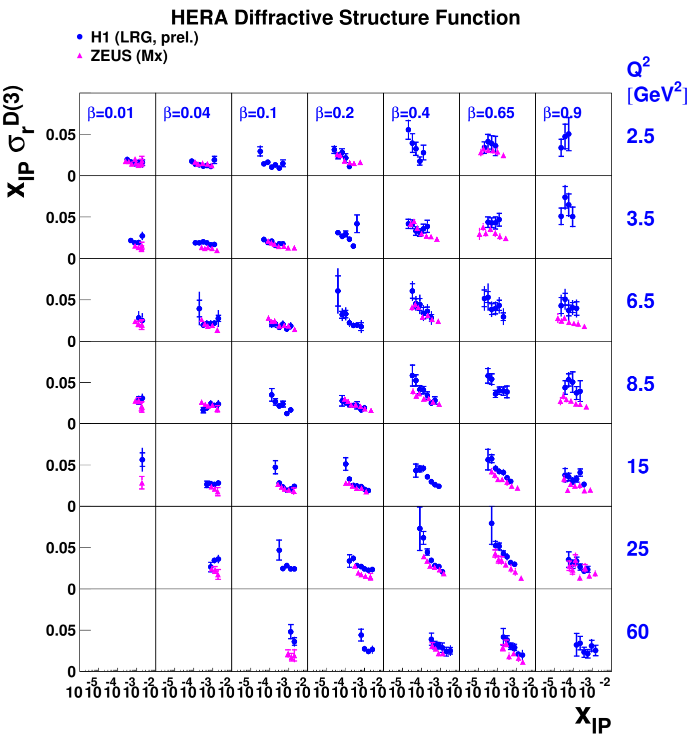

Figure 2. H1 and ZEUS reduced cross section (equal to $F_2^{D(3)}$ if F_L^D and F_3^D can be neglected) measurements as a function $x_{I\!P}$ for fixed values of Q^2 and β.

Conveniently, the Regge factorisation is applied where $F_2^{D(3)}$ is written in the form

$$F_2^{D(3)}(Q^2, x_{I\!P}, \beta) = f_{I\!P/p}(x_{I\!P}) \cdot F_2^D(Q^2, \beta),$$

using the approximation that the pomeron ($I\!P$) flux $f_{I\!P/p}(x_{I\!P})$ is independent of the $I\!P$ structure $F_2^{D(2)}$, by analogy with the hadron structure functions, β playing the role of Bjorken x_{Bj}. The $I\!P$ flux is parameterised using a Regge inspired form $f_{I\!P/p} = e^{bt}/x_{I\!P}^{2\alpha_{I\!P}(t)-1}$.

H1 [2] and ZEUS [3] measurements of $F_2^{D(3)}$ diffractive structure function are presented in Fig. 2 as a function of $x_{I\!P}$ for fixed values of Q^2 and β. The reduced cross section σ_r^D presented in the figure is equal to $F_2^{D(3)}$ if F_L^D and F_3^D can be neglected.

Both measurements are in good general agreement, although the Q^2 dependence at fixed β is stronger in the H1 measurement and the last bin in β exhibits higher values for the H1 measurement for $Q^2 < 25$ GeV^2.

To fit the $F_2^{D(3)}(Q^2, x_{I\!P}, \beta)$ points H1 includes a sub-leading Reggeon ($I\!R$) trajectory in addition to the Pomeron which is not included for the ZEUS measurement as it does not improve the quality of the fit in that case. Corresponding value of the Pomeron intercept is $\alpha_{I\!P}(0) = 1.173$ ($\alpha_{I\!P}(0) = 1.132 \pm 0.006$) from H1 (ZEUS) fit.

As shown by H1 [2], the Regge factorisation ansatz holds within the present precision of the measurement as the $F_2^{D(2)}(Q^2, \beta)$ measurement is not sensitive to the $x_{I\!P}$ value. The Q^2 dependence exhibits a more important scaling violation than in the F_2 structure function measured in non-diffractive deep inelastic scattering indicating that the exchanged object in diffraction has an important gluon content.

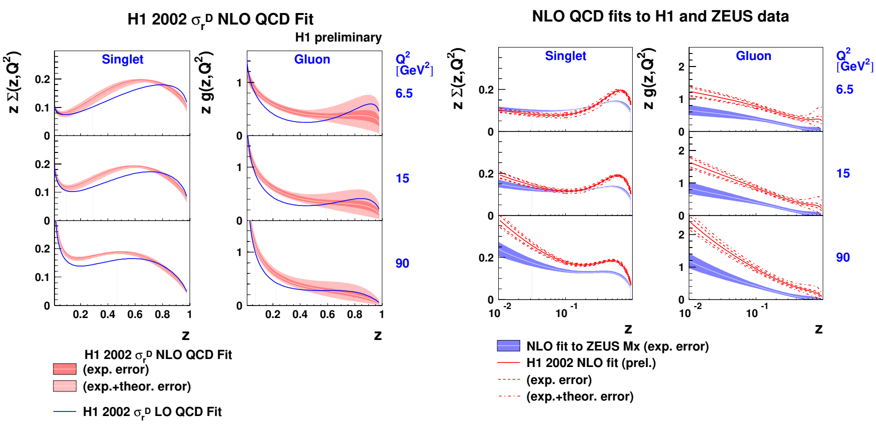

Figure 3. Quark (singlet) and gluon densities in the $I\!P$ extracted from the QCD fit of $F_2^{D(2)}(Q^2, \beta)$ as a function of z. **left)** From H1 measurement. **right)** From ZEUS measurement.

By analogy to the QCD evolution of the proton structure function F_2, one can attempt to extract the partonic structure of the Pomeron from the Q^2 evolution of $F_2^{D(2)}$. Starting the QCD evolution at $Q_0^2 = 6.5$ GeV^2, extracted partonic distributions [4,5] are shown in Fig. 3 separately for the gluon and the singlet quark components as a function of z, the Pomeron momentum fraction carried by the parton entering the hard interaction. The left 2 columns of the plots correspond to the singlet quark and the gluon components extracted from the H1 measurement; the right 2 columns from the ZEUS measurement. As a consequence of the differences between the H1 and ZEUS $F_2^{D(2)}$ a weaker gluon component is found from the ZEUS fit.

The QCD factorisation is expected to break down at large β values where higher twist terms may become important. A part of them corresponds to the contribution of the hard scale integration in the Pomeron [6]. Such a QCD Pomeron corresponds to the dominant term for exclusive Vector meson contribution like J/Ψ and for the Deeply Virtual Compton Scattering [7].

Dijet and charm productions in diffractive electroproduction
To test QCD factorisation for diffractive dijet production in electroproduction regime ($Q^2 >> 1$ GeV^2), the H1 dijet cross section [8] in the kinematic range $Q^2 > 4$ GeV^2 and $x_{I\!P} < 0.03$ is compared to the NLO QCD prediction in Fig. 4, using the extracted diffractive parton densities as obtained by H1. The cross sections were corrected to asymmetric cuts on the jet transverse momentum $p_{T,1(2)} > 5(4)$ GeV, to facilitate comparisons with NLO calculations. The inner error band of the NLO calculations represents the renormalisation scale uncertainty, whereas the outer band includes the uncertainty in the hadronisation corrections. Within the uncertainties, the data are well described in both shape and normalisation by the NLO calculations, in agreement with QCD factorisation. ZEUS measures the same process in an equivalent kinematic range and comparing it to different diffractive parton densities concludes: "the differences observed between the sets of predictions may be interpreted as an estimate of the uncertainty associated with the dPDFs... A better understanding of the dPDFs and their uncertainties is required before a firm statement about the validity of QCD factorisation can be made." [9].

The D^* meson production measurements in diffractive electroproduc-

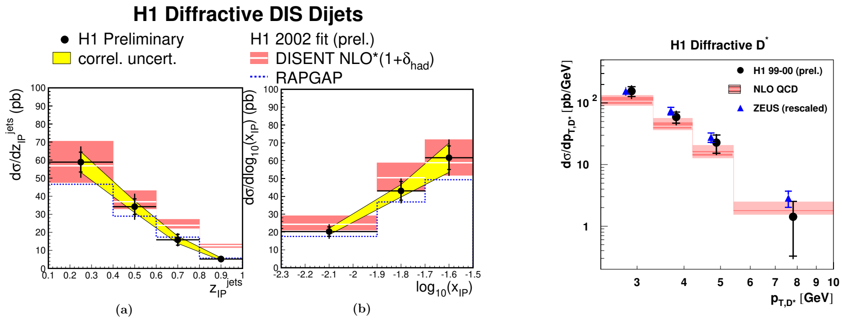

Figure 4. **left**: H1 measurement of diffractive dijet cross section in electroproduction as a function of $z_{\mathbb{P}}^{jets}$, an estimator for the parton momentum fraction of the diffractive exchange entering the hard sub-process, and as a function of $x_{\mathbb{P}}$ as measured by H1 and ZEUS. **right**: Diffractive D^* meson cross sections in electroproduction differential in p^*_{T,D^*}.

tion were achieved by H1 [10] and ZEUS [3] for the kinematic range $Q^2 > 2$ GeV^2, $x_{\mathbb{P}} < 0.03$ and $p^*_{T,D^*} > 2$ GeV, where the latter variable corresponds to the transverse momentum of the D^* meson in the photon-proton centre-of-mass frame. NLO QCD calculations were performed interfacing the H1 diffractive parton distributions. The renormalisation and factorisation scales were set to $\mu^2 = Q^2 + 4m_c^2$. A comparison of the calculations with the D^* H1 and ZEUS data is shown in Fig. 4-right. The inner error band of the NLO calculation represents the renormalisation scale uncertainty, whereas the outer error band includes variations of the charm mass and of the Peterson fragmentation function. Within the uncertainties, the data are well described in both shape and normalisation by the NLO calculations, supporting the idea of QCD factorisation.

3. Comparison with Hard Diffraction at the TEVATRON

One of the most striking features of the hard diffractive process measured at the Tevatron is a large suppression of the cross section with respect to the prediction based on the diffractive parton densities obtained from the HERA F_2^D data. Figure 5-left shows the comparison of the dijet cross section in the single-diffractive process measured by CDF at the Tevatron [11] to the prediction using the diffractive parton densities discussed in the previous section based on the H1 measurement. Although the prediction reproduces the shape of the data in the low-β region, the magnitude of the cross section is smaller by a factor 5 to 10. This indicates a strong factorisation breaking between HERA and the Tevatron: the diffractive parton densities are not universal between these two environments. Additionally, CDF has measured the ratio of double-diffractive over single-diffractive processes (shown in the right plot of Fig. 5) to be 0.19 ± 0.07. This indicates that the formation of a second gap is not (or only slightly) suppressed.

The reason for the breaking is not yet clearly known. It is usually attributed to re-scattering between spectator partons in the two beam remnants where one or more colour-octet partons are exchanged, which destroys the already formed colour-singlet state.

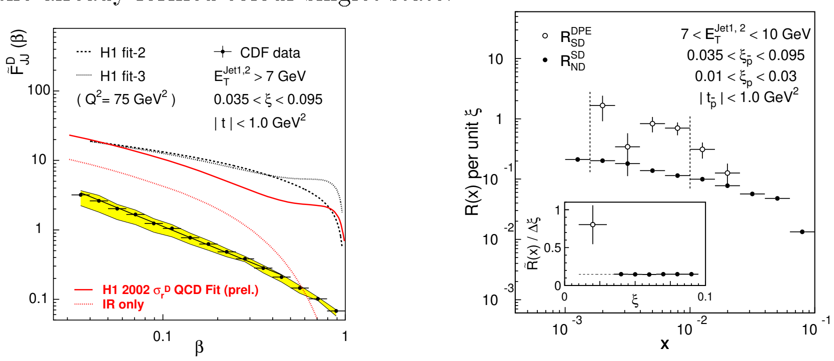

Figure 5. **left** : measured dijet cross section in single-diffractive processes in comparison with the prediction using the diffractive PDF's obtained by H1. **right** : measured dijet cross section in single-diffractive processes compared to double-diffractive processes by CDF.

Factorisation test with hard photoproduced diffraction at HERA

QCD factorisation can be further investigated within HERA looking at the diffractive dijet photoproduction ($Q^2 \sim 0$), where the hard scale is provided by the E_T of the jets. Factorisation is expected not to hold in photoproduction events, where the resolved process has a photon remnant, allowing re-scattering. On the other hand, the direct process does not have a beam remnant and the suppression of diffractive events is expected to be much smaller than in the resolved process [12].

Figure 6-left shows the dijet cross section in diffractive photoproduction measured by ZEUS as a function of x_γ^{jets} [13], the longitudinal momentum fraction of the parton that participated in the hard scattering (see Fig. 6-right diagram), reconstructed from the dijet momenta. Resolved events dominate in the low-x_γ^{jets} region while the direct process is concentrated at x_γ^{jets} close to one. The cross sections compared to the NLO QCD predic-

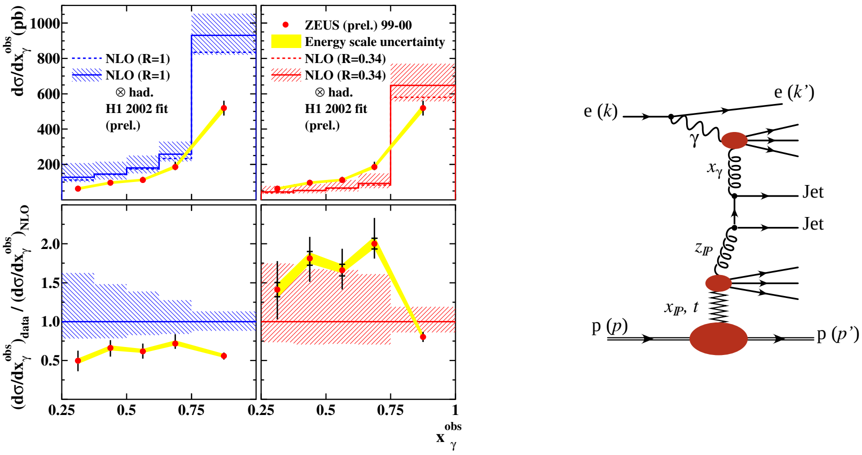

Figure 6. **left**: Dijet cross section in photoproduction at HERA measured by ZEUS as a function of x_γ^{jets}. **right**: Diagram for dijet in photoproduction at HERA.

tion exhibit a factorisation breaking both in the direct and in the resolved parts. The NLO QCD prediction required a global factor of 0.5 to be able to describe the data. Similar results have been measured by H1 [8].

Recently D^* meson photoproduction cross section in diffraction has been measured by ZEUS [14] for the kinematic range $P_T^{D^*} > 1.9$ GeV, $\eta_{D^*} < 1.6$, $130 < W < 300$ GeV and $0.001 < x_{I\!P} < 0.035$. The measurement is found to be in good agreement in shape and in normalisation with the NLO QCD prediction as shown in Fig. 7 presenting the data ratio to the theory.

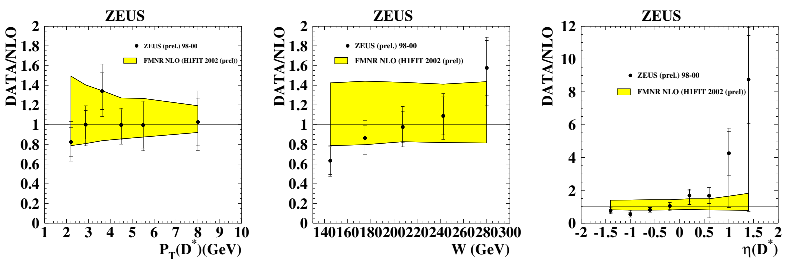

Figure 7. **left**: Ratio of the D^* meson cross section to the NLO QCD prediction in photoproduction measured by ZEUS as a function of $P_T^{D^*}$, W and η.

4. Concluding Remarks

After almost ten years of research at HERA we are reaching a perturbative QCD understanding of hard diffraction in ep interactions. The partonic structure of the diffractive exchange has been measured and is found to be dominated by gluons. In its validity domain ($Q^2 >> 1$ GeV^2 in ep collisions), the QCD factorisation holds, as confirmed by charm and dijet productions. In $p\bar{p}$ collisions, at Tevatron, a breakdown of the QCD factorisation of a factor 5 to 10 is observed for one gap formation and no (or weak) additional gap suppression is observed for a second gap formation. Rescattering corrections seem to be important in $p\bar{p}$ and in ep collisions in dijet photoproduction. The D^* photoproduction is in agreement with the NLO QCD prediction within the present precision.

A global understanding of inclusive and exclusive hard diffractions has progressed . Many more results and a deeper understanding are needed and expected with the coming data at HERA II, Run II at Tevatron, Compass and in a further future at LHC.

5. Acknowledgments

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