Experimental review of diffractive phenomena

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A review is given of the measurements of the hard diffractive interactions in recent years from two high-energy colliders, the HERA ep collider and the Tevatron $p\bar{p}$ collider. The structure of the diffractive exchange in terms of partons, the factorisation properties and the ratio of diffractive to non-diffractive cross sections are discussed.

1. INTRODUCTION

The diffractive interaction is a feature of hadron-hadron scattering at high energy corresponding to a t-channel exchange of the vacuum quantum numbers and a small momentum transfer. It has been has been described, in the past, in the framework of Regge theory, where the exchange was interpreted as the Pomeron ($I\!P$) trajectory, characterized by a weak energy dependence, in particular, with respect to the fast decrease of the total cross section at smaller energy due to Reggeon ($I\!R$) exchange: $\sigma_{Tot} = B\, W^{2(\alpha_{I\!R}-1)} + A\, W^{2(\alpha_{I\!P}-1)}$, where W is the center of mass energy, A and B normalisation factors and typically $\alpha_{I\!R} = 0.55$ and $\alpha_{I\!P} = 1.08$.

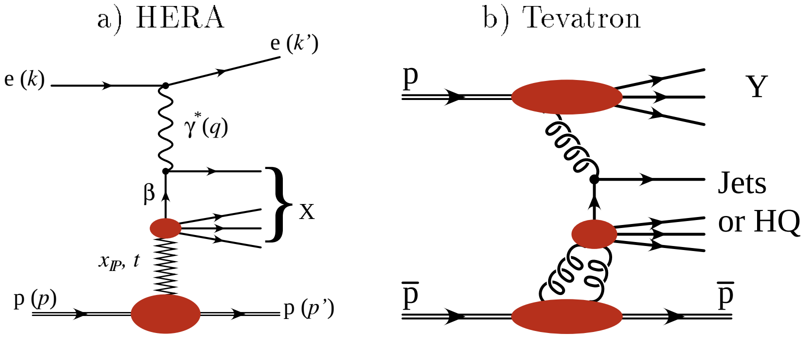


Figure 1: Basic diagrams for diffraction in presence of a hard scale at HERA and at Tevatron

Diffraction, directly related to the total cross section through the optical theorem, has two distinguishing features. First, hadron emission from the exchange itself being suppressed by its colourless nature, the two diffractively dissociated systems are separated in rapidity space, forming a large rapidity gap (LRG). Secondly, the diffractive events are observed with a small momentum transfer in both the transverse and longitudinal coordinates. The four-momentum of the exchange,

t, and the longitudinal momentum fraction of the exchange, $x_{\mathbb{P}}$, are both small; $|t|$ is typically less than the square of the nucleon mass and $x_{\mathbb{P}}$ is smaller than 0.05.

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 term 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 exchange 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 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. As in inclusive inelastic scattering (DIS) [1], the presence of a hard scale in the process is characterized by an important positive increase of the energy dependence behaviour.

This article concentrates on two topics, the factorisation properties and the ratio between diffractive and non-diffractive structure functions. Both give insight into the understanding of the nature of diffraction in terms of partons. Before reviewing recent measurement, a short discussion on the parton densities of the diffractive exchange and their relation to the diffractive cross section is given.

Although it will not be covered here, the study of diffraction has several other topics of interest in top of the diffractive exchange measurement in terms of partons. It gives an access to the nucleon structure at low $x_{Bj}$and to the parton correlations through the generalized parton distributions (GPDs) approach. It allows to test the region of validity of the different asymptotic dynamical approaches of QCD that are DGLAP and BFKL. 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, $x_{\mathbb{P}}$, β and t, where $x_{\mathbb{P}}$ and β are defined as

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

M_X being the invariant mass of the X system. $x_{\mathbb{P}}$ 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 $x_{Bj}= \beta \cdot x_{\mathbb{P}}$. 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. In the case of DIS, 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 also for hard inclusive diffraction [2] 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, $\sigma_{i\gamma}$ 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 ...

Experimentally, the t variable is usually not measured and is integrated over. In analogy with non-diffractive DIS scattering, the measured cross section is expressed in the form of a three-fold diffractive structure function $F_2^{D(3)}(Q^2, x_{I\!P}, \beta)$ (neglecting the longitudinal contribution),

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

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

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

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

assuming that the $I\!P$ flux $f_{I\!P/p}(x_{I\!P})$ is independent of the $I\!P$ structure $F_2^{D(2)}(Q^2, \beta)$, by analogy with the hadron structure functions, β playing the role of Bjorken x_{Bj}. The

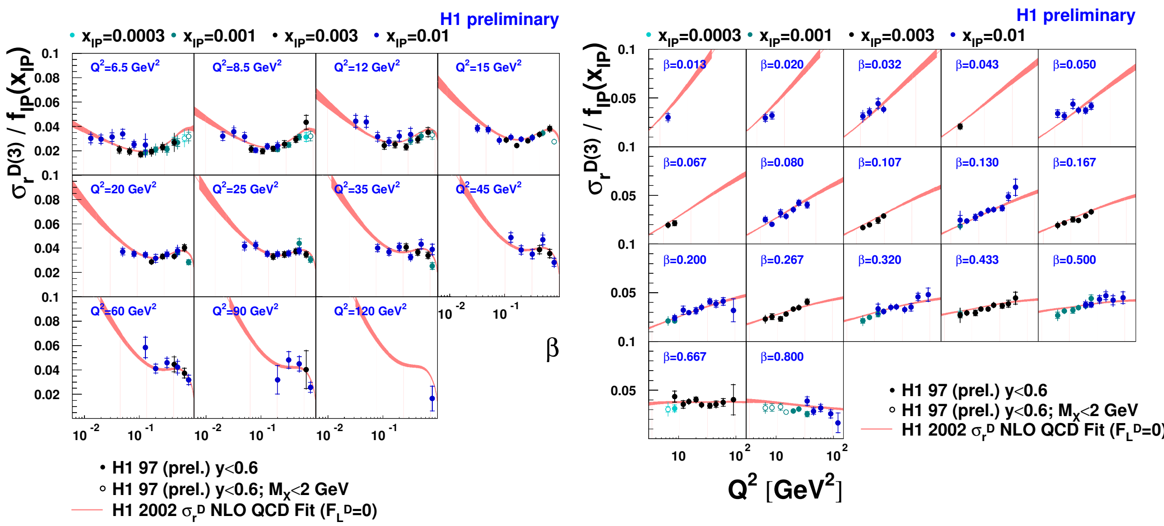


Figure 2. The $F_2^{D(2)}(Q^2, \beta)$ diffractive structure function measurement for different values of $x_{I\!P}$ as a function of Q^2 in bins of β (left plot) and as a function of β in bins of Q^2 (right plot).

$I\!P$ flux is parametrised in a Regge inspired form $f_{I\!P/p} = e^{bt}/x_{I\!P}^{2\alpha_{I\!P}(t)-1}$, where the value of the Pomeron intercept $\alpha_{I\!P}(0) = 1.173$ is used. Including the Reggeon ($I\!R$) trajectory in addition to the Pomeron, a good description of the data is obtained throughout the measured kinematic domain by H1 [3] and ZEUS [7] experiments.

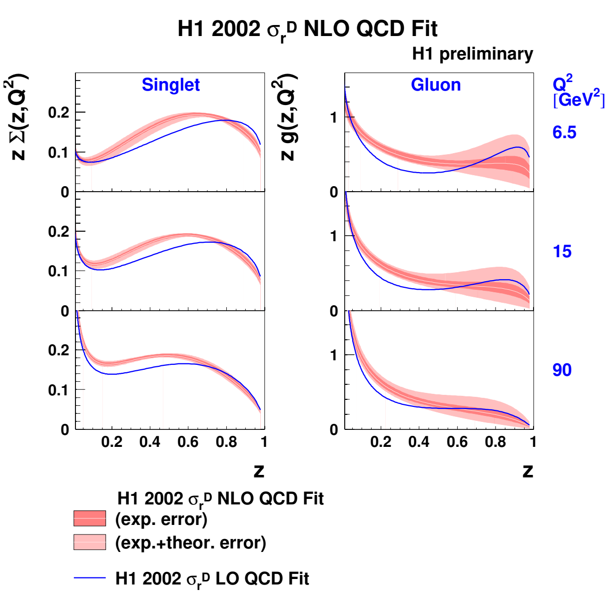


Figure 3: Quark (singlet) and gluon densities in the $I\!P$ extracted from the QCD fit of $F_2^{D(2)}(Q^2, \beta)$as a function of z.

The measured points and the fitted structure function $F_2^{D(2)}(Q^2, \beta)$ from H1 [3] is shown in Fig. 2, by the ratio of the cross section to the $I\!P$ flux, for different values of $x_{I\!P}$, as a function of β for fixed Q^2 on the left plot and as a function of Q^2 for fixed β on the right plot. The left plot shows that 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 shown on the right plot exhibits a more important scaling violation than in the F_2 structure function measured in non-diffractive deep inelastic scattering [1]. This indicates that the exchanged object in diffraction has an important gluon contain.

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 $F_2^{D(2)}(Q^2, \beta)$. Starting the QCD evolution at $Q_0^2 = 6.5$ GeV^2, H1 has extracted the partonic distributions [4] as 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. This distribution shows the dominance of gluons up to the high z values in the Pomeron partonic structure (75±15% after integration in z).

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 [5] 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. 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 renormalization scale uncertainty, whereas the outer band includes the uncertainty in the harmonization corrections. Within the uncertainties, the data are well described in both shape and normalisation by the NLO calculations, in agreement with QCD factorisation.

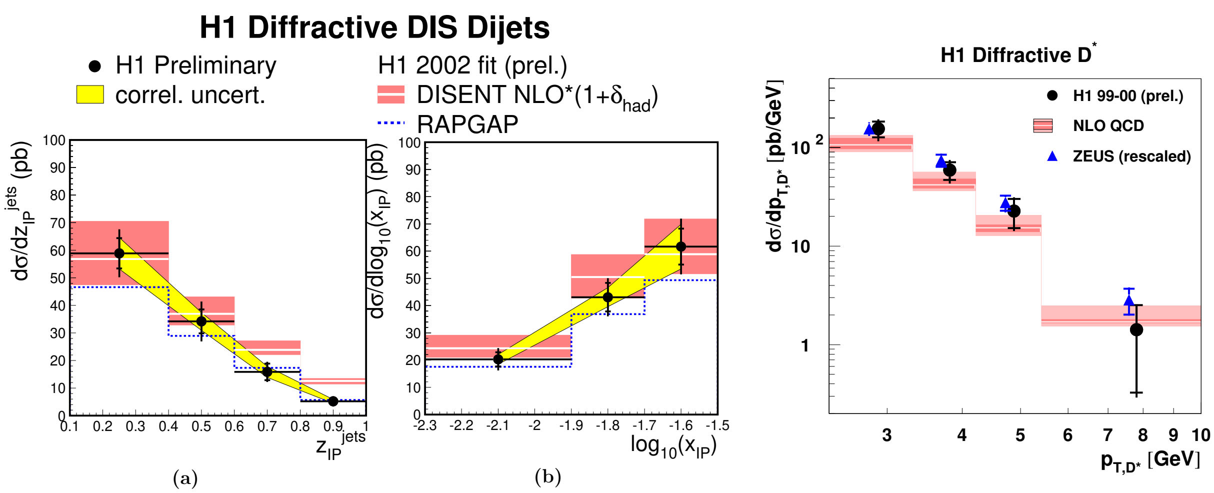


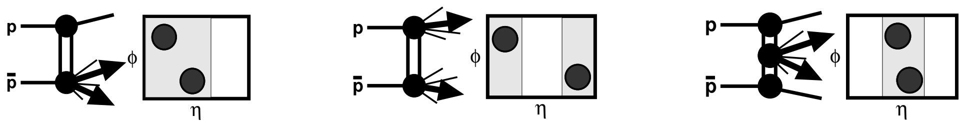
Figure 4. **left**: H1 measurement of diffractive dijet cross section in electroproduction as a function of $z_{I\!P}^{jets}$, an estimator for the parton momentum fraction of the diffractive exchange entering the hard sub-process, and as a function of $x_{I\!P}$ as measured by H1 and ZEUS. **right**: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

The D^* meson production measurements in diffractive electroproduction were published by H1 [6] and ZEUS [7] for the kinematic range $Q^2 > 2$ GeV^2, $x_{I\!P} < 0.03$ 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 calculation were performed interfacing the H1 diffractive parton distributions. The renormalization and factorisation scales were set to $\mu^2 = Q^2 + 4m_c^2$. Further parameter values are a charm quark mass of $m_c = 1.5$ GeV, a $c \to D^*$ harmonization fraction of $f(c \to D^*) = 0.233$ and $\epsilon = 0.078$ for the used Peterson fragmentation function. 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 renormalization scale uncertainty, whereas the outer error band includes variations of m_c and ϵ. Within the uncertainties, the data are well described in both shape and normalisation by the NLO calculations, supporting the idea of QCD factorisation.

3. HARD DIFFRACTION AT THE TEVATRON

At the Tevatron, the diffractive process occurs in various combinations of the large rapidity gap configuration since the both incoming protons can emit the diffractive exchange. The partonic content of the exchange is mainly studied using single-diffractive processes, where the colour-octet parton emitted from one proton undergoes a hard scatter with the diffractive exchange emitted from the other proton; the partons in the exchange are probed by the colour-octet parton replacing the virtual photon at HERA.



Single Diffraction **Double Diffraction** **Double Pomeron Exchange**

Various hard processes have been studied in Tevatron Run I data, such as W production [8] which is sensitive to the quark content of the exchange, and dijet[9, 10] and b-quark production[11], which are more sensitive to the gluonic content.

Hard diffraction at the Tevatron from Run I data and the factorisation breaking

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 [9] to the prediction using the diffractive parton densities discussed in the previous section. Although the prediction reproduces the shape of the data in the low-β region, the magnitude of the cross section is smaller by about a factor 5 to 10. A similar degree of suppression was observed in the other hard diffractive processes [8, 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 single-diffractive over double-diffractive processes (shown on in the right plot of Fig. 5) to be of 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 rescattering 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.

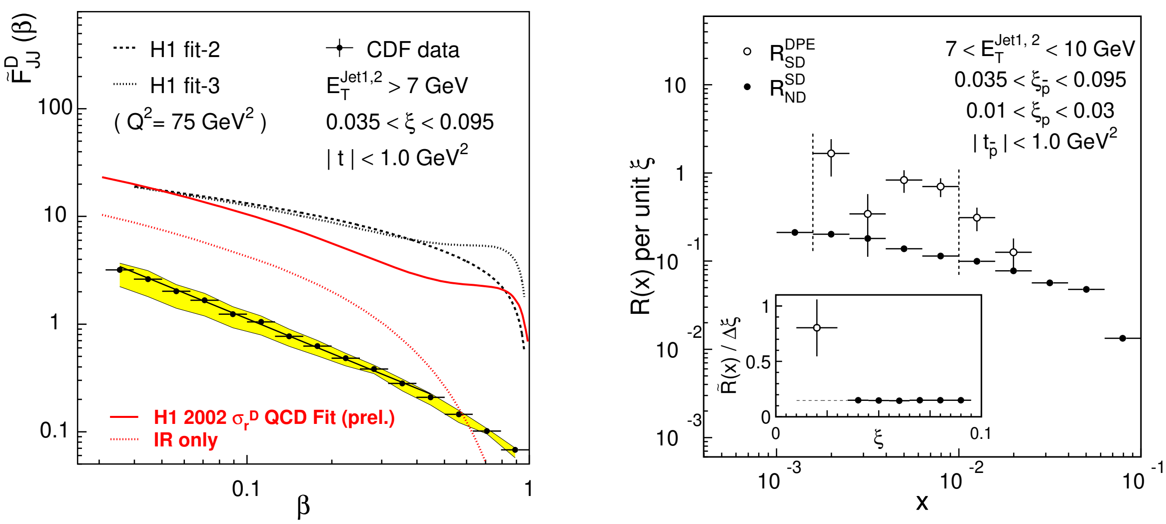


Figure 5. **left** : measured dijet cross section in single-diffractive processes in comparison with the prediction using the diffractive PDF's obtained by H1. **right** : measured dijet cross section in single-diffractive processes compared to double-diffractive processes by CDF.

Factorisation test with hard photoproduced diffraction at HERA
QCD factorisation can be tested 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.

Figure 6-left shows the dijet cross section in diffractive photoproduction measured by ZEUS as a function of x_γ^{jets} [12], 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 prediction, exhibits a factorisation breaking both in the direct and in the resolved parts. The NLO QCD prediction required a global factor of 0.34 to be able to describe the data. Similar results have been measured by H1 [5].

Summary of factorisation tests
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.

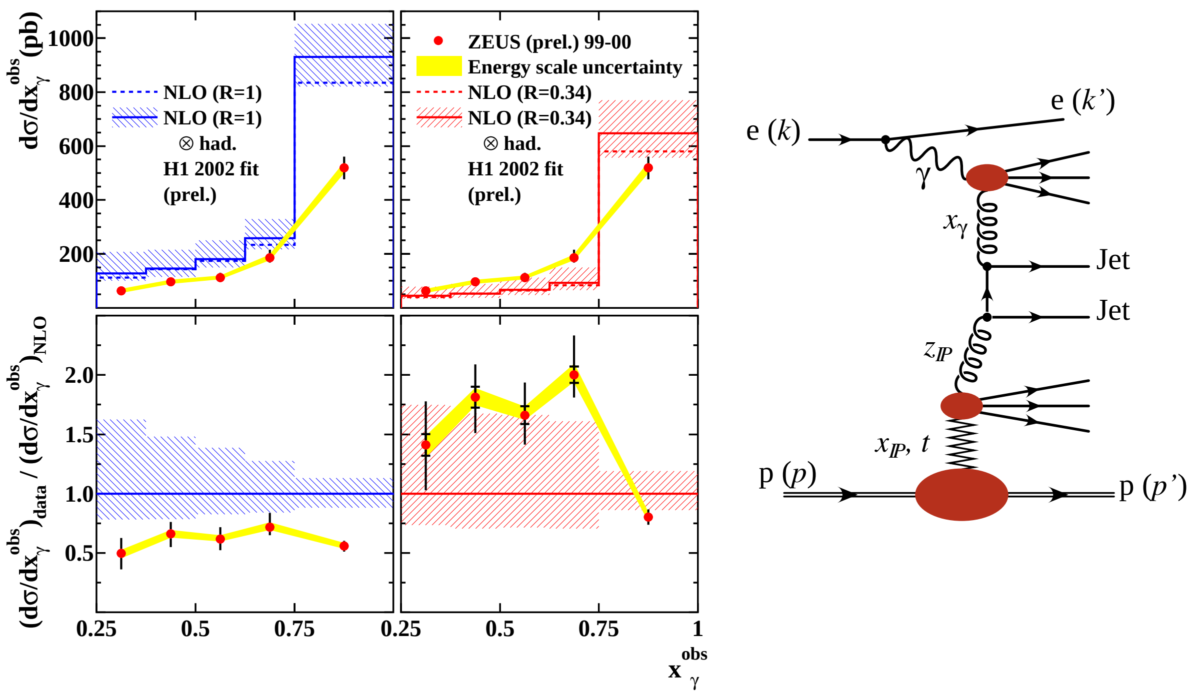


Figure 6. **left**: Dijet cross section in photoproduction at HERA measured by ZEUS as a function of $x_\gamma^{\rm jets}$. **right**: Diagram for dijet in photoproduction at HERA.

4. RATIO OF DIFFRACTIVE TO INCLUSIVE CROSS SECTIONS

Figure 7 presents CDF results from Tevatron Run II on the ratio between single-diffractive to non-diffractive cross sections [13]. In the present case the scale Q^2 corresponds to E_T^2, where E_T is the average transverse energy of the two jets. The ratio is observed to be independent of the Q^2 value.

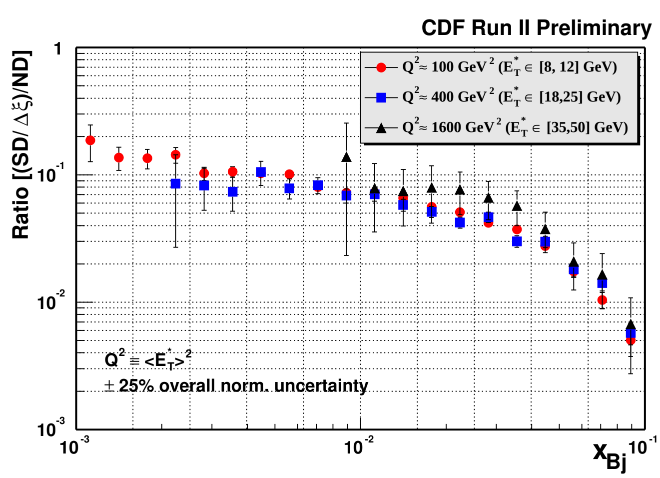


Figure 7. Ratio of single to non-diffractive cross sections in $p\bar{p}$ collisions.

The ratio of the diffractive to inclusive cross sections in ep collisions, as measured by

ZEUS [14], is presented on Fig. 8, as a function of W, for different values of Q^2 in different intervals of the invariant hadronic final state mass, M_X. Analysing this ratio, three different behaviors can be pointed out. i) For $M_X > 2$ GeV the ratio is flat in W, i.e. inclusive diffraction has the same energy dependence than the total cross section in DIS, which is not consistent with a simple two gluon exchange. Indeed, in a two gluon exchange the cross section is expected to grow like the gluon density squared, while the total cross section is proportional to the gluon density, giving a ratio proportional to the gluon density, i.e. increasing fast for decreasing x_{Bj} values (or for increasing W at fixed Q^2).

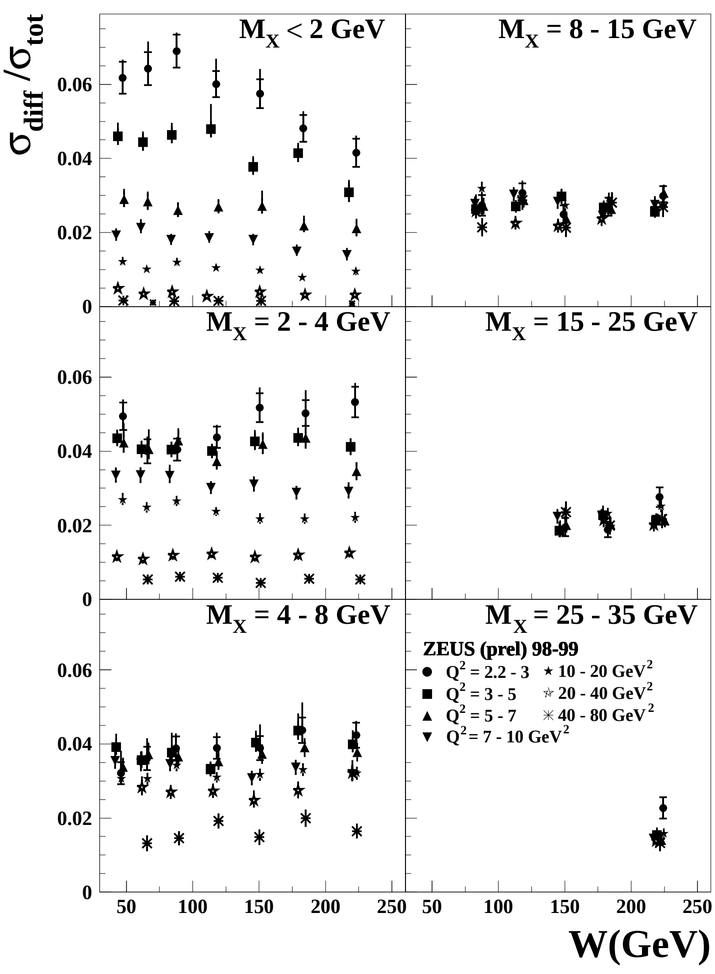


Figure 8: Ratio of single to non-diffractive cross sections in ep collisions.

ii) For $M_X > 8$ GeV, no Q^2 dependence is observed, i.e. the diffractive exchange evolves with Q^2 just like the inclusive cross section, according to the DGLAP evolution. This can be understood intuitively as when M_X is large, β is small ($\beta \simeq Q^2/(Q^2 + M_X^2)$) and the virtual photon "sees" only a small fraction of the diffractive exchange momentum. This offers a large kinematic space to radiate gluons, similarly to the "one" gluon exchange of the boson gluon fusion (main) responsible of the total cross section in DIS. In other terms, in this kinematic region the photon cannot distinguish between DIS and a diffractive exchange

iii) For $M_X < 2$ GeV. When M_X decreases, β increases and the photon "sees" more and more of the diffractive exchange up to the limit of $\beta \to 1$ where the full diffractive exchanged momentum is connected to the photon and no gluon radiation is possible. In this case we can expect that the cross section behaves like the gluon density squared. The large β region is dominated by vector meson production. Very interesting results [15, 16] show that, indeed, the J/Ψ exclusive production can be described by QCD models based on 2 gluon exchange.

5. CONCLUDING REMARKS

After almost ten years of research at HERA and at the Tevatron, we are reaching a perturbative QCD understanding of hard diffraction. The partonic structure of the diffractive exchange has been measured and is found to be dominated by gluons. The factorisation in terms of structure functions holds in ep collisions at large Q^2 but rescattering corrections are important in $p\bar{p}$ and in ep collisions in photoproduction. A global understanding of inclusive and exclusive hard diffractions has progressed recently. Many more results and a deeper understanding are expected with the coming data at HERA II, Run II at Tevatron, Compass and in a further future at LHC.

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