Diffractive interactions in ep collisions*

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The H1 and ZEUS experiments are measuring diffractive interactions in ep collisions at HERA. Performing QCD fits of these data with NLO DGLAP, diffractive parton distribution functions can be calculated. These diffractive PDFs can be used to test QCD factorisation with dijet and charm data.

1. Introduction

Quantum chromodynamics (QCD) describes the strong interactions between quarks and gluons at small distances very well, where the strong coupling constant α_S is small and the calculation becomes perturbative. However, the calculation of total cross sections, usually dominated by long range forces or "soft interactions", needs more understanding. A fraction of these interactions are characterized by the exchange of a color singlet with vacuum quantum numbers. These "diffractive" interactions are well described by Regge theory, where a leading ("Pomeron") trajectory with vacuum Quantum numbers is exchanged in the t-channel. Figure 1 shows a sketch of the generic diffractive process in ep scattering at HERA, displaying the most important variables. The hard scale of the interaction is given by the photon virtuality Q^2, W is the γp centre of mass energy, and t the squared four-momentum transfer at the proton vertex, where the proton has the four-momentum p. The colorless diffractive object ($I\!P$) carries the momentum fraction $x_{I\!P}$, and the quark struck by the photon with four-momentum q has the fraction β of the momentum of the diffractive exchange. They are defined as follows:

$$x_{I\!P} = \frac{q \cdot (p - p')}{q \cdot p} \approx \frac{Q^2 + M_X^2}{Q^2 + W^2}\,, \quad \beta = \frac{Q^2}{2q \cdot (p - p')} \approx \frac{Q^2}{Q^2 + M_X^2} = \frac{x}{x_{I\!P}}\,, \quad (1)$$

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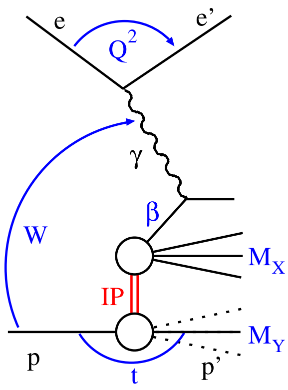

Fig. 1. Diffractive ep scattering.

with x being the Bjorken-x. The diffractively produced system X has the mass M_X. The proton can stay intact and get scattered with the four-momentum p' or dissociate in a system Y with mass M_Y.

2. Event selection

There are different methods to select diffractive events. A very clean way is to detect the scattered proton in the forward direction. H1 and ZEUS have proton spectrometers placed along the beam line in the direction of the proton beam. In addition to being free from proton dissociation background, the advantage of this selection is the possibility to measure the momentum transfer t. On the other hand, this method is limited by statistics due to small acceptance.

A high statistics sample can be obtained taking advantage of the characteristic properties of the final state, where we observe a large gap in rapidity between the leading proton (or in case of dissociation the leading baryonic system) and the photon dissociation system due to the colorless exchange. This gap can be identified by the abscence of activity in the forward part of the calorimeter. The residual proton dissociation background is about 9 % for masses $M_Y < 1.6$ GeV and can be subtracted statistically.

The third method to extract diffractive is using the fact that the M_X distributions behave differently for diffractive and non-diffractive data. Monte Carlo simulations show that the diffractive contribution is almost flat in $\ln M_X^2$ while the non-diffractive contribution is exponentially falling for decreasing M_X. The diffractive data is extracted with a fit of the variable $\ln M_X^2$. The proton dissociation background gets subtracted for masses of $M_Y > 2.3$ GeV [1].

3. Cross sections and extraction of PDFs

The differential diffractive cross section σ^D can be defined

$$\frac{d^3\sigma^D(x_{I\!P}, x, Q^2)}{dx_{I\!P}\, dx\, dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left((1 - y + \frac{y^2}{2}\right)\sigma_r^{D(3)}(x_{I\!P}, x, Q^2)\,, \qquad (2)$$

with the reduced cross section σ_r^D, which is related to the diffractive structure functions F_2^D and F_L^D, neglecting contributions from the Z^0 exchange, by

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{1+(1-y)^2} F_L D(3)\,. \qquad (3)$$

Assuming Regge factorisation, QCD fits have been performed by H1 [2] and ZEUS [3], using the DGLAP formalism to evolve the non-perturbative diffractive parton densities (dPDFs). The diffractive exchange is modeled in terms of a light flavor singlet and a gluon distribution, parameterized by a set of polynomials at a starting scale $Q_0^2 = 3$ GeV^2 in case of H1. ZEUS includes also diffractive charm data in the fit, starting at $Q_0^2 = 2$ GeV^2. H1 treats the charm quark in the massive scheme via boson-gluon fusion processes with $m_c = 1.5 \pm 0.1$ GeV, while ZEUS uses the Thorne-Roberts variable flavor number (TRVFN) scheme with $m_c = 1.45$ GeV. Both experiments find a large momentum fraction exchanged by gluons of $\sim 75 \pm 15$ % (H1) and $82 \pm 8(\mathrm{stat})^{+5}_{-16}(\mathrm{syst})$ % (ZEUS) at the initial scale. Figure 2 shows the result of the fit for ZEUS and Fig. 3 shows the diffractive PDFs from H1.

Using these PDFs, one can perform tests of the validity of the assumptions made for the QCD analysis, primarily the QCD factorisation.

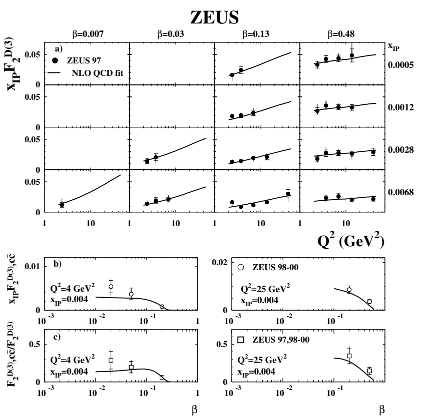

Fig. 2. NLO QCD fits from ZEUS.

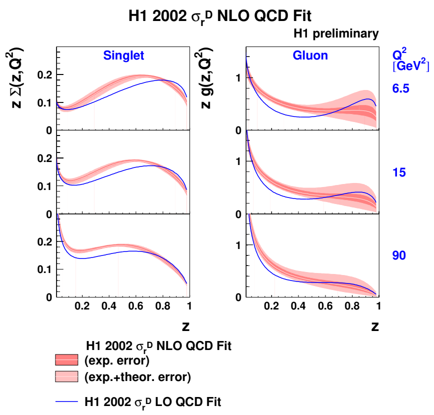

Fig. 3. Diffractive PDFs from H1.

4. Dijet and charm analyses using the diffractive PDFs

Since the PDFs are gluon dominated, there is a special interest in processes which are sensitive to photon-gluon interactions, like dijet and heavy flavor processes. The longitudinal fraction of the Pomeron momentum carried by the emitted gluon $z_{\mathbb{P}}$ is determined using the invariant mass M_{12} of the $q\bar{q}$ system.

4.1. Diffractive dijets and charm in DIS

Figure 4 shows the measured dijet cross section as a function of $z_{\mathbb{P}}$ from H1 [4], compared to the DISENT NLO calculation [5] interfaced to the H1 PDFs shown above. The error band of the NLO calculation is estimated varying the renormalisation scale by factors 0.5 and 2. Also shown is the RAPGAP [6] prediction, which contains parton showers and is based on the LO PDFs from the same fit. ZEUS has done a similar measurement [7], comparing the data to NLO QCD calculations with the H1 PDFs and the ZEUS PDFs from the measurements shown above. These describe the data well, while a third NLO calculation using the GLP fit [8] underestimates the data.

Both ZEUS [9] and H1 [10] have measured diffractive D^* production in DIS. The cross section as a function of the transverse momentum p_{T,D^*} of the D^* is shown in Fig. 5, compared to an NLO calculation using a diffractive version of the program HVQDIS [11]. The inner error band represents the renormalization scale uncertainty varied by factors 1/4 to 4, while the outer error band shows the total uncertainty, including variations of the charm mass from 1.35 to 1.65 GeV and of the parameter of the Peterson

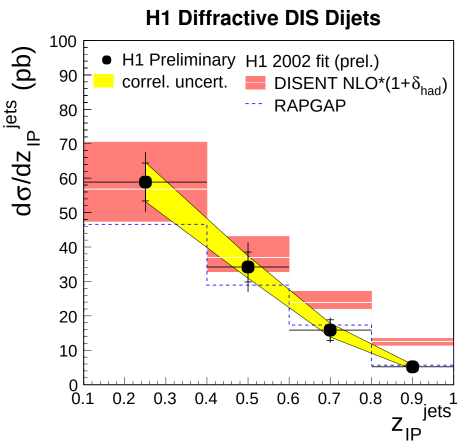

Fig. 4. Diffractive dijets in DIS.

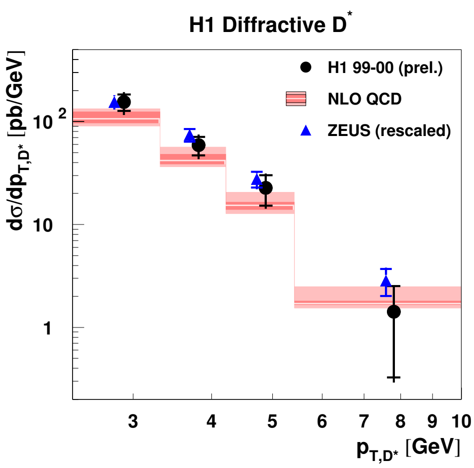

Fig. 5. Diffractive D^* in DIS.

fragmentation function ϵ from 0.035 to 0.100, added in quadrature.

Both, the dijet as well as the D^* production in DIS are reasonably well described by the NLO calculations using the H1 PDFs, supporting the assumption that factorisation holds for diffractive reactions in DIS.

4.2. Diffractive dijets and D^* in photoproduction

Applying a similar QCD calculation to diffractive dijet production at Tevatron, the observed rate is overestimated by a factor of 3 to 10, depending on the chosen diffractive PDF [12]. This factorisation breaking is explained by Kaidalov et al. [13] as being caused by secondary interactions of additional spectator quarks in the proton remnant, which are not present in virtual photons (in DIS). In photoproduction though, the photon can either participate directly in the hard scattering subprocess ("direct photon"), or fluctuate into partons ("resolved photon"). In this case only a part $x_\gamma < 1$ of the photon momentum enters the hard scattering. This resolved photon part is similar to hadron-hadron scattering and should therefore be suppressed, as seen at Tevatron. Kaidalov et al. [13] have predicted a suppression factor of 0.34 for the resolved photon contribution in diffractive dijet photoproduction.

H1 [4] and ZEUS [14] have measured diffractive dijets in photoproduction and compared the result to NLO QCD calculations. Figure 6 shows the

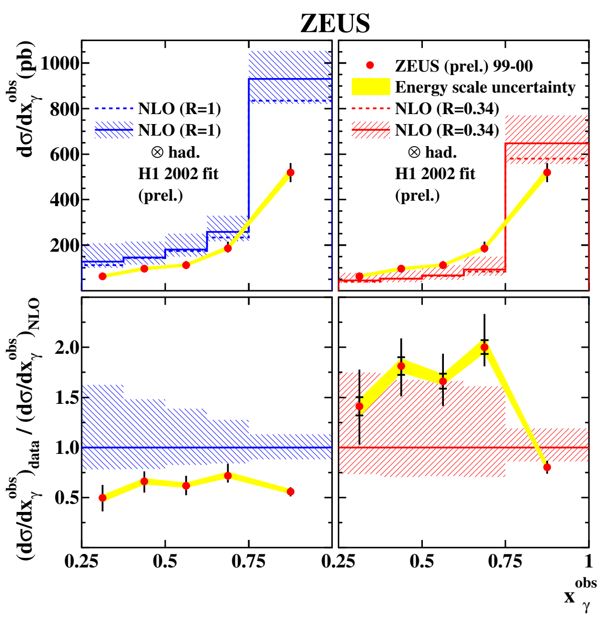

Fig. 6. Diffractive dijets in photoproduction.

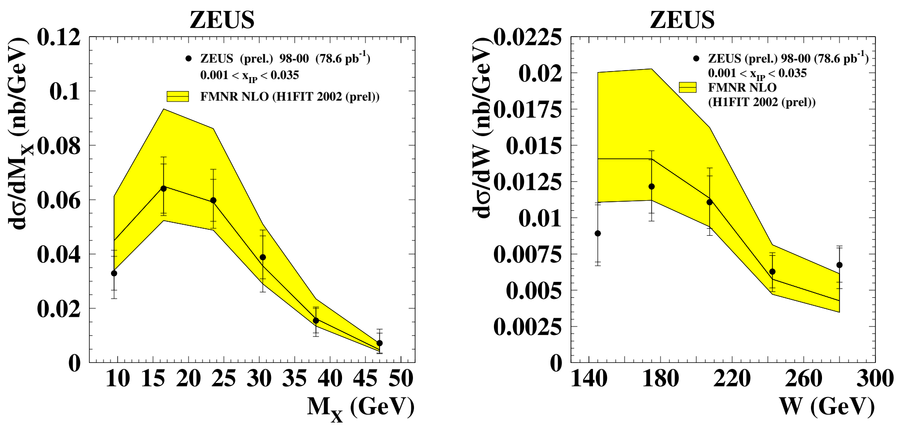

Fig. 7. Diffractive D^* in photoproduction.

cross section and the ratio of the cross section over the NLO prediction as a function of x_γ^{obs}. Although the shape is described by the NLO calculation quite well, the cross section is overestimated in all bins. Scaling the resolved part by the factor 0.34 does not describe the shape. This suggests that a global suppression is more likely than a resolved photon suppression only.

ZEUS has recently measured diffractive D^* in photoproduction [15]. Figure 7 shows the cross section in bins of M_X and W in comparison to NLO calculations using the FMNR [16] program with the H1 PDFs shown above.

The error band includes, in addition to the variation of the charm mass ($m_c = 1.5 \pm 0.2$ GeV), variations of the fragmentation and renormalisation scale by factors 0.5 and 2. The data are both in shape and in the total normalisation well described.

This is not necessarily a contradiction to the dijet results, taking into account that the inclusive D^* in photoproduction cross section is underestimated in the NLO calculations [17] by approximately the same amount the diffractive dijet cross section is overestimated. The NLO calculations for the inclusive dijets in photoproduction [18] describe the data well in shape and magnitude.

5. Conclusions

Diffractive exchange contributes a substantial part to the deep-inelastic ep scattering at HERA. Assuming Regge factorisation, the nature of the diffractive exchange can be studied with QCD fits to inclusive diffractive data. These fits show that diffractive exchange is dominated by gluons, contributing about 75 % of the exchanged momentum.

Using the PDFs obtained from the H1 and ZEUS QCD fits shown above, the factorisation assumption is successfully tested for the diffractive production of dijets and heavy flavor in DIS. Using the GLP PDFs, the data are underestimated, leading to the conclusion that the PDFs probably have a large uncertainty. Applying a similar QCD calculation to diffractive dijet production at Tevatron, the observed rate is overestimated, which is explained by secondary interactions of spectator partons in hadron-hadron interactions. This suppression should also be visible in photoproduction at HERA, in part of the reactions where the photon is resolved, but there is no clear picture yet. The diffractive dijets in photoproduction not only a suppression of the resolved part, but an overall suppression of the order of 0.5. The diffractive D^* data seem to be described by the NLO calculations, but as the inclusive D^* in photoproduction is underestimated by similar NLO calculations, one has to be careful with the interpretation of this result.

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