Factorisation breaking in diffraction

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Abstract
Diffractive and leading neutron production contribute to a significative part of the \( ep \) interaction at the HERA collider. In the theoretical models that describe these set of events some factorisation properties of the cross sections are either expected or postulated. The test of such factorisations from the H1 and ZEUS collaborations is presented here.

1 Introduction
At the \( ep \) collider HERA the internal structure of the proton can be probed by the photon, \( \gamma^* \), emitted by the electron. In diffractive interactions the outgoing proton stays intact or in a low-mass resonant state [1]. These specific events contribute significantly to the total cross section and can be modelled via the emission from the proton of a diffractive colour-singlet exchange that subsequently is probed by the \( \gamma \). The outgoing protons are accompanied by the presence of a Large Rapidity Gap (LRG), a large angular region in the direction of the scattered proton without hadronic activity [2, 3]. In recent years, perturbative QCD (pQCD) was shown to be a valuable tool to describe this subset of events, given the presence of a hard scale that allows the use of perturbative analysis [1, 3, 4]. In the case of deep inelastic scattering (DIS), high values of the virtuality of the photon, \( Q^2 \), emitted by the electron that probes the proton internal structure provide such a hard scale. When the photon exchanged is almost real (i.e. for the kinematic regime \( Q^2 \sim 0 \text{ GeV}^2 \) known as photoproduction, \( \gamma p \)) a hard scale can still be obtained by producing jets with a high transverse energy, \( E_T \), or quarks with a heavy mass.

It has been proven for diffractive DIS that the cross section can be factorised into two parts, universal parton distribution functions (dPDFs) and process-dependent coefficients that can be calculated in pQCD [5]. In spite of its theoretical proof in DIS, QCD factorisation in diffraction has been shown to fail in \( pp \) collisions at the TeVatron accelerator [6]. The Next-To-Leading (NLO) order pQCD calculations using dPDFs extracted at HERA overestimated the data by roughly a factor of ten. Such a data suppression is due to soft rescatterings between spectator partons present in the protons that may spoil the LRG used for tagging the event as diffractive (Rapidity Gap Survival probability). Phenomenological models are able to describe this suppression and predict that a similar effect should be seen at HERA in diffractive \( \gamma p \) when the low-virtuality photon exhibits a hadronic behaviour (resolved photon) [7, 8]. No suppression is expected in DIS nor in the subset of \( \gamma p \) events where the photon couples directly to a quark in the hard subprocess (direct photon).

The test of this theorem is important for proving that diffractive processes can be described by means of pQCD. Furthermore the study of diffractive final states is useful for constraining the dPDFs that are extracted from inclusive diffractive data and have large uncertainties, especially the gluon densities. Such a combined fit has been published recently by the H1 collaboration [9].
2 QCD Factorisation in diffraction

The most suited final states for testing the QCD factorisation in diffraction are the production of dijets and heavy quarks. The appealing features of these processes are

- presence of a hard scale that allows the use of pQCD;
- sensitivity to the gluon content of the diffractive exchange via the boson-gluon fusion (BGF) production process.

The NLO prediction can be compared to the measurement of the cross section in order to observe any suppression of the data relative to the theory. The relevant variables in these analyses are the virtuality of the $\gamma$, $Q^2$, the energy of the $\gamma - p$ centre-of-mass, $W$ and the fractional longitudinal momentum lost by the proton, $x_p$. In the dijets analyses the variable $z_{\mathrm{obs}}^\gamma$ is defined as the fraction of the diffractive exchange momentum carried by the parton entering the hard subprocess and is therefore the variable most sensitive to the dPDFs. In the $\gamma p$ case the variable $x_\gamma$ is introduced; it describes the fraction of photon momentum entering in the hard subprocess and is therefore a good discriminant between direct- (i.e. $x_\gamma \approx 1$) and resolved-photon (i.e. $x_\gamma$ significantly lower than 1).

New results in diffractive dijet production in DIS have become available from the ZEUS and H1 collaboration at the time of writing [9–11]. The measurement performed by the H1 collaboration of the $z_{\mathrm{obs}}^\gamma$ dependence of the differential cross section can be seen in Fig. 1. The experimental data are compared to NLO predictions using two different available dPDFs. The data favour in particular the H1 2006 t B even tough the theoretical uncertainties are large. ZEUS observes similar agreement between measured data and theoretical prediction. Additionally, the calculation using the MRW2006 t [4] provides a good description of the data, very similar to the one using the H1 2006 fit B. This agreement supports the QCD factorisation statement in the DIS regime.

In Fig. 2, the differential cross section as a function of $x_\gamma$ is presented for dijets in diffractive photoproduction for H1 and ZEUS respectively [12, 13]. The interpretation of the $p\bar{p}$ data suggests a suppression in the low $x_\gamma$ region where the photon behaves like a hadron. The H1 measurement sees a global suppression of a factor 2, independently of $x_\gamma$ while ZEUS doesn’t see any significant overestimation of the NLO compared to the data. The differences in these results can be partially addressed in the uncertainties on the theoretical calculations. The different kinematic regions covered by the two analyses can also be due to the different outcome of the analyses. For instance, in the ZEUS case, the higher cut on the jet transverse energy suppresses the resolved photon contribution.

Results from the H1 Collaboration for diffractive $D^*$ production in DIS are shown in Fig. 3 [14]. The cross section is presented as a function of the variable $\beta$, that here plays the role of $z_{\mathrm{obs}}^\gamma$ in the dijet case. The measurement is compared to both the central values of a NLO calculation using different dPDFs and to previous measurements. A consistent picture can be observed where measurements and theoretical predictions agree, again supporting QCD factorisation in diffractive DIS.

The production of $D^*$ in $\gamma p$ was measured recently by both H1 and ZEUS [14, 15]. The ZEUS measurement of the differential cross section for such a process as a function of $x_p$ is presented in Fig. 4. The NLO predictions based on different dPDFs are compared to the data.
Fig. 1: H1 measurement of the single differential cross section as a function of $z_{IP}^{obs}$. The data are shown as dots. The internal error bars represent the statistical uncertainty, the outer error bars the sum in quadrature of the statistical and uncorrelated systematic uncertainties. The hatched area shows the correlated systematic uncertainty. The measured points are compared to the NLO prediction using the (left) "H1 2006 t A" and (right) "H1 2006 fit B" dPDFs. The dark shaded band surrounding the theoretical curve represents the uncertainty coming from the dPDFs and the hadronisation corrections. The lighter shaded band is the sum in quadrature of the dPDFs uncertainty and the scale uncertainty.

and exhibit a good agreement. Such a consistency can be explained by the fact that the charm content in the resolved photon is limited and therefore $D^+$ can be produced only via BGF, i.e. direct-photon processes where QCD factorisation is expected to hold.

3 Vertex factorisation in leading neutron production

The production of leading baryons is a significant fraction of the events observed at HERA. A recent ZEUS publication presented measurements where an outgoing neutron carrying a fraction $x_L = \frac{E_n}{E_p}$ of the initial $p$ energy was detected by means of a dedicated forward instrumentation [16]. The models for the production of leading neutron at HERA largely use the One-Pion Exchange (OPE) approximation for describing such a process. The relevance of this production mechanism is more important at high values of $x_L$. The limiting fragmentation hypothesis is commonly used in this context. It states that, in the high energy limit, the production of particles in the proton-target fragmentation region is independent of the nature of the incident particle, i.e. the lepton variables $Q^2$ and $W$. Factorisation tests involve comparing semi-inclusive rates, normalised to their total cross sections, to study whether particle production from a given target is independent of the lepton variables.

The vertex factorisation can be broken by rescattering effects that occur between the leading neutron and the $\gamma$. In that case the neutron kinematics may change towards lower $x_L$ and higher $p_T$, migrating consequently outside the detector acceptance. In Fig. 5 the ratio $\rho$ is shown as a function of $x_L$. This variable is defined as the ratio of two normalised differential cross section measured in two distinct $Q^2$ regions. If the vertex factorisation holds, $\rho$ is equal to
Fig. 2: Differential cross section for dijet production in diffractive $\gamma p$ as a function of $x_\gamma$ measured by (left) H1 and (right) ZEUS. In both plots the data are shown as dots, the statistical uncertainty as the internal error bars, the sum in quadrature of the statistical and uncorrelated systematic uncertainties as outer error bars and the shaded band shows the correlated systematic uncertainty.

unity. Otherwise the enhanced rescattering in the low $Q^2$ region would lower this ratio. As seen in the plot this ratio is significantly lower than 1, meaning that vertex factorisation is violated. Two different models for this absorption process are compared to the data. The D’Alesio-Pirner model [17] implements absorption effects via rescattering between the leading neutron and the $\gamma$, in a fashion similar to the QCD factorisation breaking described in Sect. 2. When the $\gamma$ has a low virtuality its transverse size is larger and the probability that the leading neutron scatters over it is increased. The NSZ model [18] describes absorption employing the optical theorem together with multi-Pomeron exchanges . The two predictions are also presented after correcting for the different $W$ dependence of the pion cross section in DIS and $p$ cross sections. The D’Alesio-Pirner model describes well both normalisation and shape of the measurement while the NSZ one does not have a steep enough rise as a function of $x_\gamma$.

4 Conclusions

Many factorisation mechanisms are used in describing the production of leading baryons. The experimental test of them is an important step in order to build a robust theory for explaining these processes. A key tool for a QCD-motivated description of diffraction is the QCD factorisation theorem. Analyses performed by the H1 and the ZEUS collaborations show that this ansatz is valid in the DIS regime, although large theoretical uncertainties affect the power of the test. In the $\gamma p$ regime, the situation is still unclear and some discrepancies between the conclusions of the two experiments are observed. The vertex factorisation used in many phenomenological models for describing the leading neutron production has been shown by ZEUS to be broken in $\gamma p$ processes. It is interesting to notice that the model that best describes this vertex factorisation breaking implements the same rescattering effects that affects the QCD factorisation in diffraction.
Fig. 3: Differential cross section for $D^+$ meson production in diffractive DIS as a function of $\beta$, measured for two different values of $x_F$. The data are shown as dots, the statistical uncertainty as the internal error bars, the sum in quadrature of the statistical and uncorrelated systematic uncertainties as outer error bars. The two curves represent the central values of NLO predictions using two different sets of dPDFs.

References

Fig. 4: Differential cross section for $D^*$ meson production in diffractive $\gamma p$ as a function of $x_P$. The data are shown as dots, the statistical uncertainty as the internal error bars, the sum in quadrature of the statistical and uncorrelated systematic uncertainties as outer error bars. The curves represent the central values of NLO predictions using different sets of dPDFs. The theoretical uncertainty on the NLO prediction due to the scale choice is displayed as a shaded band only for the calculation using the H1 2006 fit A.

Fig. 5: The value of $\rho$, the ratio of the $x_L$ distributions for $\gamma p$ and DIS, as a function of $x_L$. The error bars show the statistical uncertainty; the shaded band show the systematic uncertainties. The theoretical predictions from two models are shown as a dashed and a dashed-dotted curve. The same predictions corrected for the $W$ dependence of the pion cross section in $\gamma p$ and DIS are shown as a solid and a dotted curve.