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Diffractive Dijet Production with Leading Proton in ep Collisions at HERA

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The cross section of the diffractive process $ep \to eXp$ is presented where the system X contains at least two jets and the leading final state proton is tagged in the H1 Very Forward Proton Spectrometer (VFPS). The measurement is performed for photoproduction with $Q^2 < 2\,\mathrm{GeV}^2$ in photon virtuality and for deep-inelastic-scattering with $4\,\mathrm{GeV}^2 < Q^2 < 80\,\mathrm{GeV}^2$. Measured cross sections are compared to next-to-leading order QCD calculations based on diffractive parton distribution functions extracted from measurements of inclusive cross sections in diffractive deep-inelastic-scattering. The results are discussed with focus on the validity of the factorisation theorem for these processes.

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1. Introduction

Hard diffraction in ep collision, firstly observed in 1993 at HERA, has been studied extensively since that time. Data from inclusive deep-inelastic scattering (DIS) were fitted to obtained diffractive parton distribution function (DPDF) [1]. The universality of these DPDFs was successfully tested for diffractive DIS production of dijet and charm [2, 3].

On the other hand in diffractive hadron-hadron interactions, where the hard scale is provided by the presence of jets, the predictions based on HERA DPDFs overestimate the data, at Tevatron by about one order of magnitude [4]. To quantify this phenomenon the so called suppression factor is introduced as an ratio of data to the theoretical predictions based on the QCD factorisation theorem. The factorisation breaking is usually explained as a consequence of additional partonic interactions between both hadrons which destroy the diffractive event signature - the rapidity gap [5]. Similar effect was recently observed at LHC by the CMS collaboration [6].

But even in diffractive ep interaction the situation is not clear. In contrast to the DIS region, in photoproduction, where virtualities of exchanged photon are small, the photon could dissociate into a low mass hadronic system. As a consequence only a fraction, denoted as x_γ, of the photon longitudinal momentum enters the hard subprocess. These so called resolved interactions resemble hadron-hadron interactions and factorisation breaking is expected by several models [7, 8, 9, 10]. The photon can still enter directly into the hard subprocess, as in DIS. Such interactions are called direct. This picture is valid only in the leading-order approach where variable x_γ is discriminating between these two processes, because: $x_\gamma = 1$ and $x_\gamma < 1$ holds for the direct and resolved photon interactions, respectively.

Dijets in diffractive photoproductions have been measured by H1 [11, 12] and ZEUS [13]. In these measurements diffractive events were selected using the large rapidity gap (LRG) method. Contrary to the theoretical expectations no significant x_γ dependence of the ratio of data over NLO QCD expectations is observed by any of these analyses. However, the overall normalisation of the data to the NLO QCD predictions is found to be about 0.6 in case of the H1 analyses but consistent with unity in case of the ZEUS measurement. The ZEUS analysis covered a slightly different kinematic by requiring higher transverse jet energies than for H1. In [14] H1 data were extrapolated into the ZEUS phase space but the apparent inconsistency was not solved in this way.

In [15] new preliminary results of an H1 measurement of diffractive dijet photoproduction were shown. The data were selected using a leading proton spectrometer, therefore no background from proton dissociation or non-diffractive dijets is present in the data. This measurement is consistent with the previous H1 results albeit with large uncertainty on the suppression factor mainly due to the theory uncertainties. To reduce this uncertainty this analysis is extended to DIS in order to apply the same method as in [12] by measuring the double ratio of measured to predicted cross sections in diffractive photoproduction to the corresponding ratio in diffractive DIS. In the double ratio many experimental and theoretical uncertainties are reduced. The leading-proton data were collected in the years 2006-2007 with a total integrated luminosity of $30\,\mathrm{pb}^{-1}$.

2. Experimental Setup

The H1 detector is described in detail elsewhere [16]. In this measurement, the diffractive

γp	DIS
$Q^2 < 2\,\mathrm{GeV}^2$	$4\,\mathrm{GeV}^2 < Q^2 < 80\,\mathrm{GeV}^2$
Common Cuts	
$0.2 < y < 0.7$ $E_T^{*\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ $E_T^{*\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ $-1 < \eta^{\mathrm{jet1,2}} < 2.5$	
$0.010 < x_{I\!P} < 0.024$ $\lvert t\rvert < 0.6\,\mathrm{GeV}^2$ $z_{I\!P} < 0.8$	

Table 1: Phase space of the diffractive dijet VFPS measurement for photoproduction (γp) and deep-inelastic scattering (DIS).

protons are directly tagged by Very Forward Proton Spectrometer (VFPS) [17]. The VFPS consists of two stations at 220 and 222 m from the interaction point and has a high track reconstruction efficiency while the beam-halo background contamination is negligible. The diffractive kinematic domain specified by relative proton energy loss $x_{I\!P}$ and proton four-momentum transfer t is chosen to be within the VFPS acceptance.

The selection of DIS events is based on the detection of a scattered positron identified as the most energetic electromagnetic cluster in the SPACAL calorimeter [18]. In photoproduction events were selected using condition of absence of such a positron candidate in SPACAL.

Jets defined by the k_T-algorithm in $\gamma^{(*)}p$ frame[1] with $R = 1$ [19] are required to have pseudorapidities $\eta^{\mathrm{jet1,2}}$ within Liquid-Argon calorimeter acceptance. Constrains on transverse jet energies $E_T^{*\mathrm{jet1,2}}$ are asymmetric [20] to avoid infrared singularities in next-to-leading order QCD predictions.

The pomeron momentum fraction entering the hard subprocess $z_{I\!P}$ is restricted to 0.8 to improve the reliability of the data to NLO QCD prediction comparison, since the DPDF set used is not defined for $z_{I\!P}$ values close to unity. The definitions of the analyses phase-spaces are summarised it table 1.

3. Theoretical Calculations

Theoretical calculations based on the collinear factorisation theorem are performed using the NLO QCD program of Frixione et.al. [21] for photoproduction and NLOJET++ [22] for DIS. Diffraction is simulated by the Resolved Pomeron Model [23] with H1 2006 Fit B DPDF [1], subleading reggeon exchange is also included. In photoproduction the resolved component is calculated using the GRV-HO [24] photon parton distribution function. The renormalization and factorisation scales are both set to $\mu_R = \mu_F = \sqrt{\left(E_T^{\mathrm{jet1}}\right)^2 + Q^2/4}$. The NLO QCD calculations are performed with the number of flavours fixed to 5 and $\Lambda_5 = 0.228\,\mathrm{GeV}$, corresponding to a 2-loop

[1]Quantities evaluated in the $\gamma^* p$ frame are denoted by the asterisk "*"

α_S of 0.118. Frixione NLO as well as NLOJET++ were successfully compared with alternative NLO QCD programs [25, 26].

The resulting parton-level cross sections are corrected for hadronisation effects by means of hadronisation corrections calculated using the leading order Monte Carlo generator RAPGAP [27]. This Monte Carlo simulation is also used for unfolding of measured data to the level of stable hadrons applying Tikhonov regularisation method [28, 29] and to correct measured cross section to QED radiation.

4. Results

The measured differential cross sections as a function of the pomeron momentum fraction entering the hard subprocess $z_{I\!P}$ and the photon momentum fraction entering the hard subprocess x_γ for photoproduction are shown in the first row of Figure 1. The NLO QCD predictions lies systematically above the data, whereas the shapes agree within uncertainties. There is no indication of resolved part ($x_\gamma \lesssim 0.8$) being more suppressed than the direct part ($x_\gamma \gtrsim 0.8$), as is predicted by KKMR model [10].

In the second row of figure 1 the measured differential cross section as a function of $z_{I\!P}$ and transverse energy of the leading jet $E_T^{*\mathrm{jet1}}$ for DIS is shown together with the NLO QCD predictions. The theoretical calculations agree with data within the uncertainties.

Integrated over the measured kinematic range the double ratio of data over NLO QCD calculations for photoproduction to data over NLO QCD calculations for DIS is:

$$\frac{(\mathrm{DATA/NLO})_{\gamma p}}{(\mathrm{DATA/NLO})_{\mathrm{DIS}}} = 0.55 \pm 0.10\,(\mathrm{data}) \pm 0.02\,(\mathrm{theor.}) \tag{4.1}$$

and is shown in Figure 2. This value is consistent with 0.5 ± 0.1 obtained in [12] using the large rapdity gap method. As shown in Figure 3 no kinematic dependence of the double ratio is observed as a function of $z_{I\!P}$ and $E_T^{*\mathrm{jet1}}$.

5. Conclusion

Diffractive dijets cross sections in photoproduction and in DIS with the leading proton detected by proton spectrometer are measured. The double ratio of measured to predicted cross sections in diffractive photoproduction to the corresponding ratio in diffractive DIS is 0.55, with no significant kinematic dependence. This double ratio is found to be consistent with previous H1 measurements, where complementary experimental methods have been used. Within the theoretical framework applied this result indicates that QCD factorisation may be broken in diffractive dijet photoproduction.

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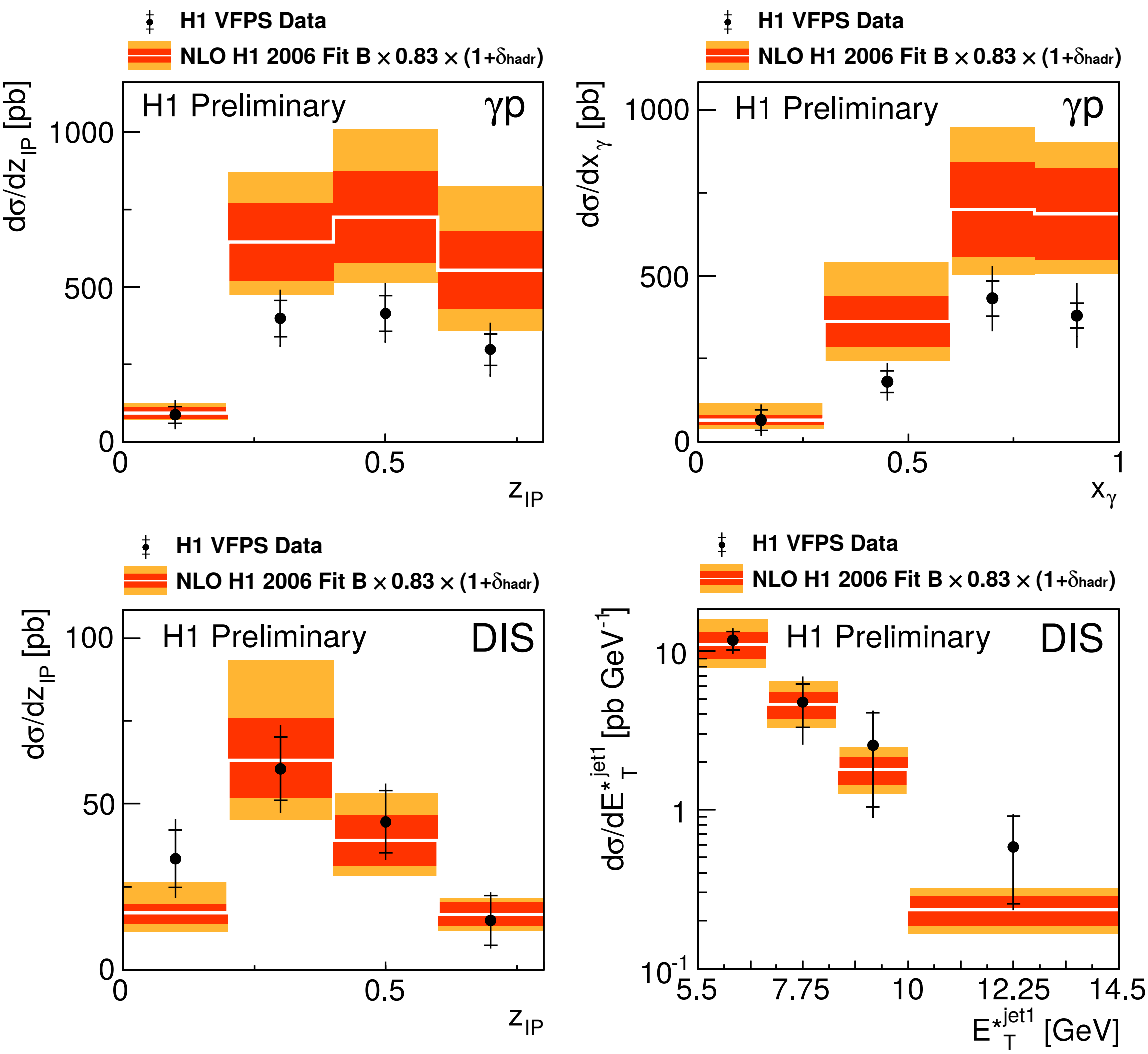

Figure 1: Diffractive dijet cross sections (top) differential in $z_{I\!P}$ and x_γ for photoproduction (γp) and differential (bottom) in $z_{I\!P}$ and $E_T^{*\text{jet1}}$ for DIS. The inner error bars represent the statistical errors. The outer error bars indicate the statistical and systematic errors added in quadrature. NLO QCD predictions based on the DPDF set H1 2006 Fit B, corrected to the level of stable hadrons, are shown as a white line. The dark shaded band indicates the DPDFs uncertainties and light shaded band indicates the DPDFs and scale uncertainties added in quadrature.

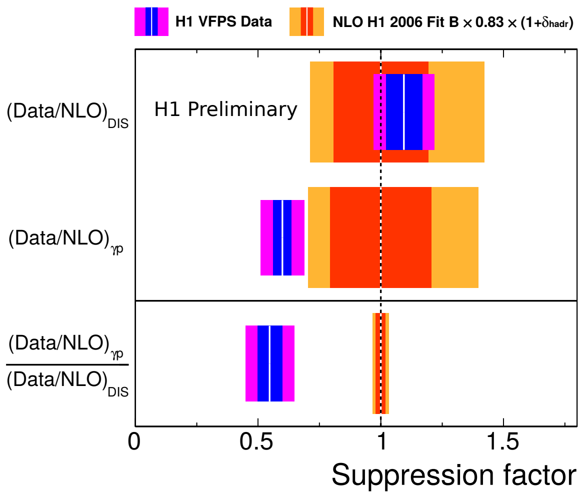

Figure 2: DIS and photoproduction (γp) integrated cross sections normalised to the NLO QCD theoretical calculations are shown as a white line. The double ratio of data over NLO QCD calculations for photoproduction to data over NLO QCD calculations for DIS is presented as a white line in the last row. The black and the dark shaded bands around the measurements correspond to the statistical and the total experimental uncertainties, respectively. The uncertainties on the NLO QCD calculations due to the PDF uncertainties are shown by the dark shaded band around unity while the total theory uncertainties are given by the light shaded band.

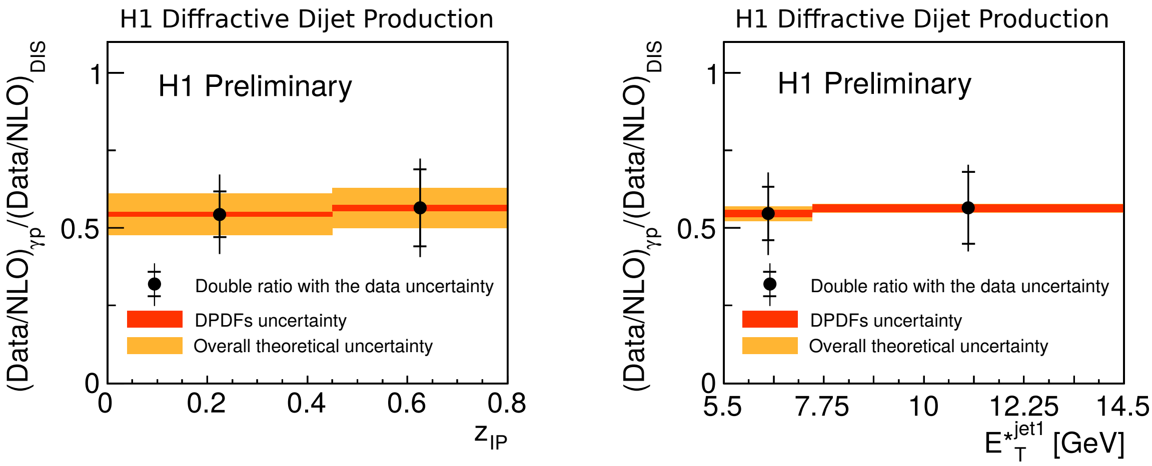

Figure 3: Cross section double ratios of data to NLO QCD prediction for photoproduction to DIS as a function of $z_{I\!P}$ and $E_T^{*\text{jet1}}$. The inner error bars represent the data statistical errors, the outer error bars indicate the data statistical and systematic errors added in quadrature. The dark shaded band indicates the DPDFs uncertainties and the light shaded band indicates the DPDFs and scale uncertainties added in quadrature.