PROCEEDINGS OF SCIENCE

Diffractive Dijet Production with a Leading Proton in ep Collisions at HERA

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The production of dijets with a tagged forward proton is measured at HERA. The data were recorded with the H1 detector at DESY in the years 2006-2007. Events with a leading proton are detected using the very forward proton spectrometer of the H1 detector. Two jets are selected with transverse momenta transverse momenta in the hadronic-centre-of-mass larger than 4 and 5.5 GeV, respectively. The analysis is performed both in the regime of deep-inelastic scattering (DIS), with momentum transfer $Q^2 > 4\,\mathrm{GeV}^2$ and for photoproduction (γp), with $Q^2 < 2\,\mathrm{GeV}^2$. Cross sections are measured single-differentially in various kinematic quantities. For DIS, the data are found to be in good agreement with NLO QCD calculations based on diffractive parton densities determined from inclusive diffractive cross section measurements. For γp, the cross sections are found to be overestimated by approximately a factor of two.

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1. Introduction

At HERA, reactions of electrons or positrons and protons, $ep \to eX$, are probed at centre-of-mass energies of 320 GeV. Two kinematic regimes are distinguished, depending on the negative momentum transfer squared Q^2 from the ingoing to the outgoing electron[1]. At high $Q^2 > 4\,\mathrm{GeV}^2$, the process is referred to as deep-inelastic scattering (DIS), whereas at low $Q^2 < 2\,\mathrm{GeV}^2$ the process is called photoproduction (γp). In the analysis presented here [1], dijet production in both diffractive γp and diffractive DIS is studied. The reaction may be written as $ep \to eXp$, where X is a hadronic system which contains two jets. The outgoing proton is detected in the H1 Very Forward Proton Spectrometer (VFPS) [2].

QCD calculations for this process are based on diffractive parton densities (DPDFs). A corresponding factorisation theorem is known for the case of diffractive DIS [4] but not for diffractive γp. The DPDFs describe the probability to find a parton with longitudinal momentum fraction z_{IP} in the proton, given that there is a diffractive signature, characterised by a longitudinally momentum fraction $1 - x_{IP}$, momentum transfer t of the outgoing proton and a hard scale μ. They are folded with hard matrix elements to describe jet production at next-to-leading order in the strong coupling. A hard scale $\mu^2 = \langle E_T^{\star jet}\rangle^2 + Q^2$ is provided by the jet transverse momentum $\langle E_T^{\star jet}\rangle$ and in the case of DIS by the momentum transfer Q^2.

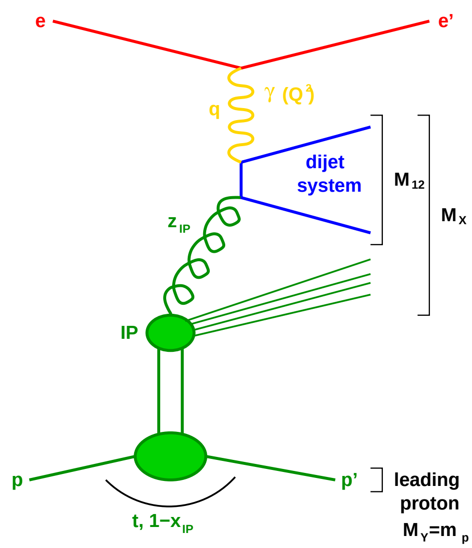

Figure 1: Diffractive dijet production with a leading proton at HERA.

Experimentally, the DPDFs are determined from inclusive diffractive DIS cross section measurements, where no requirements on the hadronic final state X are made. As suggested by the scheme shown in figure 1, the DPDFs are determined with the ad-hoc assumption that they factorise into a probability to find a colourless object IP in the proton and parton density functions, ascribed to the structure of IP. The probability or "flux factor" is taken to depend on x_{IP} and t only, whereas the parton density functions of IP only depend on the variable z_{IP} and the hard scale μ.

For the present analysis, the H1 2006 DPDF fit B [3] is used to predict cross sections. The present measurements focuses on testing the factorisation assumptions both in the DIS and in the γp kinematic domain. Factorisation in diffractive DIS has been validated by experiment [5, 6, 7, 8, 9, 10]. In hadron-hadron collisions clear evidence for a suppression of the cross section as compared to the expectation by about one order of magnitude is observed [11, 12]. For diffractive γp, dijet production has been measured at HERA [13, 14, 15]. A suppression of about a factor of two is observed in the two independent analyses by the H1 experiment, whereas in the ZEUS analysis no suppression is seen [14].

[1]Throughout this paper, the term electron or the variable e is used to denote both electrons and positrons, unless otherwise stated.

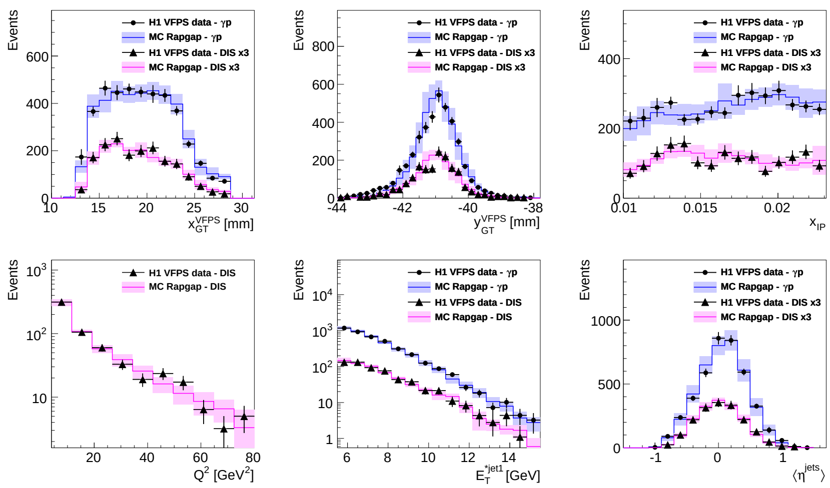

Figure 2: Control distributions of selected reconstructed quantities.

2. Data Analysis

The analysis [1] is based on events recorded with the H1 detector [16] in the years 2006 and 2007, corresponding to an integrated luminosity of $30\,\mathrm{pb}^{-1}$ for γp and $50\,\mathrm{pb}^{-1}$ for DIS. DIS events are identified by the presence of an electron in the H1 rear calorimeter (SpaCal) [17], whereas γp events are identified by the absence of an electron in the SpaCal or the liquid-argon calorimeter. These requirements limit the accessible kinematic range to $4 < Q^2 < 80\,\mathrm{GeV}^2$ for DIS and to $Q^2 < 2\,\mathrm{GeV}^2$ for γp. The inelasticity y is also restricted, in order to ensure that both the scattered electron and the hadronic final state are well measured. Diffractive events with a leading proton are selected by requiring a tagged proton in the H1 VFPS detector [2]. The VFPS has a high geometrical acceptance (full coverage in azimuth), but restricts the accessible range in the forward proton longitudinal momentum x_{IP} and in the momentum transfer at the proton vertex $|t|$. All selection criteria are summarised in table 1. The hadronic final state X is reconstructed from the detected tracks and calorimeter clusters, using an energy-flow algorithm. The four-vectors of the hadronic objects are boosted to the $\gamma^\star p$ rest-frame and jets are reconstructed using the inclusive k_T jet algorithm [18] with P_T recombination scheme and distance parameter $R = 1$. Dijet events are accepted if there are at least two jets with transverse momenta of the leading (sub-leading) jet fulfilling the conditions $E_T^{\star jet1} > 5.5\,\mathrm{GeV}$ ($E_T^{\star jet2} > 4\,\mathrm{GeV}$). The jet pseudorapidity is restricted in the laboratory frame to $-1 < \eta^{jet1,2} < 2.5$, in order to ensure that the jets

	Photoproduction	DIS
Event kinematics	$Q^2 < 2\,\mathrm{GeV}^2$	$4 < Q^2 < 100\,\mathrm{GeV}^2$
	$0.2 < y < 0.7$	
Leading proton	$0.01 < x_{IP} < 0.024$	
	$\lvert t\rvert < 0.6\,\mathrm{GeV}^2$	
		$z_{IP} < 0.8$
Dijets	$E_T^{\star jet1} > 5.5\,\mathrm{GeV}$	
	$E_T^{\star jet2} > 4\,\mathrm{GeV}$	
	$-1 < \eta^{\mathrm{jet1,2}} < 2.5$	

Table 1: Analysis phase space.

are well contained[2]. The events are selected in an extended analysis phase space, in order to ensure that migrations near the phase space boundaries are be well controlled. Only after correcting for detector effects, the phase space is restricted to the boundaries described in the text. For unfolding from detector objects to the particle level, a regularised matrix unfolding technique is applied. The response matrix is constructed using the RAPGAP event generator interfaced to the GEANT-based simulation of the H1 detector. Control distributions of reconstructed variables at detector level are shown in figure 2. The variables shown are: the local VFPS coordinates X^{GT}_{VFPS} and Y^{GT}_{VFPS}, the proton fractional momentum loss x_{IP} measured with the VFPS, the momentum transfer Q^2 (DIS events only), the leading jet transverse momentum $E_T^{\star jet1}$ and the average jet pseudorapidity $\langle \eta^{jet} \rangle$. All reconstructed variables are well described by the RAPGAP simulation.

3. Cross section measurements

Single-differential cross sections are measured as a function of various variables. For γp it is particularly interesting to look at the variable x_γ, which is sensitive to the longitudinal momentum fraction of the photon entering the hard process. In a simplified view, the photon has a hadronic structure at small x_γ but has no structure at $x_\gamma = 1$. As can be seen in figure 3, the shape in x_γ is well described by the NLO calculation, but the normalisation is not. This observation is consistent with earlier measurements [13, 14, 15]. Integrated over the full phase-space, the cross section for dijet production in diffractive DIS is measured to be $30.5 \pm 1.6(\text{stat}) \pm 2.8(syst)$ pb, in agreement with the NLO prediction of $28.3^{+11.4}_{-6.4}(\text{scale})^{+3.0}_{-4.0}(\text{DPDF}) \pm 0.8(\text{hadr})$. In γp, however, the cross section is measured to be $237 \pm 14(\text{stat}) \pm 31(syst)$ whereas the prediction is $430^{+172}_{-98}(\text{scale})^{+48}_{-61}(\text{DPDF}) \pm 13(\text{hadr})$. The systematic uncertainties, summarised in table 2, stem in about equal part from the understanding of the VFPS detector, the hadronic energy scale, uncertainties of the RAPGAP simulation and the overall normalisation.

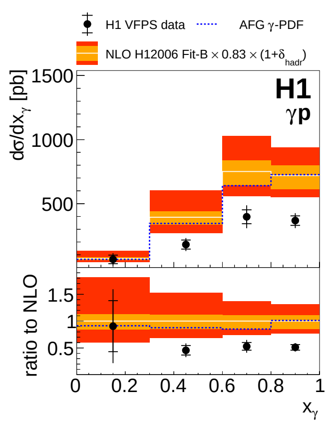

Figure 3: Diffractive dijet photoproduction cross section as a function of the variable x_γ.

Figure 4 shows the cross sections in DIS and γp as a function of the variables z_{IP}, $E_T^{\star jet1}$ and the difference in rapidity, $|\Delta\eta|$. In general, all single-differential cross sections are well described in DIS. In γp, the shapes are well described but the overall normalisation is off by approximately a factor of two. This effect also can be seen in figure 5, where the ratio of the measured to predicted cross section is depicted as a function of Q^2.

Systematic uncertainty	DIS	γp
VFPS detector	3.0%	5.3%
Hadronic energy scale	4.4%	7.2%
RAPGAP model	4.3%	6.9%
Normalisation	6.0%	6.0%
Total	9.1%	12.8%

Table 2: Summary of systematic uncertainties.

[2]The z axis is pointing along the proton flight direction. Polar angles θ are measured with respect to the z axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

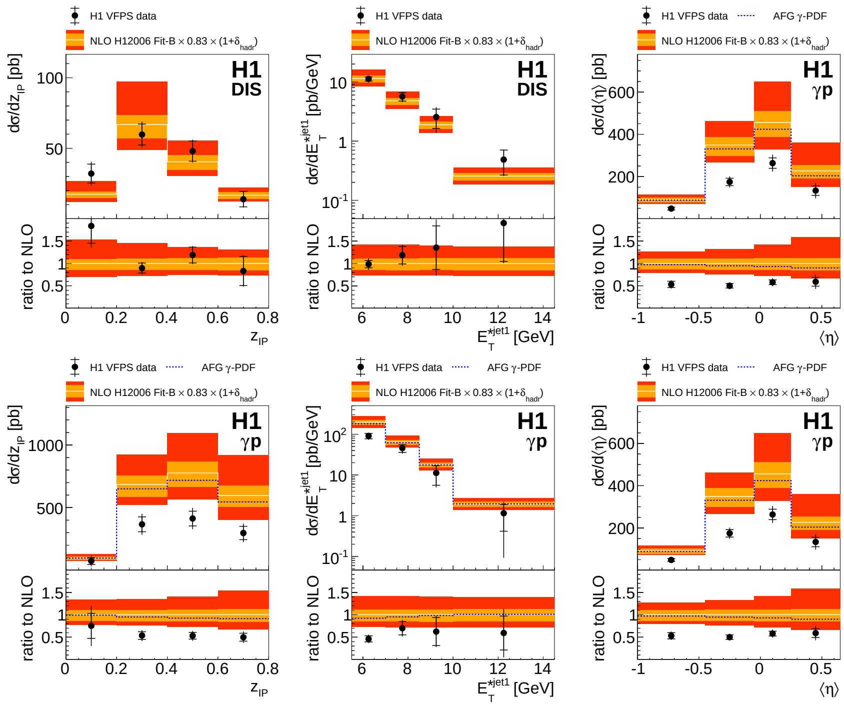

Figure 4: Diffractive dijet production with a leading proton; single-differential cross sections in DIS and in photoproduction.

In the DIS regime, the ratio is compatible with one, whereas for photoproduction the ratio is close to one half.

4. Cross section ratios

In order to possibly reduce the impact of systematic uncertainties, ratios of cross sections in γp to DIS and double-ratios data to theory are also investigated. For the NLO prediction, the assumption is made that variations of the scale μ have to be applied consistently to the DIS and γp predictions. This leads to cancellations of scale uncertainties in the ratio. For the measurements, however, the systematic uncertainties do not reduce. The main reason are the model uncertainties, which are not correlated between DIS and γp and thus are enlarged in the ratio. For the integrated cross section, the double-ratio of γp to DIS, data to theory is found to be $0.511 \pm 0.085(\text{data})^{+0.022}_{-0021}(\text{theory})$. This is consistent with an earlier H1 analysis [13] of independent data. The present measurement, with a tagged forward proton, is free of proton dissociative contributions, as opposed to the earlier measurements. Hence one may conclude that proton dissociation certainly is not the dominant source of the suppression.

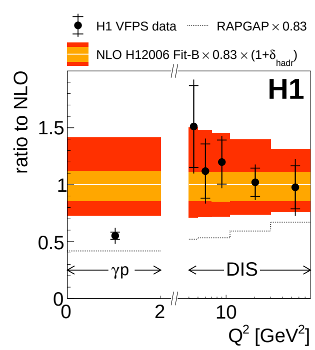

Figure 5: Ratio of measured to predicted diffractive dijet cross section as a function of Q^2.

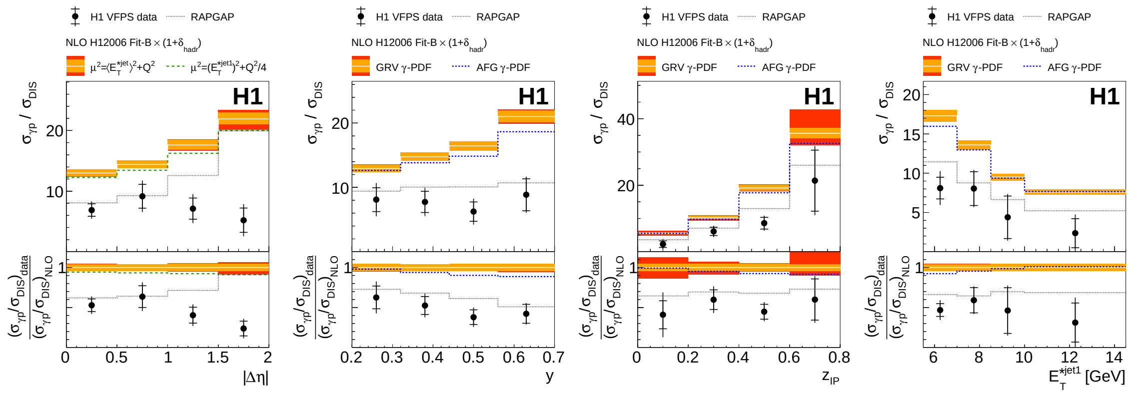

Figure 6: Ratio of γp to DIS diffractive dijet cross sections and double ratio of data to NLO prediction.

Possible shape dependencies of the cross section ratios are also investigated. Figure 6 shows cross section ratios in the variables $|\Delta\eta|$, y, z_{IP} and $E_T^{\star jet1}$. The double ratios are significantly different from unity, but no significant shape dependencies are observed. The largest deviation from a constant are observed in $|\Delta\eta|$, however the data are still compatible with a constant at a fit probability of 15%.

5. Summary

Diffractive dijet production with a leading proton is measured both in the regime of deep-inelastic scattering (DIS), $Q^2 > 4\,\mathrm{GeV}^2$, and in the photoproduction regime (γp), $Q^2 < 2\,\mathrm{GeV}^2$. The data exploit for the first time the H1 Very Forward Proton Spectrometer, which has a large acceptance and thus small normalisation uncertainties. Single-differential cross sections, cross-section ratios and double ratios of γp to DIS are extracted. Next-to-leading order QCD (NLO) calculations are able to describe the measured diffractive DIS dijet cross sections, whereas they are off in normalisation in γp. The observed γp cross sections correspond to a suppression factor of $0.511 \pm 0.085(\mathrm{data})^{+0.022}_{-0021}(\mathrm{theory})$, assuming that scale uncertainties of the NLO calculations largely cancel in the double ratio γp to DIS, data to NLO. This result is in agreement with earlier H1 measurements [13, 15].

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