Vector meson production at HERA

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Abstract. Exclusive ϕ electroproduction and proton-dissociative diffractive photoproduction of J/ψ mesons has been studied in ep collisions with the ZEUS detector at HERA, using an integrated luminosity of 65 pb^{-1} and 112 pb^{-1}, respectively. The ϕ cross section was measured as a function of Q^2, W, t and helicity angle θ_h in the kinematic range of $2 < Q^2 < 70$ GeV^2, $35 < W < 145$ GeV and $|t| < 0.6$ GeV^2. The J/ψ photoproduction cross section was measured for $|t|$ up to 20 GeV^2 in the range of $50 < W < 150$ GeV as a function of $|t|$ and W. Both measurements are compared to other vector meson cross sections and predictions from theoretical models.

Keywords: diffraction, vector meson, electroproduction, photoproduction, high t
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INTRODUCTION

The ZEUS experiment at the HERA electron-proton collider has made extensive studies of vector meson (VM) production [1–3]. The ZEUS data cover a wide kinematic region, in which perturbative QCD (pQCD) is expected to be applicable, as well as regions in which no hard scale is present and non-perturbative processes dominate. The diffractive production of vector mesons gives the opportunity to explore the partonic nature of the diffractive exchange and to investigate the transition region between soft physics, already explored by fixed targed experiments, and the hard, pQCD physics.

The production of ϕ and J/ψ vector mesons has been studied in the diffractive process, $ep \to e\ V\ Y$, with Y being either a scattered proton (exclusive production of ϕ), or a proton remnant system (proton dissociative production of J/ψ).

The characteristic variables for these processes are: the mass of the vector meson, M_{VM}, the centre-of-mass energy of the $\gamma^* p$ system, W, the photon virtuality, Q^2, and the square of the four momentum, $|t|$, transferred at the proton vertex.

In QCD, the diffractive production of vector mesons can be viewed, in the proton rest frame, as a sequence of processes which are well separated in time. The incoming electron emits a virtual photon, which then fluctuates into a $q\bar{q}$ pair. This pair scatters elastically off the proton, and long after the interaction forms a vector meson. Due to this time separation, the cross section can be factorised [4] into terms representing the $q\bar{q}$ coupling to the photon, the dipole scattering cross section on the proton, and the final state formation of the vector meson.

The non-perturbative approach, based on Regge phenomenology [5] and the Vector Dominance Model (VDM) gives a successful description of light vector meson (ρ, ω, ϕ) production at low values of Q^2 and $|t|$. In this approach diffractive interactions are mediated by the exchange of the vacuum quantum numbers which corresponds to soft Pomeron exchange. This approach predicts a weak energy dependence of the cross section ($\sigma \propto W^{0.22}$), shrinkage of the diffractive peak with increasing W, $d\sigma/dt \propto e^{-bt}(W/W_0)^{4(\alpha_{IP}(t)-1)}$, with $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}t$ and $b = b_0 + 4\alpha' \ln(W/W_0)$ and S-Channel Helicity Conservation, SCHC, (the VM retains the helicity of the photon).

For large values of Q^2, M_{VM} or $|t|$ the process is expected to be 'hard' and hence pQCD should be applicable. In this approach the colour dipole interacts with the proton (or a single parton in it) by the exchange of a colour singlet state, which is assumed to be a two-gluon system or gluon ladder (the latter is often called the hard or pQCD pomeron). The $q\bar{q}$ scattering off the proton is described by pQCD, while the transitions $\gamma \to q\bar{q}$ and $q\bar{q} \to VM$ are modelled with the respective wave functions. The cross section is proportional to the square of the gluon density $g(x,Q^2)$ in the proton: $\sigma \propto \alpha_s^2(Q^2)/Q^6[xg(x,Q^2)]^2$, with $x \approx Q^2/W^2$ (valid for small x) [4]. Thus, in the presence of a hard scale, a steep rise of the cross section with W is predicted, along with a weak t dependence, little shrinkage with increasing W, dominant longitudinal γ^* polarisation and possible SCHC violation.

Exclusive ϕ production allows the study of the transition region between soft and hard dynamics and data to be confronted with theoretical predictions. These results are an update of previous measurements and have been performed using a significantly larger data sample.

In proton-dissociative J/ψ photoproduction $|t|$ serves as a hard scale. This process, with an extended $|t|$ range and larger statistics, compared to previous results, is a very promising test of the BFKL based models.

In this paper these new results from ZEUS are reported.

EXCLUSIVE ϕ IN DIS

Analysis. The exclusive production of ϕ mesons, $ep \to e\phi p$, was measured in the kinematic range of $2 < Q^2 < 70$ GeV^2, $35 < W < 145$ GeV and $|t| < 0.6$ GeV^2. The data correspond to an integrated luminosity of 65.1 pb^{-1} and were collected during the 1998-2000 running period. The signature of exclusive ϕ electroproduction consists of the scattered electron and two oppositely charged kaons from the ϕ decay. The scattered proton is deflected through a small angle and escapes undetected down the beam pipe. The identification and energy measurement of the scattered electron is based on the information from the main calorimeter. The ϕ signal was reconstructed from the properties of the decay kaons. Non-exclusive events and the events with the proton dissociation were rejected if there were additional energy deposits in the calorimeter or other detectors above the noise level.

Results. The cross sections were measured as a function of W, Q^2, $|t|$ and the helicity angle, θ_h. The ratio $R = \sigma_L/\sigma_T$ was studied as a function of Q^2 and W. The data are compared to the cross sections for other vector mesons as well to predictions from theoretical models.

The $\gamma^* p$ cross section rises with W as $\sigma \propto W^\delta$, where δ does not depend on Q^2 or t. The measured value of $\delta \approx 0.4$ lies between the 'soft' diffraction value and that observed

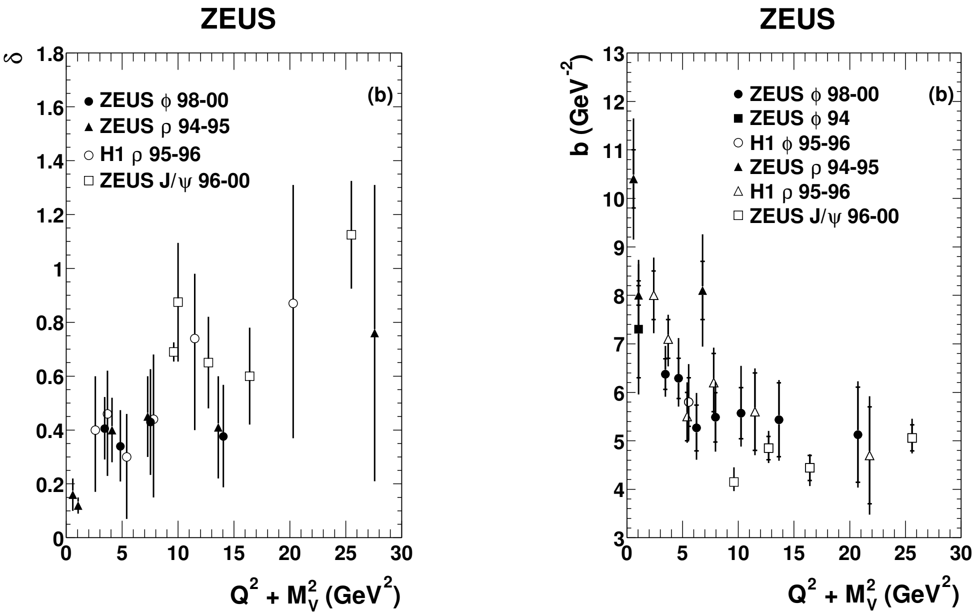

FIGURE 1. The extracted values of δ and b for ϕ as a function of $Q^2 + M^2_{VM}$ compared with results from other vector mesons. The error bars represent the quadratic sum of the statistic and systematic uncertainties.

in exclusive J/ψ production.

The Q^2 dependence of the cross section, fitted with a function of the form $(Q^2 + M^2_\phi)^{-n}$, shows that there is no a single value of n which is valid over the whole range of Q^2. The fit parameter n varies from $n = 2.087 \pm 0.055(\text{stat.}) \pm 0.050(\text{syst.})$ for $2.4 \leq Q^2 \leq 9.2$ GeV^2 to $n = 2.75 \pm 0.13(\text{stat.}) \pm 0.07(\text{syst.})$ for $9.2 \leq Q^2 \leq 70$ GeV^2. The longitudinal, σ_L, and transverse, σ_T, components of the cross section have been extracted from the measured ratio R. Both cross sections show different Q^2 dependence.

The t dependence is well described over the whole range of Q^2 and at $W = 75$ GeV by an exponential form $d\sigma/dt = d\sigma/dt|_{t=0} \cdot e^{bt}$, where b shows no the Q^2 dependence. The Pomeron trajectory was extracted from the W dependence of the differential cross section, $d\sigma/dt$, for $Q^2 = 5$ GeV^2 yielding an intercept of $\alpha_{IP}(0) = 1.10 \pm 0.02(\text{stat.}) \pm 0.02(\text{syst.})$ and a slope of $\alpha'_{IP} = 0.08 \pm 0.09(\text{stat.}) \pm 0.08(\text{syst.})$. The measured value of α'_{IP} is closer to the values measured in hard processes than in soft ones.

The data were compared to the available measurements of $ep \to e\,Vp$ [6–12] and the parameters δ and b were found to scale as a function of $Q^2 + M^2_V$ (Fig. 1). The Q^2 dependence of R is well described by the expression $a(Q^2/M^2_\phi)^b$, yielding $a = 0.51 \pm 0.07(\text{stat.}) \pm 0.05(\text{syst.})$ and $b = 0.86 \pm 0.11(\text{stat.}) \pm 0.05(\text{syst.})$. The value of R was found also to scale with Q^2/M^2_V.

The measured quantities were compared with two different leading order theoretical

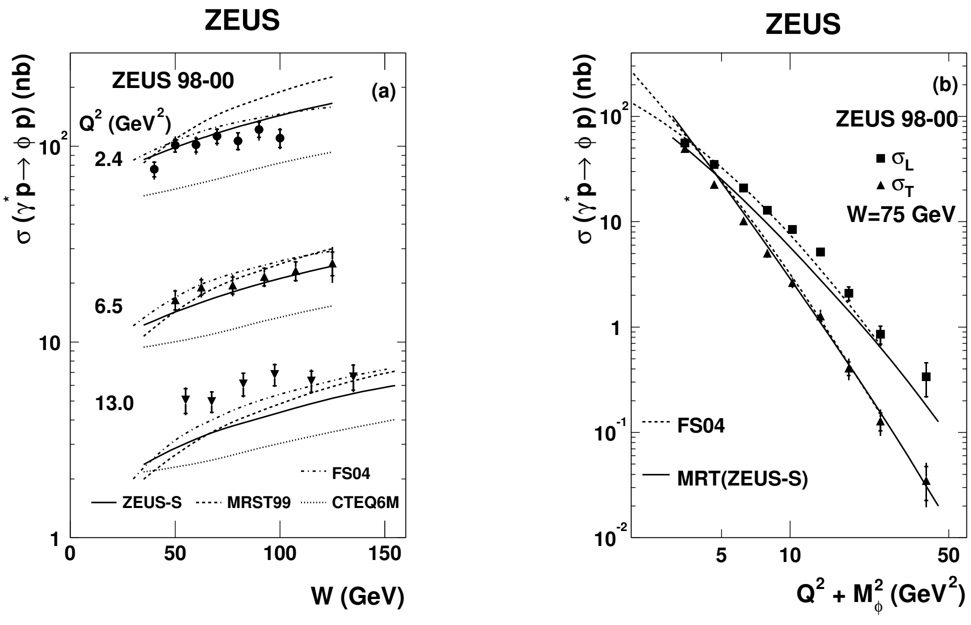

FIGURE 2. Exclusive ϕ cross sections are shown as a function of W and $Q^2 + M_\phi^2$. The data are compared to the MRT and FS04 predictions. The inner bars correspond to the statistical uncertainty and the outer to the statistical and systematic uncertainty added in quadrature.

predictions (Fig. 2): the Martin, Ryskin and Teubner (MRT) [13] model using three different gluon distributions: ZEUS-S, CTEQ6M and MRST99 and predictions by Forshaw and Shaw (FS04) [14]. The W dependence of the $\gamma^* p$ cross section is reproduced well by the FS04 predictions, especially for higher values of Q^2, while the MRT model using the ZEUS-S and CTEQ6M parametrisations is compatible with the data. The predictions based on MRST99 are too steep. Both models generally describe the Q^2 dependence, although for smaller values of Q^2 the normalisation is not well reproduced. The power-law dependence of R with Q^2 is reproduced by the theoretical predictions but is systematically low. The value of R is weakly dependent on W, this observation being confirmed by both the MRT and FS04 models.

PROTON-DISSOCIATIVE J/ψ PHOTOPRODUCTION

Analysis. The data used in this analysis were collected in 1996 - 2000 and correspond to an integrated luminosity of 112 pb^{-1}. The signature of proton dissociative J/ψ photoproduction, $ep \to eJ/\psi Y$, consists of two oppositely charged muons from the J/ψ decay, the dissociated proton and the lack of the scattered electron in the main detector. The electron is scattered at small angle and escapes undetected down the beam pipe. The low mass hadronic states originating from the scattered proton are registered in

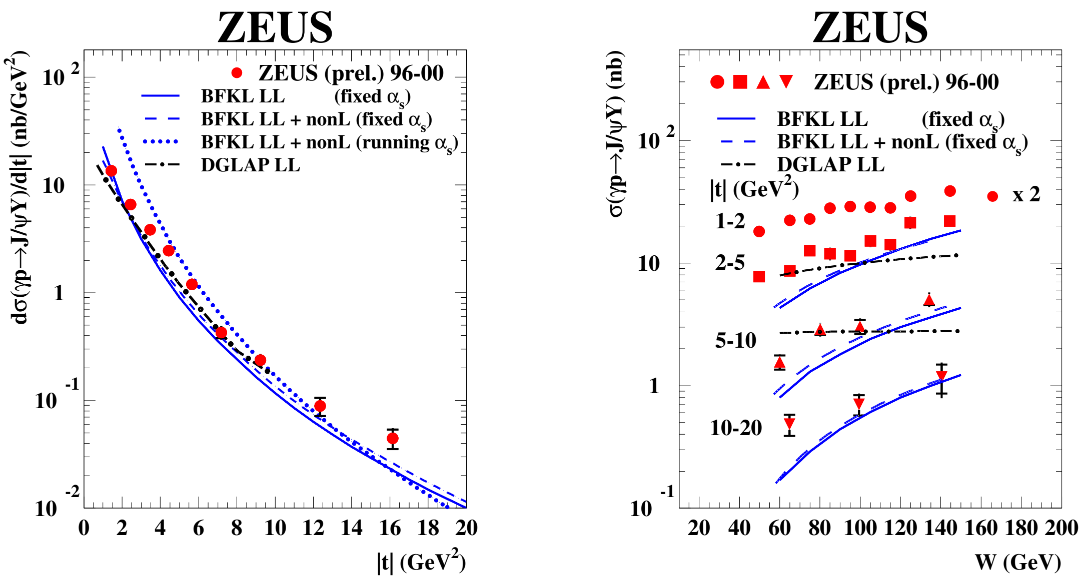

FIGURE 3. The differential cross section $d\sigma/d|t|$ and the cross section as a function of W for the process $\gamma p \to J/\psi\, Y$. The inner bars correspond to the statistical uncertainty and the outer to the statistical and systematic uncertainty added in quadrature. The solid line represents the results of BFKL LL with fixed α_s and the dashed (dotted) line – including non-leading corrections (nonL) with fixed (running) α_s. The dashed-dotted curve is a prediction based on DGLAP LL calculations.

the forward part of the calorimeter or in the forward detectors. The J/ψ mesons were reconstructed from the decay muons measured in the central tracking detector. Events with additional energy deposits above the noise level and not associated with lepton candidates or with products of dissociated proton were rejected.

In order to compare the cross sections with theoretical predictions and previous measurements, an additional cut of $z > 0.95$ was applied. This ensures the diffractive nature of the interaction and also restricts the invariant mass of the system Y to be $M_Y < 30$ GeV through the relation $z = 1-(M_Y^2 - t)/W^2$, where $z = (P\cdot v)/(P\cdot q)$ is the event elasticity, i.e. the fraction of virtual photon energy transferred to the J/ψ in the proton rest frame.

Events were required to be in a kinematic range where the properties of the final state particles are properly measured and the acceptance is well defined, which is satisfied for $1 < |t| < 20$ GeV^2, $40 < W < 160$ GeV and $M_Y < 30$ GeV.

Results. The cross section was measured as a function of $|t|$ and W. The energy dependence was fitted to the form $\sigma \propto W^\delta$ and the measured values of δ are found to rise with $|t|$. The Pomeron trajectory determined from δ, with an intercept of $\alpha_{IP}(0) = 1.153 \pm 0.048(\text{stat.}) \pm 0.039(\text{syst.})$ and a slope of $\alpha'_{IP} = -0.020 \pm 0.014(\text{stat.}) \pm 0.010(\text{syst.})$, is quite different from that of the 'soft' Pomeron [15] but is consistent with the prediction for that of the BFKL Pomeron[16, 17]. The data are in good agreement with previous measurements.

The data were compared with pQCD models (Fig. 3) based on BFKL [18–20] and DGLAP [21] evolution performed in the leading logarithmic (LL) approximation. The

BFKL model also provides calculations which include non-leading corrections (nonL) and for fixed and running α_s. The parameters of both pQCD models are those which best describe previous HERA measurements[22]. The BFKL LL and BFKL nonL predictions with fixed α_s as well as the DGLAP LL calculations generally describe the $|t|$ dependence of the cross section but rather underestimate its magnitude, while the BFKL nonL calculations with running α_s give a steeper $|t|$ dependence and are unable to describe the data across the whole range of $|t|$.

For the W dependence of the cross section the predictions are only available for $|t| > 2$ GeV^2 and, in the case of the BFKL-based model, only for fixed α_s. The DGLAP LL predictions are not able to describe the W dependence while the BFKL LL predictions quantitatively reproduce the rise of the cross section.

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