PROCEEDINGS OF SCIENCE

Vector meson production at ZEUS

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The diffractive production of vector mesons $ep \to eVMY$, with $VM = \rho^0, \omega, \phi, J/\psi, \psi'$ or Υ and with Y being either the scattered proton or a low mass hadronic system, has been extensively investigated with the ZEUS experiment at HERA. HERA offers a unique opportunity to study the dependence of the cross section on different scales: the mass of the vector meson, m_{VM}, the centre-of-mass energy of the γp system, W, the photon virtuality, Q^2 and the four-momentum transfer squared at the proton vertex, $|t|$. Strong interactions can be investigated in the transition from the hard to the soft regime.

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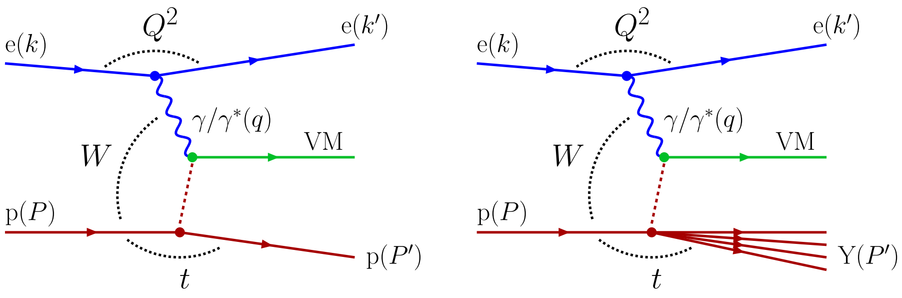

Figure 1: Schematic representation of exclusive vector meson production: elastic (left) and proton dissociative (right).

1. Introduction

The ZEUS experiment at the HERA electron-proton collider have provided extensive studies of vector meson (VM) production [1, 2]. The HERA data cover wide kinematic regions, in which perturbative QCD (pQCD) is expected to be applicable, as well as regions in which there is no hard scale 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 target experiments, and the hard, QCD physics.

The production of vector mesons like the ρ^0, ω, ϕ, J/ψ, ψ' and Υ has been studied in the diffractive process $ep \to eVMY$, as shown in Fig. 1 with Y being either a proton (elastic process) or a proton remnant system (proton-dissociative process). The characteristic variables for such a process are: the mass of the vector meson, m_{VM}, the centre-of-mass energy, W, of the $\gamma^* p$ system, the photon virtuality, Q^2, and the four momentum, $|t|$, transferred at the proton vertex. The dependence of the cross section on these variables has been studied in the following kinematic ranges: 20 GeV $< W <$ 290 GeV and 0 GeV$^2 \leq Q^2 \leq$ 100 GeV^2, where $Q^2 \approx 0$ is usually referred to as photoproduction. The elastic processes are usually studied for $|t| < 1$ GeV^2 while proton dissociative production is measured up to 20 GeV^2.

The diffractive electroproduction of vector mesons at high energies can be modelled in the proton rest frame in which the incoming electron emits a virtual photon which subsequently fluctuates into a $q\bar{q}$ pair. Next, after the interaction with the proton via color singlet exchange the $q\bar{q}$ recombines into a bound vector meson. All these processes are well separated in time and the cross section can be factorized by using the dipole cross section on the proton [3]. If the transverse momentum is small, the quarks form a colour dipole, whose transverse size is large. The interaction with the proton looks then similar to soft hadron-hadron scattering. When the transverse size of the colour dipole is small the interaction with the proton may be calculated perturbatively.

The non-perturbative approach, based on Regge phenomenology [4] 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 the diffractive interaction is mediated by the exchange of the vacuum quantum numbers which corresponds to soft Pomeron exchange. This approach predicts: 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 $b = b_0 + 4\alpha' \ln(W/W_0)$), 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 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 [3]: $\sigma \propto \alpha_s^2(Q^2)/Q^6[xg(x,Q^2)]^2$, with $x \approx Q^2/W^2$ (valid for small x). Thus, in the presence of a hard scale a steeper rise of the cross section with W is predicted, along with a weaker t dependence of the cross section and smaller shrinkage with increasing W, dominant longitudinal γ^* polarization and possible SCHC violation. The slope b is expected to be universal.

The next sections present a review of the ZEUS results of the vector meson production and their dependence on the different scales as well as a comparison with the theoretical expectations.

2. The W dependence

In photoproduction the total cross section as well as those for light vector mesons (ρ, ω, ϕ), $\sigma_{\gamma p \to VM\, p}$, has the form $\sigma \propto W^\delta$ with $\delta = 0.22$ as predicted by Regge phenomenology, while for heavy vector mesons, where the mass provides a large scale, the W dependence is much steeper ($\delta \approx 0.7$ for J/ψ). This is understood, as described above, in terms of the rise of the gluon density at low x. In the case of J/ψ the hard scale is present, already in photoproduction, due to the large mass of the charm quarks.

The gluon density rises more steeply towards low x as Q^2 increases. This means that δ is expected to be Q^2 dependent. Such an effect is observed in the cross section of light vector mesons, ρ, ϕ [8] and for dipions [12], where the production mechanism, $ep \to e\pi^+\pi^- p$, has similar features. The cross sections measured for different Q^2 values rise with increasing W and steepen with Q^2. Even for small values of Q^2 the observed parameter δ is above the value predicted for the soft regime and, especially in ρ case for $Q^2 > 10$ GeV^2, becomes very similar to that for J/ψ. In contrast to the light vector mesons the J/ψ cross section shows the same W dependence for a wide Q^2 range, including photoproduction. The parameter δ, as measured by ZEUS and H1, plotted in Fig. 2(left) as a function of $Q^2 + m_{VM}^2$ shows perfect consistency between all vector mesons. The variable $Q^2 + m_{VM}^2$ used as the hard scale strongly reduces flavour dependence. The diffraction slope b plotted as a function of $Q^2 + m_{VM}^2$ confirms that observation and has an universal value of $4-5$ GeV^{-2} for sufficiently large $Q^2 + m_{VM}^2$, Fig. 2(right).

Determination of the effective QCD Pomeron trajectory is possible via simultaneous measurement of the cross section dependence on W and $|t|$. The results are fitted to the form $d\sigma/dt \sim W^{4(\alpha_{IP}(t)-1)}$ and the resulting values of the intercept and slope of the Pomeron trajectory differ significantly from those of the soft Pomeron i.e. $\alpha' = 0.115 \pm 0.018(stat.)^{+0.008}_{-0.015}(syst.)$ (ZEUS) [5], and $\alpha' = 0.25$ (Regge theory) [6].

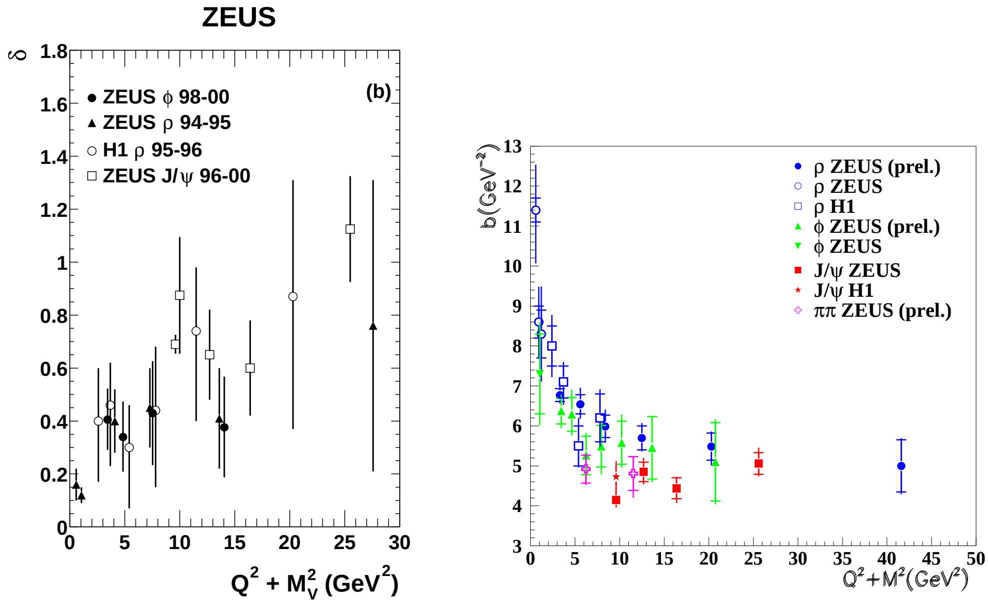

Figure 2: The parameter δ as a function of $Q^2+m^2_{VM}$ for ZEUS and H1 results of different vector mesons production (left). The parameter b as a function of $Q^2+m^2_{VM}$ for ZEUS and H1 results of the production of different vector mesons (right).

3. The Q^2 dependence

The transition between soft and hard regime in Q^2 dependence is very well illustrated by light vector meson data. The cross section can be described with a function of the form $\sigma \propto (Q^2+m^2_{VM})^{-n}$. The extrapolation of this parametrization, in the case of the J/ψ, covers the whole range of Q^2 yielding $n = 2.44 \pm 0.08$ [7]. The light vector mesons data suggest that the parameter n increases with Q^2: in the case of ϕ meson [8] $n = 2.087 \pm 0.055(stat.) \pm 0.050(syst.)$ for 2.4 GeV^2 $\leq Q^2 \leq$ 9.2 GeV^2 and $n = 2.75 \pm 0.13(stat.) \pm 0.07(syst.)$ for 9.2 GeV^2 $\leq Q^2 \leq$ 70 GeV^2 and in the case of ρ meson $n = 2.44 \pm 0.09(stat.)$ for $Q^2 >$ 10 GeV^2. pQCD also predicts much steeper Q^2 dependence for the transverse part of the cross section, σ_T, in comparison with the longitudinal part, σ_L. In Fig. 3 a very good agreement is shown between the ϕ cross section and theoretical predictions.

4. Helicity studies

Studies of the helicity provide sensitive tests of the polarization states of the photon and the vector meson. The production and decay of the vector meson are described in terms of the spin density matrix elements. The element r^{04}_{00} represents the probability to produce the longitudinal vector meson from either the transverse or longitudinal photon. Scaling of this variable with Q^2/m^2_{VM} is observed for different mesons, as shown in Fig. 4(left). For very small Q^2 values r^{04}_{00} is close to zero, since for $Q^2 \to 0$ the longitudinal part of cross section is vanishing. The r^{04}_{00} element is also directly related to the ratio of longitudinal to transverse cross section, $R = \sigma_L/\sigma_T \sim 1/\varepsilon\, r^{04}_{00}/(1-r^{04}_{00})$,

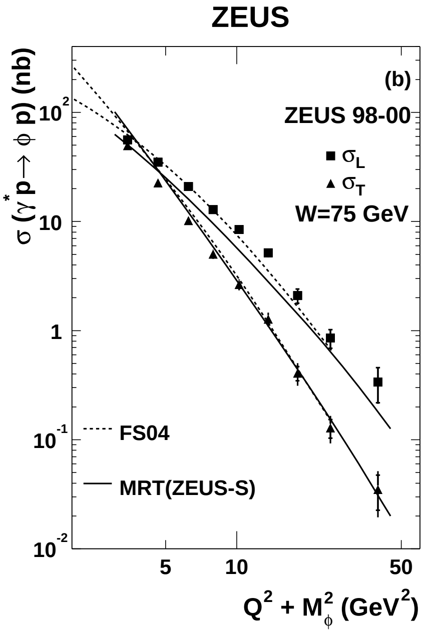

Figure 3: Exclusive ϕ cross section as a function of $Q^2 + m^2_{VM}$ for $W = 75$ GeV [8]. The data are compared to MRT [9] and FS04 [10] predictions. The ZEUS-S [11] gluon density was used in the MRT model.

which is valid under assumption of SCHC. The dominance of the longitudinal photon as well as the vector meson polarization have been observed, along with the rise of R with Q^2. This rise is reproduced by pQCD calculations, as shown in Fig. 4(right).

5. High-$|t|$

In the J/ψ proton dissociative photoproduction, $\gamma p \to J/\psi\, Y$, along with the large mass of the meson, large $|t|$ can be a hard scale. In contrast to elastic data, the differential cross section follows a power law dependence of the form $|t|^{-n}$. A fast rise of the cross section with W is observed. The effective Pomeron trajectory was extracted in the same way as for exclusive processes, yielding $\alpha' = -0.02 \pm 0.014(stat.) \pm 0.010(syst.)$ GeV^{-2} [13]. This value is very similar to that obtained with the H1 data [14]. Data are reproduced by pQCD calculation based on BFKL [15, 16] and DGLAP [17] models, as shown in Fig. 5

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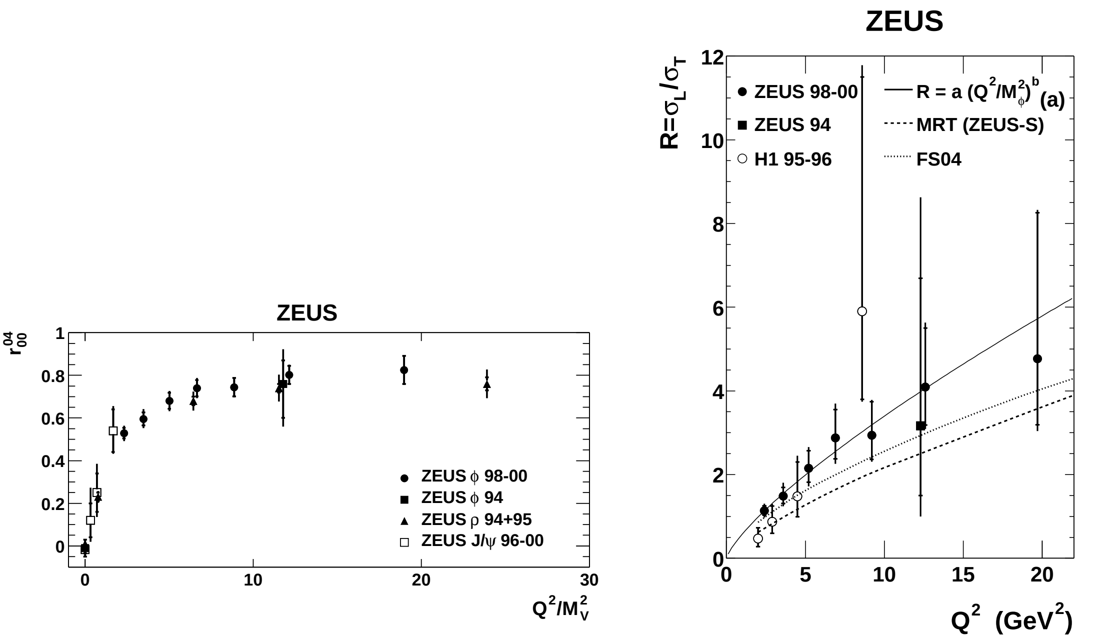

Figure 4: The values of r^{04}_{00} as a function of Q^2/m^2_{VM} are plotted for different vector mesons (left). Ratio $R = \sigma_L/\sigma_T$ as a function of Q^2 for exclusive ϕ production [8]: the full line is the result of the fi t shown in the plot, the dashed lines indicate theoretical calculations [9, 10, 11] (right).

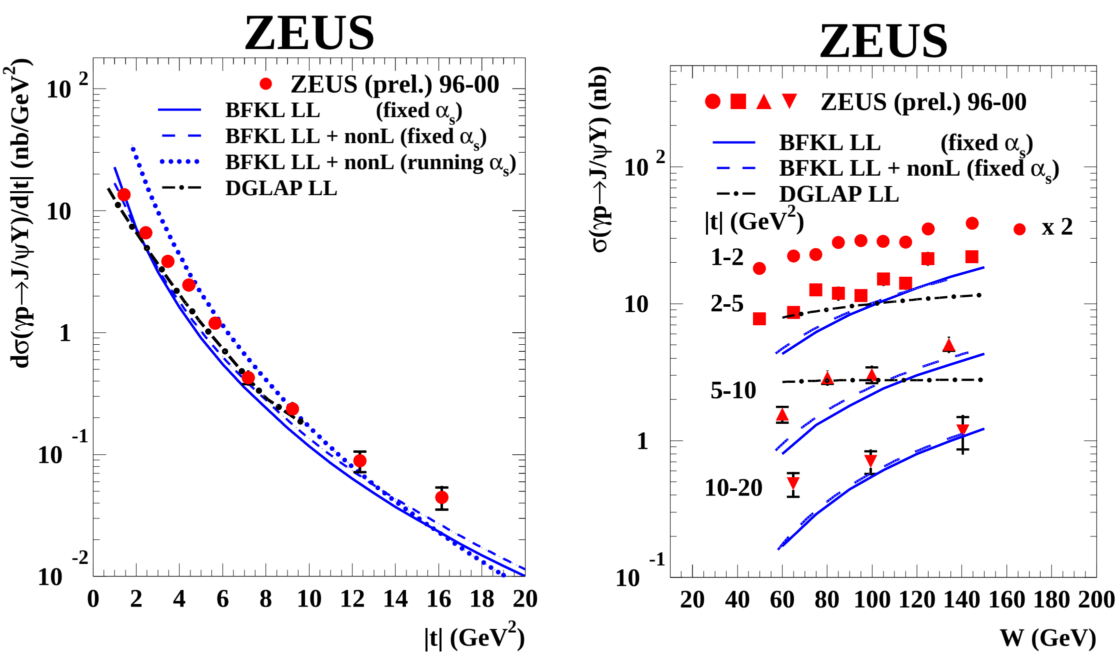

Figure 5: The differential cross section for J/ψ proton-dissociative photoproduction [13] as a function of $|t|$ (left). The cross section as a function of W in four bins of $|t|$. The data are compared to pQCD predictions based on BFKL [15, 16] and DGLAP [17] calculations (right).

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