Vol. 33 (2002) ACTA PHYSICA POLONICA B No 11

ENERGY DEPENDENCE OF EXCLUSIVE VECTOR–MESON PRODUCTION IN *ep* INTERACTIONS AT HERA*

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(Received June 21, 2002)

The energy dependence of exclusive vector–meson (V) production is studied using the ZEUS data. The SU(4) universality of V cross sections in the $Q^2 + M_V^2$ scale is tested. The energy dependence of the ratio of the cross sections for V production to the total $\gamma^* p$ cross section is compared with expectations based on pQCD and Regge approaches.

PACS numbers: 13.60.Le, 12.38.Bx

1. Introduction

The energy dependence of the cross section for a given reaction is sensitive to the dominant production mechanism leading to this particular process. In this talk, the energy dependence of the cross section for exclusive electroproduction of vector–mesons (V) in ep interactions at HERA is discussed. First, we present an update of an earlier study [1] of the universality of V cross sections, scaled by the SU(4) factors, when plotted as a function of $Q^2 + M_V^2$ [2], where Q^2 is the virtuality of the photon in the reaction $\gamma^* p \to V p$, and M_V is the mass of V. The main new ingredient consists of the precise measurements of the J/ψ cross section [3, 4]. Secondly, we investigate the ratios of the V production cross sections, σ_V, to the total $\gamma^\star p$ cross section, $\sigma_{\rm tot}(\gamma^* p)$, as obtained from the measurements of the F_2

* Presented at the X International Workshop on Deep Inelastic Scattering (DIS2002) Cracow, Poland, 30 April–4 May, 2002.

† Supported in part by the Israel Science Foundation(ISF), by the German Israel Foundation (GIF) and by the Israel Ministry of Science.

structure function of the proton. The ratios are compared to expectations based on perturbative QCD (pQCD) and Regge approaches.

In order to minimize normalization uncertainties, we use for this study only data from the ZEUS Collaboration [3–6].

2. Universality of the $Q^2 + M_V^2$ scale

It was shown [1] that if vector–meson cross sections are weighted by the appropriate SU(4) factor and plotted as function of W for fixed values of the variable $Q^2 + M_V^2$, all light V's (ρ^0, ω, ϕ) lie on a universal curve. However, this was not the case for the J/ψ. Since then, the preliminary ZEUS J/ψ photoproduction cross sections have been published [3] and new preliminary data on exclusive electroproduction of J/ψ, covering a wider W range, became available [4].

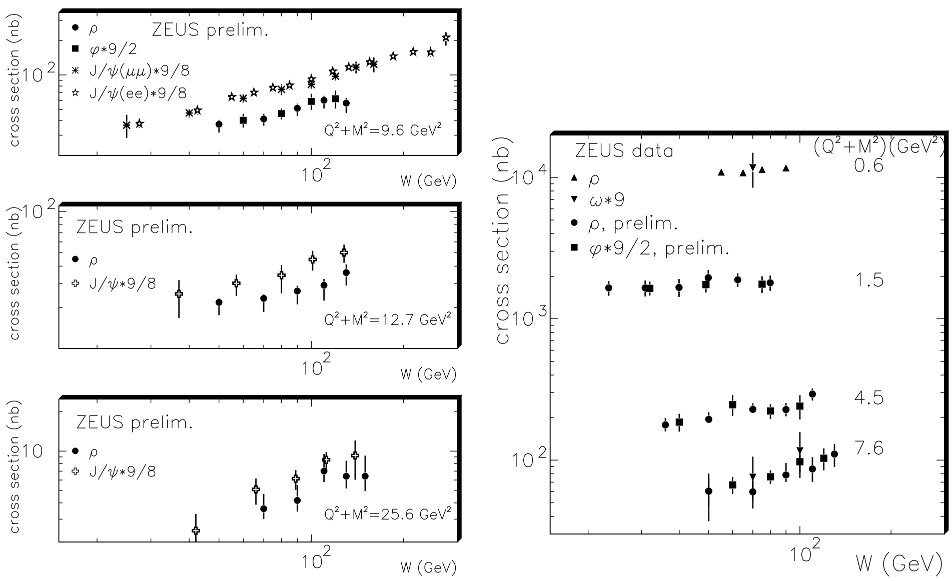

Fig. 1. Comparison of vector–meson cross section values, weighted by the SU(4) factors, plotted as a function of W at fixed $Q^2 + M_V^2$, as indicated in the figure.

Fig. 1 shows the updated cross sections weighted by the appropriate SU(4) factors, as function of W. For $Q^2 + M_V^2 = 9.6$ GeV^2, the J/ψ cross sections are about 40% higher than that of the light V's. Also at higher scales, where errors are larger, the J/ψ cross section values lie systematically above those for the ρ^0. Thus, the updated data confirm the earlier conclusion that there is no simple universality for V production if $Q^2 + M_V^2$ is used as a scale.

3. The ratio $\sigma_V/\sigma_{\rm tot}$

The total $\gamma^* p$ cross section, $\sigma_{\rm tot}(\gamma^* p)$, exhibits a rise with W, which becomes steeper with increasing Q^2. It is of interest to compare the W dependence of exclusive V production to that of the inclusive cross section. To this end we study the ratio

$$r_V \equiv \frac{\sigma(\gamma^* p \to Vp)}{\sigma_{\rm tot}(\gamma^* p)}\,, \tag{1}$$

for each of the V's, as a function of W for fixed Q^2. Before presenting the data we discuss the expectations for r_V using pQCD and Regge arguments.

3.1. Expectations for r_V in pQCD

In pQCD, the forward cross section for longitudinally polarized photons is expected [7] to behave as

$$\left.\frac{d\sigma_{\rm L}}{dt}\right|_{t=0} \propto \frac{1}{Q^6}\,\alpha_{\rm S}^2\left(Q^2\right)\left[xg(x,Q^2)\right]^2, \tag{2}$$

where x is the Bjorken scaling variable and $xg(x,Q^2)$ is the gluon density in the proton.

Assuming an exponential t behavior of the form $d\sigma_V/dt \sim e^{bt}$, one gets the following expectation

$$r_V \propto \left(1+\frac{1}{R}\right)\frac{W^{2\lambda}}{b} \approx \frac{W^{2\lambda}}{b}\,. \tag{3}$$

In expression (3) we have used the fact that both the gluon density distribution and the proton structure function have a similar $x^{-\lambda(Q)}$ dependence and that the ratio R of the V production cross section induced by longitudinal and transverse virtual photons, $R=\sigma_{\rm L}/\sigma_{\rm T}$, increases with Q^2 but is W independent [6] and thus can be neglected.

Using Regge phenomenology arguments [8], one expects $\sigma_V \sim W^{4(\alpha_{\mathbb{P}}(0)-1)}/b$ and $\sigma_{\rm tot} \sim W^{2(\alpha_{\mathbb{P}}(0)-1)}$, where $\alpha_{\mathbb{P}}(0)$ is the intercept of the Pomeron trajectory, and

$$r_V \propto \frac{W^{2(\alpha_{\mathbb{P}}(0)-1)}}{b}\,, \tag{4}$$

which is the same as (3), if we write $\lambda = 2(\alpha_{\mathbb{P}}(0)-1)$.

Both in pQCD and Regge approaches the ratio r_V rises with W. The W dependence is not strongly affected by b since both for the exclusive electroproduction of ρ^0 and the photoproduction of J/ψ shrinkage was found to be small [3, 6].

When calculating r_V one has to ensure that both cross sections are taken at the same hard scale. Since for σ_V the scale is usually chosen as $(Q^2+M_V^2)/4$, $\sigma_{\rm tot}$ is calculated at that scale.

The W dependence of r_V is shown in Fig. 2 for the electroproduction of ρ^0 and J/ψ, for fixed values of the scale, as indicated in the figure. While for the J/ψ case the ratio $r_{J/\psi}$ seems to show the expected rise with W, the ratio r_ρ is independent of W, reminiscent of the behavior found in inclusive diffraction at large Q^2 [9]. The behavior of r_ρ cannot be explained by either pQCD nor by the Regge calculations.

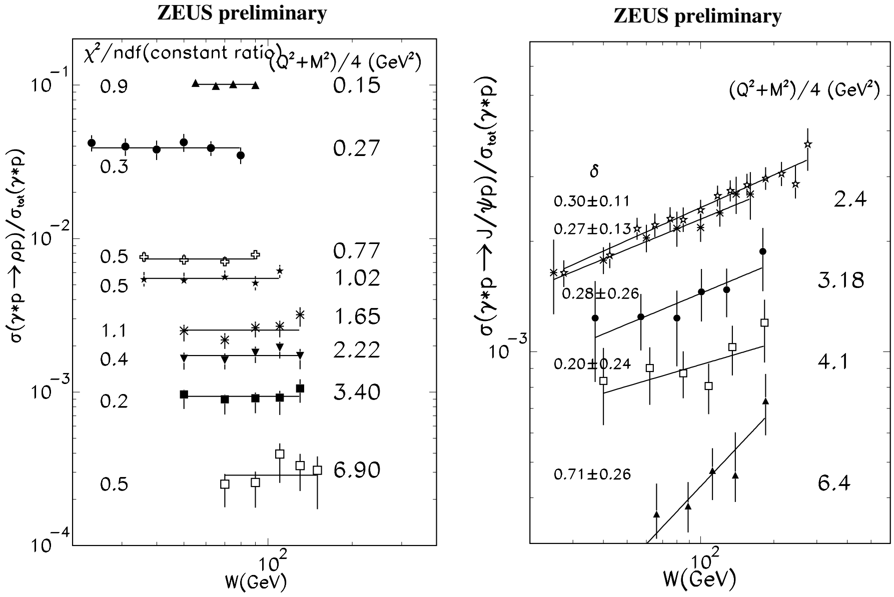

Fig. 2. The ratio $\sigma_V/\sigma_{\rm tot}$ as function of W for $V=\rho^0$ (left-hand side) and for $V=J/\psi$ (right-hand side), at fixed values of scales, as indicated in the figure.

4. The ratio $\sigma^2_{\rm tot}/\sigma_V$

Following the discussion in Section 3, it is of interest to study the ratio $\sigma^2_{\rm tot}/\sigma_V$, as it contains information about the Q^2 behavior in the pQCD approach as well as about the slope b, in both approaches.

In order to calculate the pQCD expectations for $\sigma^2_{\rm tot}/\sigma_V$, we include also the terms having a Q^2 dependence and obtain

$$\frac{\sigma^2_{\rm tot}}{\sigma_V}\propto\frac{Q^2}{\alpha_{\rm S}^2(Q^2)\left(1+\frac{1}{R}\right)}\,b\approx\frac{Q^2}{\alpha_{\rm S}^2(Q^2)}\,b\,. \tag{5}$$

This comes about since $\sigma_{\rm tot} \sim 1/Q^2$ and $\sigma_V \sim 1/Q^6$. The contribution of $1/R$ is negligible. Thus, if one neglects the Q^2 variation of $\alpha_{\rm S}$ in the Q^2 range discussed in this paper

$$\frac{\sigma^2_{\rm tot}}{Q^2\sigma_V} \propto b \tag{6}$$

and, apart from some numerical W-independent factor, one obtains the slope b.

Fig. 3 shows the ratio (6) for the ρ^0 and for the J/ψ mesons. While in the case of ρ^0 one sees a slight Q^2 dependence of the ratio, the ratio is Q^2 independent for the J/ψ. This result is in agreement with what is known from direct measurements of the Q^2 dependence of b for both V's [4, 10].

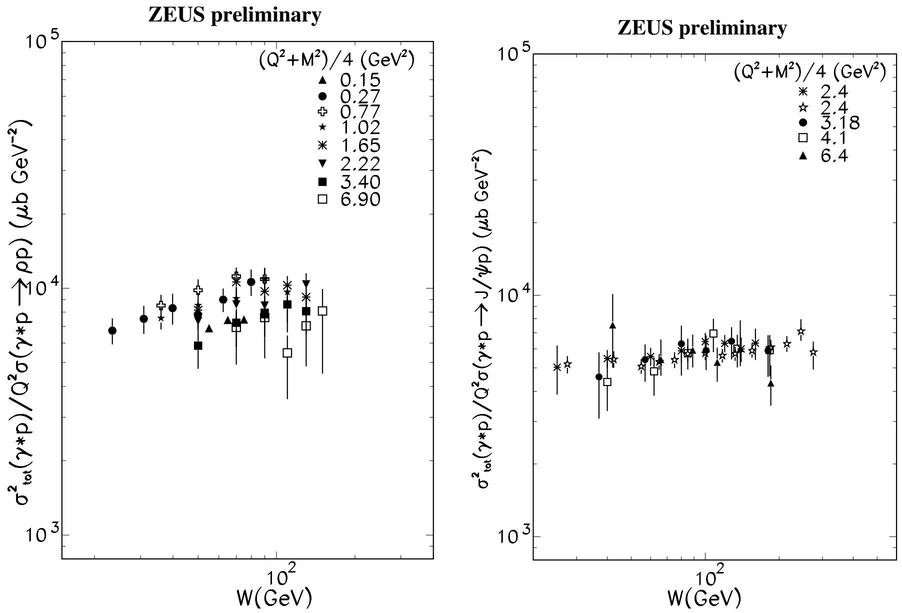

Fig. 3. The ratio $\sigma^2_{\rm tot}/(Q^2\sigma_V)$ as function of W for $V = \rho^0$ (left hand side) and for $V = J/\psi$ (right hand side), at fixed values of scales, as indicated in the figure.

Reversing the argument, especially in the J/ψ case, where the lack of Q^2 dependence of b is known, Fig. 3 reflects the behavior of the propagator term, $1/Q^6$, in σ_V, as expected in pQCD or pQCD-inspired models.

One can use the optical theorem, together with the Vector Dominance Model (VDM) [11], to obtain the following relation

$$\sigma^2_{\rm tot} = \frac{4\pi\alpha_{em}\sigma_\rho\, b}{\frac{4\pi}{\gamma^2_{\gamma\rho}}}\,, \tag{7}$$

where $4\pi/\gamma^2_{\gamma\rho}$ is the strength of the direct γ–ρ^0 coupling. This relation assumes ρ-dominance, which is a good assumption as the ρ^0 contributes $\approx 85\%$ to the VDM relation. If b is measured in units of GeV^{-2}, and a value of 0.5 [12] is used for the γ–ρ^0 coupling, one obtains from Eq. (7)

$$0.014\frac{\sigma^2_{\rm tot}}{\sigma_\rho} = b\,. \tag{8}$$

Fig. 4 shows the left hand side of Eq. (8), as function of W, for fixed values of the scale. For the ρ^0 photoproduction data, after correcting for the assumed ρ-dominance, one gets good agreement with the value measured [5].

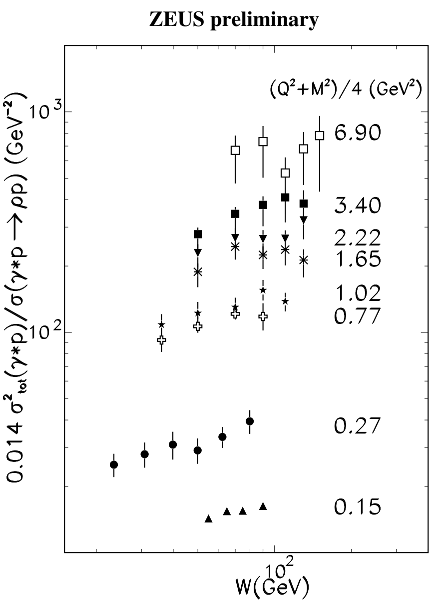

Fig. 4. The ratio $0.014\sigma^2_{\rm tot}/\sigma_\rho$ as function of W at fixed values of scales, as indicated in the figure.

While the W dependence is consistent with the slight shrinkage measured [6], the resulting values at higher scales come out much too high and increase with the scale, contrary to direct measurements [10]. This is not surprising since in Eq. (8) we have used the value of the direct γ–ρ^0 coupling at $Q^2{=}0$. In fact, the direct coupling is Q^2 dependent, and can be expressed as

$$\frac{4\pi}{\gamma^2_{\gamma\rho}(Q^2)} = \frac{4\pi}{\gamma^2_{\gamma\rho}(0)} f_{\gamma\rho}(Q^2)\,, \tag{9}$$

where $f_{\gamma\rho}(Q^2)$ is the γ–ρ^0 form-factor. One can use the measured values of b [10] to calculate the form-factor using Eq. (7),

$$\frac{4\pi}{\gamma^2_{\gamma\rho}(Q^2)} = \frac{4\pi\alpha_{em}\sigma_\rho}{\sigma^2_{\rm tot}}\; b(Q^2)\,. \tag{10}$$

Fig. 5 shows the resulting values of the γ–ρ^0 form-factor, as function of Q^2. A function of the form $\sim (1+Q^2/m^2)^{-n}$ was fitted to the data, resulting in the parameters $m^2 = 0.18 \pm 0.06\,\mathrm{GeV}^2$, and $n = 0.94 \pm 0.10$. To restore a good agreement with measurements, a $1/Q^2$ dependence has to be introduced through the form-factor.

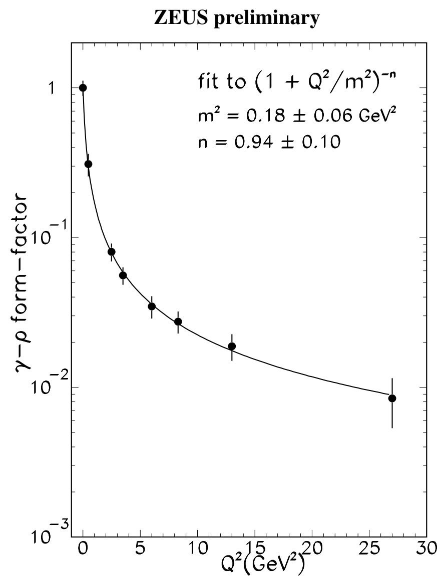

Fig. 5. The γ–ρ^0 form-factor as function of Q^2. The curve is a fit of the form $(1+Q^2/m^2)^{-n}$ to the data.

5. Summary

We can summarize the results of this study as follows:

- The SU(4)-weighted cross sections of the light vector–mesons lie on a universal curve when plotted at a scale of $Q^2 + M_V^2$. This is not the case for the J/ψ meson.
- The ratio of the cross section of exclusive ρ^0 electroproduction to that of the total $\gamma^* p$ one is W independent, for fixed values of Q^2. This behavior cannot be explained by either the pQCD nor by the Regge phenomenology approaches. The ratio rises with W for the J/ψ vector–meson, consistent with the expectations.

- The ratio $\sigma_{\rm tot}^2/\sigma_V$ shows the $1/Q^6$ dependence predicted by pQCD for the V's cross section. This ratio also provides an indirect way to learn about the W and Q^2 behavior of the slope b.
- In order to make the VDM approach agree with the data, one would need to introduce a γ–ρ^0 form factor which has a $1/Q^2$ dependence.

I would like to thank Andrzej Eskreys, Danuta Kisielewska and the whole local organizing committee for creating a wonderful atmosphere in hosting this workshop.

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