Electroproduction of Vector Mesons

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The energy dependence of the cross section for exclusive electroproduction of vector mesons is discussed as a way to learn about the interplay of soft and hard interactions. The question of determining the scale of these processes is addressed.

1 Introduction

Exclusive electroproduction of vector mesons (VMs) is a particularly good process for studying the transition from the soft to the hard regime of strong interactions [1], the former being well described within the Regge phenomenology while the latter - by perturbative QCD (pQCD). The interest in this interplay comes from the need to understand at which scale a partonic language is applicable. The exclusive electroproduction of VMs can then be used to extract information about the generalized parton distributions (GPDs) [2], an essential addition to understanding the partonic wave-function of the proton.

Among the most striking expectations [1] in this transition is the change of the logarithmic derivative δ of the cross section σ with respect to the $\gamma^* p$ center-of-mass energy W, from a value of about 0.2 in the soft regime to 0.8 in the hard one, and the decrease of the exponential slope b of the differential cross section with respect to the squared-four-momentum transfer t, from a value of about 10 GeV^{-2} to an asymptotic value of about 5 GeV^{-2} when the virtuality Q^2 of the photon increases.

2 Exclusive vector meson photoproduction

The soft to hard transition can be seen by studying the W dependence of the cross section for exclusive vector meson photoproduction, from the lightest one, ρ^0, to the heavier ones, up to the Υ. The scale in this case is set by the mass of the vector meson, as in photoproduction $Q^2 = 0$. Figure 1 shows $\sigma(\gamma p \to V p)$ as function of W for light and heavy vector mesons. For comparison, the total photoproduction cross section, $\sigma_{tot}(\gamma p)$, is also shown. The data at high W can be parameterised as W^δ, and the value of δ is displayed in the figure for each reaction. One sees clearly the transition from a shallow W dependence for low scales to a steeper one as the scale increases.

3 Exclusive vector meson electroproduction

One can also check this transition by varying Q^2 for a given vector meson. The cross section $\sigma(\gamma^* p \to \rho^0 p)$ is presented in Fig. 2 [3] as a function of W, for different values of Q^2. The cross section rises with W in all Q^2 bins. In order to quantify this rise, the logarithmic derivative δ of σ with respect to W is obtained by fitting the data to the expression $\sigma \sim W^\delta$ in each of the Q^2 intervals. The resulting values of δ from the recent ZEUS measurement are compiled in Fig 3. Also included in this figure are values of δ from

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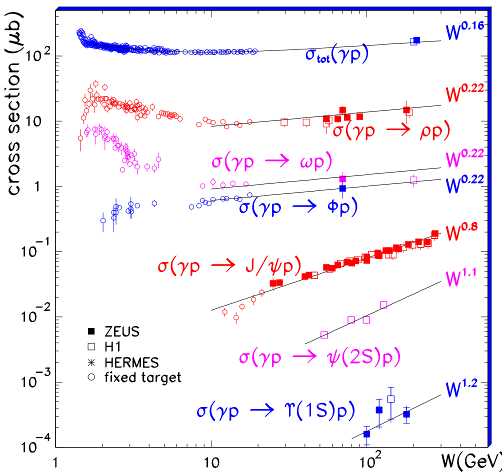

Figure 1: Total and exclusive vector meson photoproduction data, as a function of W. The curves are fits of the form $\sim W^{\delta}$.

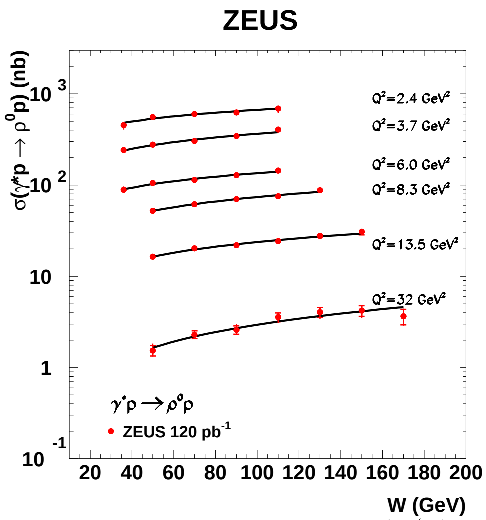

Figure 2: *The W dependence of $\sigma(\gamma^* p \to \rho^0 p)$ for different Q^2 values, as indicated in the figure. The lines are the result of a fit of the form W^{δ} to the data.*

other measurements [4] for the ρ^0 as well as those for ϕ [5, 6], J/ψ [7, 8] and γ [9, 10] (Deeply Virtual Compton Scattering (DVCS)). In this case the results are plotted as a function of $Q^2 + M^2$, where M is the mass of the vector meson. One sees an approximate universal behaviour, showing an increase of δ as the scale becomes larger, in agreement with the expectations mentioned in the introduction. The value of δ at low scale is the one expected from the soft Pomeron intercept [11], while the one at large scale is in accordance with twice the logarithmic derivative of the gluon density with respect to W. The differential cross section, $\mathrm{d}\sigma/\mathrm{d}t$, has been parameterised by an exponential function $e^{-b|t|}$ and fitted to the data of exclusive vector meson electroproduction and also to DVCS. The resulting values of b as a function of the scale $Q^2 + M^2$ are plotted in Fig. 4. As expected, b decreases to a universal value of about 5 GeV^{-2} as the scale increases.

4 The effective scale of vector mesons

Figures 3 and 4 might give the impression that the variable $Q^2 + M^2$ can serve as an effective scale for vector mesons. In the following we will show that this is not the case and that further study is needed to determine this scale.

One way to study this question is to look at the W dependence of the cross section ratio r_V of exclusive vector meson electroproduction to that of the total $\gamma^* p$ one, $r_V \equiv \sigma(\gamma^* p \to Vp)/\sigma_{tot}(\gamma^* p)$. It was shown [12] that using pQCD arguments this ratio should have, at fixed Q^2, a W dependence of the form $r_V \propto W^{2\lambda}/b$, where λ is the parameter describing the increase of the proton structure function F_2 with decreasing x, $F_2 \propto x^{-\lambda}$. Using Regge arguments, one obtains that $r_V \propto W^{2(\alpha_{I\!P}(0)-1)}/b$, where $\alpha_{I\!P}(0)$ is the intercept of the Pomeron trajectory. Since $\lambda = \alpha_{I\!P}(0) - 1$, both approaches predict the same r_V behaviour. The variable b is the exponential slope of the differential cross section. Both in

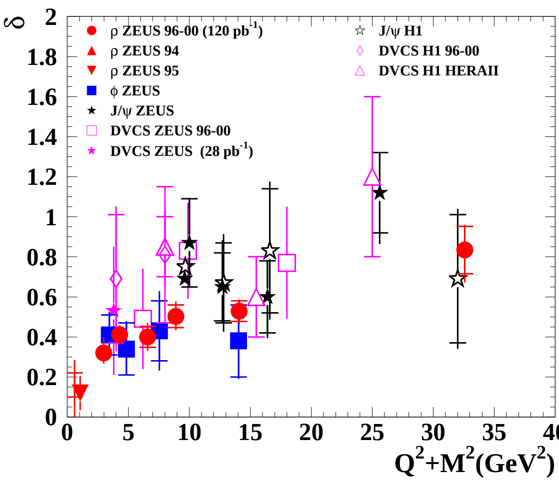

Figure 3: *A compilation of the value of δ from a fit of the form W^{δ} for exclusive vector-meson electroproduction, as a function of $Q^2 + M^2$. It includes also the DVCS results.*

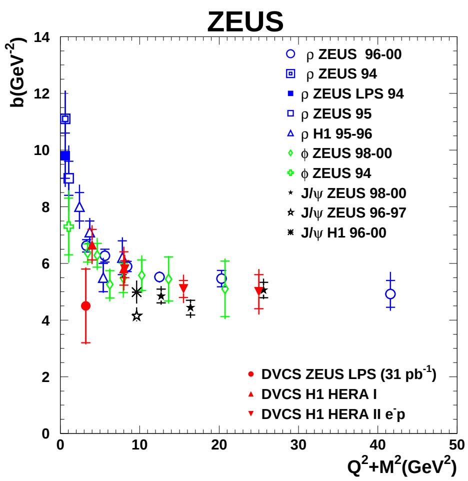

Figure 4: A compilation of the value of the slope b from a fit of the form $d\sigma/d|t| \propto e^{-b|t|}$ for exclusive vector-meson electroproduction, as a function of $Q^2 + M^2$. Also included is the DVCS result.

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 J/ψ shrinkage was found to be small [3, 7].

When calculating the ratio r_V one has to ensure that both cross sections are taken at the same hard scale, which we denote as Q^2_{eff}. Clearly, for the total inclusive cross section, the effective scale is Q^2. In Fig. 5 one can see the Q^2 dependence of λ resulting from fitting the F_2 data in the low-x region ($x < 0.01$) to the form $F_2 \sim x^{-\lambda}$. For photoproduction and the low Q^2 region, the value of λ is in good agreement with that expected from the Pomeron intercept ($\lambda = \alpha_{I\!P}(0) - 1$). Starting at about $Q^2 >$1 GeV^2, the value of λ rises logarithmically with Q^2. It is of interest to see if r_V shows the expected $W^{2\lambda}$ behaviour.

It is not clear what is the effective scale for exclusive vector meson electroproduction. One suggested scale, originally for the J/ψ [13], is $Q^2_{eff} = (Q^2 + M^2)/4$. Frankfurt, Koepf and Strikman [14] calculated the effective scale for ρ, J/ψ and Υ, and find that their effective scale for the J/ψ and for the Υ are significantly larger than that suggested by [13]. One can parameterise [15] their effective scale for the ρ^0 as $Q^2_{eff} = \left(\frac{Q^2}{2.65}\right)^{0.887}$.

As the most precise data at present are those of the exclusive electroproduction of ρ^0 [3], we will use these data to investigate the question of the effective scale. The ratio $\sigma(\gamma^* p \to \rho^0 p)/\sigma_{tot}(\gamma^* p)$ as a function of W, for different fixed effective scales, seems to be constant with W and shows a possible W dependence only at the highest scale. We have shown earlier that this ratio is expected to grow with W like $W^{2\lambda}$ in both the pQCD and the Regge approaches. This would thus indicate that the λ values obtained from this ratio are inconsistent with those obtained in the inclusive total deep inelastic cross section case.

We can in fact compare directly the values of δ obtained from the W dependence of the

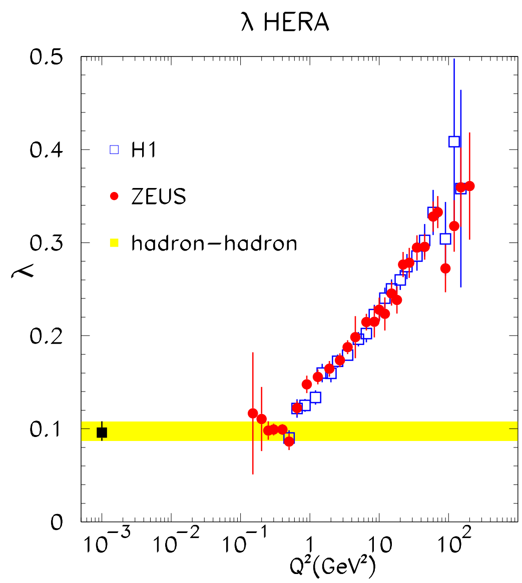

Figure 5: The values of λ, obtained by fitting the proton structure function F_2 to the form $\sim x^{-\lambda}$, as a function of Q^2. The shaded band shows $\alpha_{I\!P}(0)$-1 as obtained from hadron-hadron total cross section data.

ρ^0 cross section, shown in Fig. 3, to the λ values shown in Fig. 5, keeping in mind that $\delta = 4\lambda$. This is shown in Fig. 6, for the effective scale $(Q^2 + M^2)/4$. The λ values obtained from the W dependence of the ρ^0 are lower than those of the inclusive one for all but the highest effective scale of the ρ^0. This is true also for $Q^2_{eff} = Q^2 + M^2$ as well as for the effective scale suggested in [14].

One way to find experimentally the right effective scale is to force the λ from the ρ^0 to agree with that of the inclusive data. This is shown in Fig. 7. The resulting values of Q^2_{eff} are much smaller than $(Q^2 + M_\rho)/4$ for low Q^2 values and can be described by the following ad hoc parameterisation $Q^2_{eff} = 0.23e^{0.1Q^2}$. The fact that the Q^2_{eff} in the exclusive ρ^0 electroproduction is much smaller than Q^2 of the photon might be due to the presence of the convolution of the soft ρ^0 wave-function and the small size longitudinal photon wave-function. This is a clear sign of the interplay of soft and hard physics [1].

Unfortunately, the precision of the data on exclusive electroproduction of J/ψ does not allow a similar study.

In principle, the question of the effective scale should not be an issue at all. If we were able to perform calculations in pQCD to all orders, we would know exactly what is the right scale. However, as long as we do not yet have a full calculation, precision measurements of exclusive electroproduction of vector mesons would be helpful to resolve this problem.

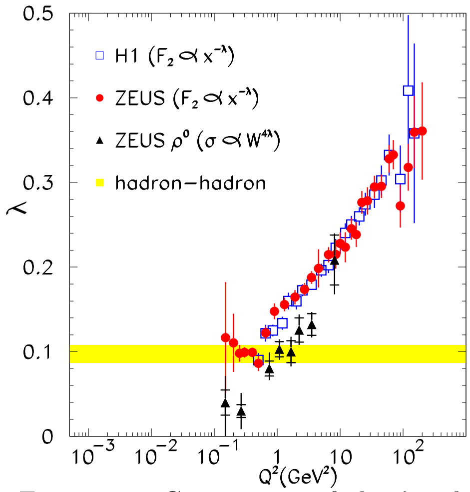

Figure 6: Comparison of the λ values obtained from the exclusive electroproduction of ρ^0 with those from the total inclusive cross section, as a function of Q^2 for an effective scale of the ρ^0 of $Q^2_{eff} = (Q^2 + M^2)/4$.

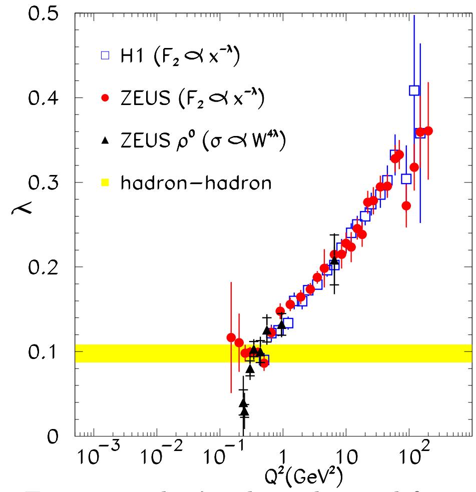

Figure 7: The λ values obtained from the exclusive electroproduction of ρ^0 together with those from the total inclusive cross section, as a function of Q^2. The effective scale of ρ^0 was chosen so that the two λ agree.

5 Summary

The HERA data are a good source to observe the interplay of soft and hard dynamics, through the study of energy dependences of different processes.

The process of exclusive electroproduction of vector mesons at high scales is a good source to study perturbative QCD. It is important to understand the issue of the effective scale. This is an essential step in relating the production of exclusive VMs with the GPDs, the ultimate source of knowledge about the 3-dimensional partonic structure of the proton. For the ρ^0, the effective scale is much smaller than the Q^2 of the photon. Better precision measurements are needed for the ϕ, J/ψ and DVCS to get a determination of the effective scale in these processes.

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