Vector Mesons at HERA

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Abstract. The rich experimental landscape of exclusive vector meson production at the high energy electron–proton collider HERA is reviewed, with emphasis on the transition from soft to hard diffraction and perturbative QCD interpretations.

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INTRODUCTION

Exclusive vector meson (VM) production at HERA, $e\ p \rightarrow e\ VM\ Y$, is illustrated in Fig. 1(left): the intermediate photon converts into a diffractively scattered $q\bar{q}$ pair forming a VM, while the proton remains intact or is diffractively excited into the system Y. Here Q^2 is the negative square of the photon four-momentum, W the photon-proton center of mass energy ($W \simeq Q^2/x$, x being the Bjorken scaling variable) and t the square of the four-momentum transfer at the proton vertex. The closely related process consisting in the Deeply Virtual Compton Scattering (DVCS), see Fig. 1(middle and right), will also be considered in the following.

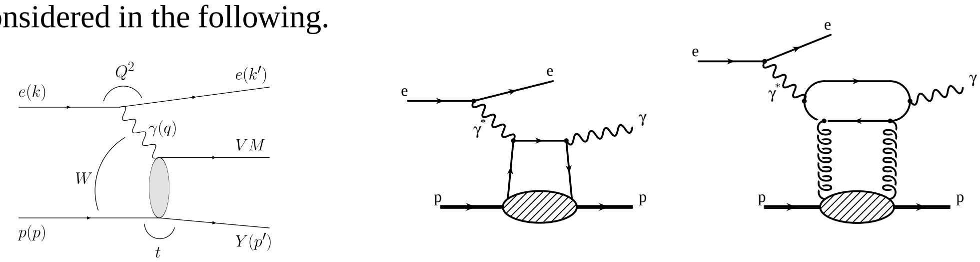

FIGURE 1. (left) Diffractive vector meson electroproduction; (middle and right) DVCS process (LO and NLO diagrams).

The bulk of diffractive processes is governed by soft physics, which is described by Regge theory, whereas the presence of a hard scale allows the use of perturbative calculations and the QCD understanding of diffraction. The scale can be provided by the photon virtuality Q, the quark mass or the momentum transfer $\sqrt{|t|}$.

At large energy, VM production can be described in the proton rest frame as the factorisation of three processes: the fluctuation of the virtual photon into a $q\bar{q}$ colour

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dipole [1, 2], the (flavour independent) elastic (or proton dissociative) dipole-proton scattering, and the $q\bar{q}$ recombination into the final state VM. The dipole-proton scattering is governed by the transverse size of the dipole, the characteristic scale of the interaction for longitudinal amplitudes of light VM and for heavy VM being $(Q^2+M_V^2)/4$. Cross sections are thus expected to scale with this variable [3, 4] (for light VM transverse amplitudes, the scale is reduced by photon wave function effects).

The dipole-proton scattering is modelled in perturbative QCD (pQCD) as the exchange of a colour singlet two-gluon system (leading order) or a BFKL ladder (LL $1/x$ approximation). Cross sections are thus given by the square of the gluon density in the proton, which is rapidly increasing at small x [5, 6]. The ensuing strong increase with W of VM production is a characteristic feature of hard diffraction. Beyond the LL $1/x$ approximation, k_t-unintegrated gluon distributions obtained from the Q^2 logarithmic derivative of the usual gluon distribution are used [3, 4, 7, 8]. Kinematics implies that, for large VM masses or large Q^2 values, the longitudinal momenta carried by the two gluons are different [9].

In a complementary approach, a collinear factorisation theorem [16] has been proven in QCD for VM longitudinal amplitudes in the deep inelastic (DIS) domain, for all values of x. This approach relies on generalised parton distributions (GPD), which take into account parton longitudinal correlations and the t dependence (see e.g. the calculations of [17]).

The studies at HERA cover the elastic and proton dissociative production of real photons (DVCS process) [18, 19] and of ρ [20, 21, 22, 23, 24], ω [25], ϕ [21, 26, 24, 27], J/ψ[28, 29, 30], $\psi(2s)$ [31] and Υ [32, 33] mesons, in a large phase space domain: $0 < Q^2 < 90$ GeV^2, $30 < W < 300$ GeV, $0 < |t| < 30$ GeV^2. The photoproduction ($Q^2 \simeq 0$) of light VM at small $|t|$ is governed by soft physics, whereas heavy VM production is hard and pQCD calculable. The transition from soft to hard diffraction is studied with light VM electroproduction ($Q^2 >$ a few GeV^2). Large $|t|$ studies, that give specific access to hard BFKL-type processes, will not be discussed here. Cross sections, expressed in terms of $\gamma^* p$ scattering, are measured as a function of Q^2, W and t, and angular distributions give access to spin density matrix elements and helicity amplitudes.

FROM SOFT TO HARD DIFFRACTION:

The mass scale

Total cross sections for VM photoproduction as a function of the proton-photon center of mass energy W are parameterized, in a Regge inspired form, as $\sigma(\gamma^* p) \propto W^{\delta}$ with $\delta = 4\ (\alpha_{I\!P}(\langle t \rangle) - 1)$ and $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha^{'}_{I\!P} \cdot t$. The soft Pomeron trajectory measured in hadron-hadron interactions with intercept $\alpha_{I\!P}(0) \simeq 1.1$ and slope $\alpha^{'}_{I\!P} \simeq 0.25$ GeV^{-2} describes well the weak energy dependence of the total photoproduction cross section and of light vector meson production. The energy dependence of heavy vector mesons is strikingly different, with much larger values of δ and $\alpha_{I\!P}(0)$. This hard behaviour confirms QCD expectations, the hard scale being provided by the heavy quark mass.

Dependences in t and interaction size

The t dependences of DVCS and VM production provide informations on the transverse size and the dynamics of the processes, and on the scales relevant for the dominance of perturbative, hard effects.

For $|t| \lesssim 1-2$ GeV^2, the $|t|$ distributions are exponentially falling with slopes b: $\mathrm{d}\sigma/\mathrm{d}t \propto e^{-b|t|}$. In an optical model approach, the diffractive b slope is given by the convolution of the transverse sizes of the interacting objects: $b = b_{q\bar{q}} + b_Y + b_{I\!P}$, with contributions of the $q\bar{q}$ dipole, of the diffractively scattered system (the proton or the excited system Y) and of the exchange (“Pomeron") system. Neglecting effects related to differences in the WF, universal b slopes are thus expected for all VM with the same $q\bar{q}$ dipole sizes, i.e. with the same values of the scale $\mu^2 = (Q^2 + M_V^2)/4$. Conversely, elastic and proton dissociative slopes are expected to differ for all VM production at the same scale by the same amount, $b_p - b_Y$. Measurements of elastic and proton dissociative b slopes for DVCS and VM production are presented in Fig. 2 as a function of the scale μ^2. In the DVCS case, the virtual photon couples directly to a quark (at LO) leading to the use of the scale $\mu^2 = Q^2$.

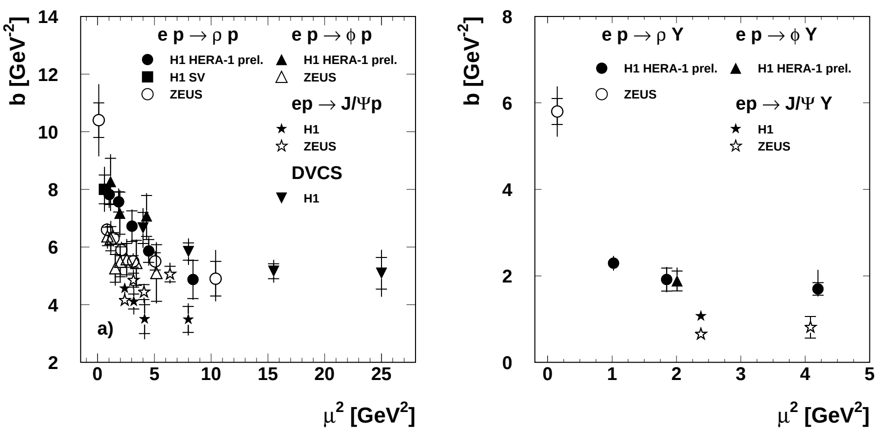

FIGURE 2. Measurement of (left) the elastic and (right) the proton dissociative slopes b of the exponential t distributions, as a function of the scale $\mu^2 = (Q^2 + M_V^2)/4$ for VM production and $\mu^2 = Q^2$ for DVCS.

For J/ψ production, the elastic b slope is $\lesssim 4.5$ GeV^{-2}, with no visible Q^2 dependence. This value may be directly related to the proton form factor, giving a radius of the order of 0.6 fm, following the relation $\langle r^2 \rangle \simeq 2 \cdot b(\hbar c)^2$ [11]. If the proton charge radius of about 0.8 fm essentially arises from the valence quark spatial distribution, this suggests that the gluons in the proton may be distributed more centrally than the quarks. For proton dissociative J/ψ production, the b slope is below 1 GeV^{-2}, putting an upper

[2] Differences between the H1 and ZEUS measurements for elastic scattering are due to differences in background subtraction. The major effect is due to the subtraction of ρ' production by H1, a contribution evaluated to be negligible by ZEUS. Another difference concerns the values used for the b slopes of the proton dissociative contamination.

limit to the transverse size of the exchange (with the assumption that $b_Y \simeq 0$ for proton dissociation).

At variance with J/ψ production, which is understood as a hard process already in photoproduction, a strong decrease of b slopes for increasing values of $\mu^2 = (Q^2+M_V^2)/4$ is observed for light VM production, both in elastic and proton dissociative scattering. A similar scale dependence is observed for DVCS. This is consistent with a shrinkage of the size of the initial state object with increasing Q^2, i.e. in the VM case a shrinkage of the colour dipole. It should however be noted that, both in elastic and proton dissociative scatterings, b slopes for light VM remain larger than for J/ψ when compared at the same values of the scale $(Q^2+M_V^2)/4$ up to $\gtrsim 5$ GeV^2. This indicates either that WF effects should be considered, either that the purely perturbative domain may require larger scale values.

Dependences in Q^2

The intercept $\alpha_{I\!P}(0)$ of the effective trajectory quantifies the energy dependence of the reaction for $t = 0$. The evolution of $\alpha_{I\!P}(0)$ with μ^2 is shown in Fig. 3-left. Light VM production at small μ^2 gives values of $\alpha_{I\!P}(0) \lesssim 1.1$, similar to those measured for soft hadron–hadron interactions. In contrast larger values, $\alpha_{I\!P}(0) \gtrsim 1.2$, are observed for DVCS, for light VM at large Q^2 and for heavy VM at all Q^2. This is related to the large parton densities in the proton at small x, which are resolved in the presence of a hard scale: the W dependences of the cross section is governed by the hard $x^{-\lambda}$ evolution of the gluon distribution, with $\lambda \simeq 0.2$ for $Q^2 \simeq M^2_{J/\psi}$. The W dependences of VM cross sections, measured for different Q^2 values, are reasonably well described by pQCD models (not shown).

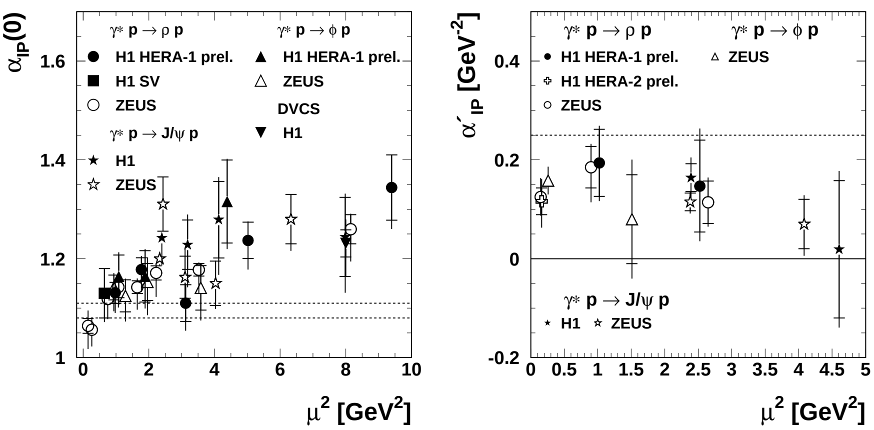

FIGURE 3. Values of (left) the intercept $\alpha_{I\!P}(0)$ and (right) the slope $\alpha'_{I\!P}$ of the effective Pomeron trajectory, obtained from fi ts of the W cross section dependences to the form $d\sigma/dt \propto W^{4(\alpha_{I\!P}(0)+\alpha'\cdot t-1)}$. The scales are $\mu^2 = Q^2$ for DVCS and $\mu^2 = (Q^2+M_V^2)/4$ for VM production. The dotted lines represent typical values for hadron–hadron scattering.

MATRIX ELEMENTS AND σ_L/σ_T

Measurements of the VM production and decay angular distributions give access to spin density matrix elements, which are related to the helicity amplitudes $T_{\lambda_V \lambda_\gamma}$. Analyses of ρ, ϕ and J/ψ photo- and electroproduction indicate the dominance of the two s-channel helicity conserving (SCHC) amplitudes, the transverse T_{11} and the longitudinal T_{00} amplitudes, In the accessible Q^2 ranges, J/ψ production is mostly transverse, whereas for light VM electroproduction the longitudinal amplitude T_{00} dominates (see Fig. 4a). In ρ and ϕ electroproduction, a significant contribution of the transverse to longitudinal helicity flip amplitude T_{01} is observed. The amplitude ratio T_{01}/T_{00} decreases with Q^2 (Fig. 4b) and increases with $|t|$ (Fig. 4d), as expected (see e.g. [8]); the SCHC amplitude ratio T_{11}/T_{00} decreases with $|t|$ (Fig. 4c) .

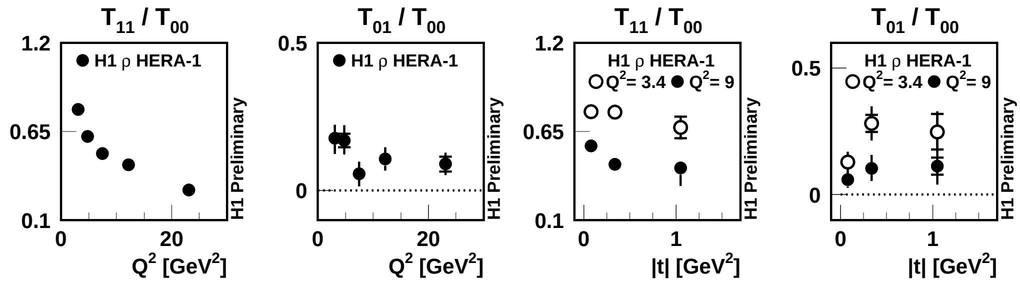

FIGURE 4. Amplitude ratios T_{11}/T_{00} and T_{01}/T_{00} as a function of Q^2 and $|t|$ (for two bins in Q^2), for ρ electroproduction. The dotted lines represent the SCHC approximation.

The cross section ratio R for ρ electroproduction is also found to depend very significantly on the dipion mass $M_{\pi\pi}$ (not shown), in line with the Q^2/M_V^2 dependence if the relevant mass is the dipion mass rather than the nominal ρ resonance mass. Following the MRT model approach [7], this suggests a limited influence of the WF on VM production.

CONCLUSIONS

Studies of VM production and DVCS at HERA provide a rich and varied field for the understanding of QCD and the testing of perturbative calculations over a large kinematical domain, covering the transition from the non-perturbative to the perturbative domain. Whereas soft diffraction, similar to hadronic interactions, dominates light VM photoproduction, typical features of hard diffraction, in particular hard W dependences, show up with the developments of hard scales provided by Q^2, the quark mass or $|t|$. The size of the interaction is accessed through the t dependences. Calculations based on pQCD, notably using k_t-unintegrated gluon distributions and GPD approaches, and predictions based on models invoking universal dipole–proton cross sections describe the data relatively well.

The measurement of spin density matrix elements gives a detailed access to the polarisation amplitudes, which is also understood in QCD.

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