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Diffractive electroproduction of ρ and ϕ mesons at H1

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Diffractive electroproduction of ρ and ϕ mesons is measured at HERA with the H1 detector in the elastic and proton dissociative channels. The data correspond to an integrated luminosity of 51 pb^{-1}. They are analysed in the kinematic range of squared photon virtuality $2.5 \leq Q^2 \leq 60$ GeV^2, photon–proton centre of mass energy $35 \leq W \leq 180$ GeV and squared four-momentum transfer to the proton $|t| \leq 3$ GeV^2. The total, longitudinal and transverse cross sections are measured as a function of Q^2, W and $|t|$. The measurements show a transition to a dominantly “hard" behaviour, typical of high gluon densities and small $q\bar{q}$ dipoles, for Q^2 larger than 10 to 20 GeV^2. They support flavour independence of the diffractive exchange, expressed in terms of the scaling variable $(Q^2+M_V^2)/4$, and proton vertex factorisation. The spin density matrix elements are measured as a function of kinematic variables. The ratio of the longitudinal to transverse cross sections, the ratio of the helicity amplitudes and their relative phases are extracted. Several of these measurements have not been performed before and bring new information on the dynamics of diffraction in a QCD framework. The measurements are discussed in the context of models using generalised parton distributions or universal dipole cross sections.

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1. Introduction

This analysis [1] is devoted to the study of diffractive electroproduction of ρ and ϕ vector mesons (designed in the following as VM), in the elastic and in the proton dissociative channels: $e+p \to e+Y+VM$; $\rho \to \pi^+ + \pi^-$ and $\phi \to K^+ + K^-$, where Y represents the elastically scattered proton or a diffractively excited baryonic system of mass M_Y, well separated in rapidity from the vector meson. The kinematic domain of the measurement is: $2.5 < Q^2 < 60$ GeV^2, $35 < W < 180$ GeV, $|t| < 3$ GeV^2 and $M_Y < 5$ GeV^2, where $Q^2 = -q^2$, q being the virtual photon four-momentum, W is the photon-proton centre of mass energy and t is the square of the four-momentum transfer from the incident proton to the scattered system Y. The present data were taken by H1 from 1996 to 2000 at the HERA collider, corresponding to a total luminosity of 51 pb^{-1}.

2. Theory

Within the QCD formalism, two main complementary approaches are used to describe VM production: dipole factorisation and collinear factorisation.

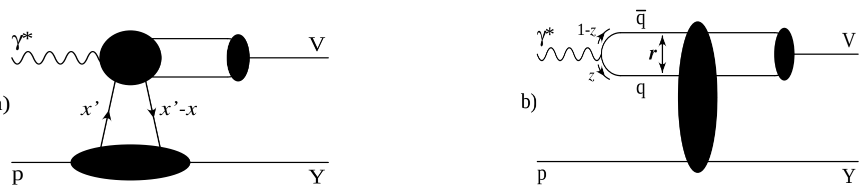

Figure 1: Representative diagrams of a) the GPD approach and b) the low x dipole approach for VM production.

2.1 Dipole approach of VM production

At high energy, i.e. small x, VM production can be described by the dipole approach. In the proton rest frame, the amplitude can be factorised into three contributions (see Fig. 1b): the fluctuation of the virtual photon into a $q\bar{q}$ colour dipole, the elastic or proton dissociative dipole–proton scattering, and the $q\bar{q}$ recombination into the final state VM.

The cross section for VM production can be computed at small x and for all Q^2 values, i.e. also in the absence of a hard scale, through models [2, 3] using universal dipole–proton cross sections measured in inclusive processes. In the presence of a hard scale (large quark mass or Q), the dipole–proton scattering is modelled in perturbative QCD (pQCD) as the exchange of a colour singlet system consisting of a gluon pair (at lowest order) or a BFKL ladder (at leading logarithm approximation, LL $1/x$). At these approximations, the cross sections are proportional to the square of the gluon density $|xG(x)|^2$ in the proton. The pQCD calculations [4, 5, 6, 7] use k_t-unintegrated gluon distributions. The typical interaction scale is $\mu^2 \simeq z(1-z)(Q^2+M_V^2)$, where z is the fraction of the photon longitudinal momentum carried by the quark. For heavy VM (in the non-relativistic wave function (WF) approximation) and for light VM production from longitudinally polarised photons, $z \simeq 1/2$ and the cross sections are expected to scale with the variable $\mu^2 = (Q^2+M_V^2)/4$. In contrast, for light VM production by transversely polarised photons, contributions with $z \to 0,1$ result in the presence of large dipoles and the damping of the scale μ, thus introducing non-perturbative features even for non-small Q^2.

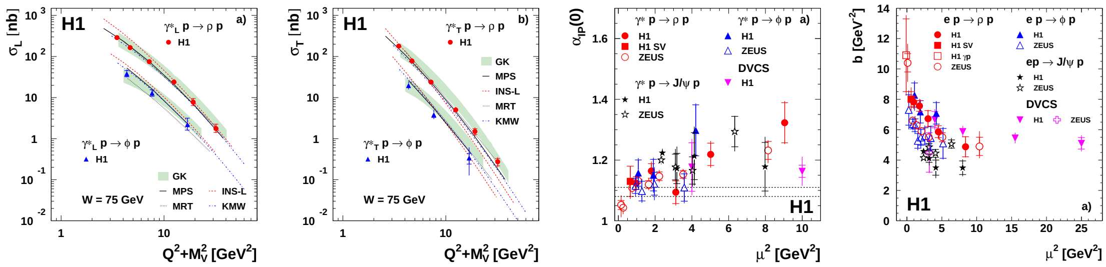

Figure 2: $(Q^2+M_V^2)$ dependences of the longitudinal and transverse $\gamma * p$ cross sections for ρ and ϕ elastic production with $W = 75$ GeV; The intercept $\alpha_{I\!P}(0)$ of the effective Pomeron trajectory for VM. The dotted lines represent typical values for hadron–hadron scattering; Measurement of the elastic slopes b of the exponential t distributions for VM production and for DVCS.

2.2 Collinear factorisation and GPD

In a complementary approach (see Fig. 1a), a collinear factorisation theorem [8] has been proven in QCD for longitudinal amplitudes in the DIS domain, which does not require low x values. This allows separating contributions from different scales, a large scale at the photon vertex, provided by the photon virtuality Q (or the quark mass), and a the proton structure. The latter is described by Generalised Parton Distributions (GPD), which take into account the distribution of transverse momenta of partons with respect to the proton direction and longitudinal momentum correlations between partons. They account for "off-diagonal" or "skewing" effects arising from the kinematic matching between the initial state (virtual) photon and the final state, VM or real photon for DVCS. GPD calculations have been performed for light VM electroproduction [9].

3. Results

3.1 Cross section measurements

The Q^2+M^2 dependences of the longitudinal and transverse γ*p cross sections are presented in Fig. 2 for elastic ρ and ϕ production for $W = 75$ GeV. Overall normalisation errors of 4.7% for ρ and 5.4% for ϕ mesons are not included in the error bars. The GPD model predictions (GK [9]) are slightly too flat, both for σ_L and for σ_T, but the global normalisations are within the theoretical and experimental errors. The k_t-unintegrated model (INS [5]) gives predictions which are too high and also too steep for σ_T. The dipole saturation model (MPS [2] and KMW[3]) describes the data relatively well, although the predictions are falling slightly too fast with Q^2+M^2.

The W dependences of the cross sections for ρ and ϕ production [1, 10, 11] have been extracted for several Q^2 values and are characterised by power law fits. The W dependences of ρ, ϕ elastic production cross sections are summarised in Fig. 2 in the form of the $\mu^2 = (Q^2+M^2)/4$ dependence of $\alpha_{I\!P}(0)$ including earlier measurements from J/ψ [12, 13, 14] and DVCS [15] with $\mu^2 = Q^2$. For light vector mesons, W dependences of the elastic cross section are close or slightly harder than the soft behaviour up to μ^2 values of the order of 5 GeV^2. An increase is then observed, up to values of $\alpha_{I\!P}(0)$ of the order of 1.2-1.3, compatible with J/ψ measurements. This is related to the hardening of the gluon distribution with the hard scale of the interaction and confirms a transition from soft to hard diffraction.

3.2 t dependences

The t dependence provides information on the size and the dynamics of the processes and on the scales relevant for the dominance of perturbative, hard effects. Whereas total cross sections (F_2 measurements) are related, through the optical theorem, to the scattering amplitudes in the forward direction, diffractive final states provide a unique opportunity to study the region of non-zero momentum transfer t. This gives indirect information on the variable conjugate to t, the transverse size of the interaction.

For $|t| \lesssim 1-2$ GeV^2, the $|t|$ distributions are exponentially falling with slopes b: $\mathrm{d}\sigma/\mathrm{dt} \propto \mathrm{e}^{-\mathrm{b}|\mathrm{t}|}$. 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 μ^2.

Measurements of elastic b slopes for DVCS [15] and VM [1, 12, 10, 11, 13, 14] production are presented in Fig. 2 as a function of μ^2. For J/ψ elastic production, the b slope is $\lesssim 4.5$ GeV^{-2}, with no visible Q^2 dependence. 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 $(Q^2+M_V^2)$ is observed for light VM production. 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 b slopes for light VM remain larger than for J/ψ when compared at the same values of the scale mu^2 up to $\gtrsim 5$ GeV^2. The purely perturbative domain may thus require larger scale values.

3.3 Proton vertex factorisation

Figure 3 presents, as a function of Q^2, the ratios of the elastic and proton dissociative γ^*p cross sections for ρ meson production for $W = 75$ GeV and $M_Y < 5$ GeV/c^2. The overall normalisation error on the ratios, which is not included in the error bars, is 2.4%. No significant dependence with Q^2 of the ratios is observed in the range $2.5 < Q^2 < 60$ GeV^2. These observations support the factorisation of diffractive amplitudes into photon vertex contributions and proton vertex processes.

3.4 Polarisation measurements

Informations on the spin and parity properties of the exchange and on the contributions of the various polarisation amplitudes are accessed through the distributions of production and decay angles which characterise VM production and two-body decays. These angular distributions allow the measurement at HERA of 15 spin density matrix elements (SDME) given in the form r^i_{jk}, which are normalised bilinear combinations of the complex helicity amplitudes $T_{\lambda_V,\lambda_\gamma}$, λ_γ and λ_V being the helicities of the virtual photon and of the VM.

The Q^2, t and (for ρ only) the invariant mass $m_{\pi\pi}$ dependences of these 15 SDME's have been measured for ρ and ϕ messon production. The ratio between the longitudinal (σ_L) and the

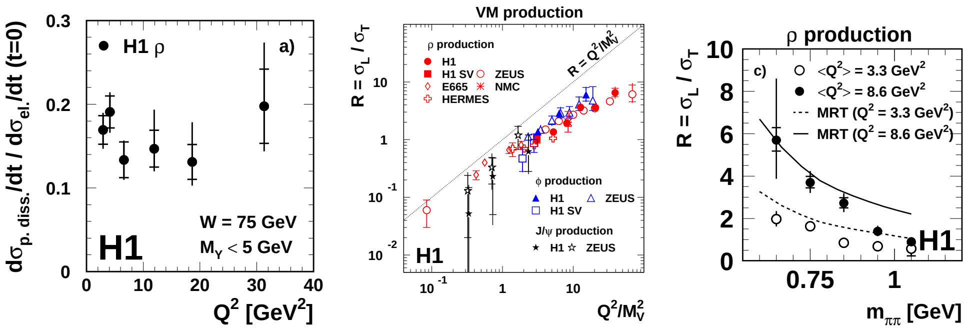

Figure 3: Q^2 dependence of the ratio of proton dissociative ($M_Y < 5$ GeV/c^2) to elastic γ^*p cross sections for ρ meson production, with $W = 75$ GeV at $t = 0$; $R = \sigma_L/\sigma_T$ as a function of Q^2/M_V^2 for ρ, ϕ and J/ψ production and of $m_{\pi\pi}$ for ρ production.

transverse (σ_T) γ^*p cross-sections have been extracted from these SDME. Fig. 3 shows the ratio σ_L/σ_T for ρ meson production as a function of the two pions invariant mass mesured by H1 and as a function of Q^2/M_V^2 for ρ, ϕ and J/ψ. A striking decrease of the cross section ratio R with the increasing $m_{\pi\pi}$ is observed as already reported by the ZEUS experiment [10]. A simple interpretation of the $m_{\pi\pi}$ dependence follows from the general, "naive" Q^2/M^2 dependence of the cross section ratio, if the mass M is understood as that of the quark pair (i.e. the dipion mass), rather than the nominal resonance mass.

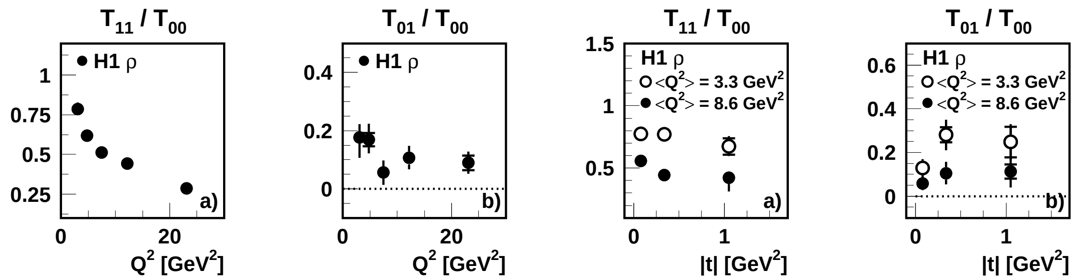

Figure 4: Amplitude ratios as a function of Q^2 and t for ρ and ϕ productions.

Following the presentation in ref. [7], the amplitude relative strengths, measured with reference to the dominant T_{00} amplitude, are computed from global fits to the 15 SDME measurements, all amplitudes being taken as purely imaginary. Results are shown in Fig. 4 as a function of Q^2 and t for ρ production. The strong decrease with Q^2 of the $|T_{11}|/|T_{00}|$ amplitude ratio is related to the usual Q^2 dependence of the cross section ratio $R = \sigma_L/\sigma_T$. For the first time, a Q^2 dependence of the non s-channel helicity conservation (SCHC) $|T_{01}|/|T_{00}|$ ratio is observed. The normalised T_{01} helicity flip amplitude is increasing with t confirming previous SCHC violation observation. Conversely, and for the first time, a decrease with t of the $|T_{11}|/|T_{00}|$ amplitude ratio, for ρ and for ϕ production is observed. The decrease of $|T_{11}|/|T_{00}|$ with t, which is not taken into account in perturbative QCD calculations [7], is needed to compensates the increase of $|T_{01}|/|T_{00}|$ and ensure unitarity.

4. Conclusions

In conclusion, studies of VM production 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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