Regularities of vector–meson electroproduction: transitory effects or early asymptotics?

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Abstract

We discuss recent HERA results on vector–meson electroproduction $\gamma^* p \to Vp$ and demonstrate that universality of the initial and final state interactions responsible for the transition between the on– and off–mass shell states allows to explain energy independence of the ratio of exclusive ρ electroproduction cross section to the total cross section. We also predict explicit mass dependence of this ratio for other vector mesons.

Introduction

Besides the studies of the structure function F_2 in DIS at low x the important measurements of the cross–sections of elastic vector meson production were performed in the experiments H1 and ZEUS at HERA [1, 2].

As it follows from this data the integral cross section of the elastic vector meson production $\sigma^V_{\gamma^* p}(W^2, Q^2)$ increases with energy in a way similar to the $\sigma^{tot}_{\gamma^* p}(W^2, Q^2)$ dependence on W^2 [3]. It appeared also that the growth of the vector–meson electroproduction cross–section with energy is steeper for heavier vector mesons. Similar effect also takes place when the virtuality Q^2 increases.

The most recent data of ZEUS Collaboration evidently demonstrated an energy independence of the ratio of the cross section of exclusive ρ electroproduction to the total cross section [4]. Such behavior of this ratio is at variance with perturbative QCD results [5], Regge and dipole approaches [4, 6]. Recent review of the related problems and success of the various theoretical approaches can be found in [7].

Of course, the energy range of the available data is limited and the above mentioned contradiction could probably be avoided due to fine tuning of the appropriate models. But this is merely a general statement and it needs to be checked in each particular case. Meanwhile, it would be interesting to pay attention to a model where such an energy independence is an inherent one. To be more specific this energy independence was obtained in the approach based on the off-shell extension of the s–channel unitarity [8]. It is worth to note also that the approach developed in [8] and its application to the elastic vector meson production processes $\gamma^* p \to Vp$ leads to mass dependence of the corresponding cross–sections which is in a good agreement with the experiment [9] and it allows us to make predictions for the explicit mass dependence of the ratio $r_V = \sigma^V_{\gamma^* p}(W^2, Q^2)/\sigma^{tot}_{\gamma^* p}(W^2, Q^2)$.

Vector–meson electroproduction

There is no universal, generally accepted method to ensure unitarity of the scattering matrix. However, long time ago arguments based on analytical properties of the scattering amplitude were put forward [10] in favor of the rational form of unitarization. Unitarity relations can be written for both real and virtual external particles scattering amplitudes. However, implications of unitarity are different for the scattering of real and virtual particles. The extension of the U–matrix unitarization scheme (rational form of unitarization) for the off-shell scattering was considered in [8]. It was supposed as usual that the virtual photon fluctuates into a quark–antiquark pair $q\bar{q}$ and this pair can be treated as an effective virtual vector meson state. There were considered limitations the unitarity provides for the $\gamma^* p$–total cross-sections and geometrical effects in the energy dependence of $\sigma^{tot}_{\gamma^* p}$. It was shown that the solution of the extended unitarity equations augmented by an assumption of the Q^2–dependent constituent quark interaction radius results in the following dependence at high energies:

$$\sigma^{tot}_{\gamma^* p} \sim (W^2)^{\lambda(Q^2)}, \tag{1}$$

where $\lambda(Q^2)$ is saturated at large values of Q^2 and reaches unity. However, off–shell unitarity does not require transformation of this power-like dependence into a logarithmic one at asymptotic energies. Thus, power–like behavior of the cross–sections with the exponent depending on virtuality could be of asymptotic nature and have a physical ground. It should not be regarded merely as a transitory behavior or a convenient way to represent the data.

The extended unitarity for the off–mass–shell amplitudes F^{**} and F^* has the structure similar to the equation for the on–shell amplitude F, but in the former case it relates different amplitudes[1]. The important point in the solution of the extended unitarity is the factorization in the impact parameter representation at the level of the input dynamical quantity — U–matrix:

$$U^{**}(s,b,Q^2)U(s,b) - [U^*(s,b,Q^2)]^2 = 0. \tag{2}$$

Eq. (2) reflects universality of the initial and final state interactions when transition between on– and off–mass shell states occurs. Although this factorization does not survive at the level of the amplitudes $F^{**}(s,t,Q^2)$, $F^*(s,t,Q^2)$ and $F(s,t)$ (i.e. after unitarity equations are solved and Fourier-Bessel transform is performed), it is essential for the energy independence of the ratio of the exclusive ρ electroproduction cross section to the total cross section.

The above result (1) is valid when the interaction radius of the virtual constituent quark is rising with virtuality Q^2. The dependence of the interaction radius

$$r_{Q^*} = \xi(Q^2)/m_Q. \tag{3}$$

[1]Notations for amplitudes correspond to the cases of amplitudes with both initial and final mesons are off mass shell, only initial meson is off mass shell and both mesons are on mass shell, respectively. Note that $\sigma^{tot}_{\gamma^* p}$ is determined by the imaginary part of the amplitude F^{**}, whereas $\sigma^{V}_{\gamma^* p}$ is determined by the square of another amplitude F^*.

on Q^2 comes through the dependence of the factor $\xi(Q^2)$ (in the on-shell limit $\xi(Q^2) \to \xi$). The origin of the rising of the interaction radius of the virtual constituent quark with virtuality Q^2 might be of dynamical nature and stem from the emission of the additional $q\bar{q}$–pairs in the nonperturbative structure of a constituent quark. The available experimental data are consistent with the $\ln Q^2$–dependence of the radius [8]:

$$\xi(Q^2) = \xi + a \ln\left(1 + \frac{Q^2}{Q_0^2}\right).$$

The introduction of the Q^2 dependent interaction radius of a constituent quark, which in this approach consists of a current quark surrounded by the cloud of quark–antiquark pairs of different flavors [11], is the main issue of the off–shell extension of the model, which provides at large values of W^2

$$\sigma^{tot}_{\gamma^* p}(W^2, Q^2) \propto G(Q^2)\left(\frac{W^2}{m_Q^2}\right)^{\lambda(Q^2)} \ln\frac{W^2}{m_Q^2}, \tag{4}$$

where

$$\lambda(Q^2) = \frac{\xi(Q^2) - \xi}{\xi(Q^2)}. \tag{5}$$

The value of parameter ξ in the model is determined by the slope of the differential cross–section of elastic scattering at large t region [12] and it follows from the pp-experimental data that $\xi = 2$.

Inclusion of the heavy vector meson production into this scheme is straightforward: the virtual photon fluctuates before the interaction with proton into the heavy quark–antiquark pair which constitutes the virtual heavy vector meson state. After interaction with proton this state turns into a real heavy vector meson.

Integral exclusive (elastic) cross–section of vector meson production in the process $\gamma^* p \to Vp$ when the vector meson in the final state contains not necessarily light quarks can be calculated directly:

$$\sigma^{V}_{\gamma^* p}(W^2, Q^2) \propto G_V(Q^2)\left(\frac{W^2}{{m_Q}^2}\right)^{\lambda_V(Q^2)} \ln\frac{W^2}{{m_Q}^2}, \tag{6}$$

where

$$\lambda_V(Q^2) = \lambda(Q^2)\frac{\tilde{m}_Q}{\langle m_Q\rangle}. \tag{7}$$

In Eq. (7) $\tilde{m}_Q$ denotes the mass of the constituent quarks from the vector meson and $\langle m_Q\rangle$ is the mean constituent quark mass of the vector meson and proton system. Of course, for the on–shell scattering ($Q^2 = 0$) we have a standard Froissart–like asymptotic energy dependence.

It is evident from Eqs. (4) and (6) that $\lambda_V(Q^2) = \lambda(Q^2)$ for the light vector mesons, i.e. the ratio

$$r_V = \sigma^{V}_{\gamma^* p}(W^2, Q^2)/\sigma^{tot}_{\gamma^* p}(W^2, Q^2) \tag{8}$$

does not depend on energy for $V = \rho, \omega$. For the case of the heavy vector meson production J/Ψ and Υ the respective cross–section rises about two times faster than the total cross–section; Eq. (7) results in

$$\lambda_{J/\Psi}(Q^2) \simeq 2\lambda(Q^2), \quad \lambda_{\Upsilon}(Q^2) \simeq 2.2\lambda(Q^2),$$

i.e.

$$r_{J/\Psi} \propto (W^2)^{\lambda(Q^2)}, \quad r_{\Upsilon} \propto (W^2)^{1.2\lambda(Q^2)}.$$

Corresponding relations for the φ–meson production are the following

$$\lambda_{\varphi}(Q^2) \simeq 1.3\lambda(Q^2), \quad r_{\varphi} \propto (W^2)^{0.3\lambda(Q^2)}.$$

In the limiting case when the vector meson is very heavy, i.e. $\tilde{m}_Q \gg m_Q$ the relation between exponents is

$$\lambda_V(Q^2) = \frac{5}{2}\lambda(Q^2).$$

The quantitative agreement of Eq. (6) with experiment was demonstrated in [9]. This agreement is in favor of relation (7) which provides explicit mass dependence of the exponent in the power–like energy dependence of cross–sections. Thus, the power-like parameterization of the ratio r_V

$$r_V \sim (W^2)^{\lambda(Q^2)(\tilde{m}_Q - \langle m_Q \rangle)/\langle m_Q \rangle}$$

with m_Q and Q^2–dependent exponent could also have a physical ground. It would be of interest, therefore, to check experimentally the predicted energy dependence of the ratio r_V.

The dependence of the constituent quark interaction radius $r_{Q^*} = \xi(Q^2)/m_Q$ on its mass and virtuality gets an experimental support and the non–universal energy asymptotic dependence Eqs. (6) and (7) and predicted in [8] does not contradict the high–energy experimental data on elastic vector–meson electroproduction. Of course, as it was already mentioned in the Introduction, the limited energy range of the available experimental data allows other parameterizations, e. g. universal asymptotic Regge–type behavior with Q^2–independent trajectories (cf. [13, 14, 15]), to treat the observed experimental regularities as transitory effects.

It seems, however, that scattering of virtual particles reaches the asymptotics much faster than scattering of the real particles and the Q^2–dependent exponent $\lambda(Q^2)$ reflects asymptotic dependence and not the "effective" preasymptotic one. Although the relation between $\xi(Q^2)$ and $\lambda(Q^2)$ implies saturation of the Q^2-dependence of $\lambda(Q^2)$ at large values of Q^2, the power–like energy dependence itself will survive at asymptotic energies. The early asymptotics of virtual particle scattering is correlated with the peripheral impact parameter behavior of the scattering amplitude for the virtual particles. The respective profiles of the amplitudes F^{**} and F^* are peripheral when $\xi(Q^2)$ increases with Q^2 [8].

The energy independence of the ratio $r_\rho = \sigma^{\rho}_{\gamma^* p}/\sigma^{tot}_{\gamma^* p}$ reflects universality of the initial and final state interactions responsible for the transition between the on– and off–mass shell states. This universality is a quite natural assumption leading to factorization Eq. (2) at the level of the U–matrix [8]. Thus, the off–shell unitarity is the principal origin of the observed energy independence of the ratio r_ρ.

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References

[1] ZEUS Collaboration, S. Chekanov et al., Eur. Phys. J. C **24** (2002) 345

[2] H1 Collaboration, C. Adloff et al., Phys. Lett. B **483** (2000) 23

[3] A. M. Cooper-Sarkar, R. C. E. Devenish and A. De Roeck, Int. J. Mod. Phys. A **13** (1998) 3385

[4] A. Levy, Acta Physica Polonica B **33** (2002) 3547; hep-ex/0301022

[5] S. J. Brodsky, L. Frankfurt, J.F. Gunion, A. H. Mueller and M. Strikman, Phys. Rev. D **50** (1994) 3134

[6] A. Bialas, Acta Physica Polonica B, **33** (2002) 3983

[7] P. V. Landshoff, hep-ph/0209364

[8] S. M. Troshin and N. E. Tyurin, Eur. Phys. J. C **22** (2002) 667

[9] M. A. Perfilov and S. M. Troshin, hep-ph/0207306

[10] R. Blankenbecler and M. L. Goldberger, Phys. Rev. **126** (1962) 766

[11] S. M. Troshin and N. E.Tyurin, Nuovo Cim. **106A** 327 (1993); Phys. Rev. D **49** (1994) 4427

[12] S. M. Troshin and N. E. Tyurin, Theor. Math. Phys. **50** (1982) 150

[13] V.A. Petrov and A.V. Prokudin, hep-ph/9912245, in Proceedings, International Conference, 8th Blois Workshop, EDS'99, Protvino, Russia, June 28-July 2, 1999, p. 95, V.A. Petrov and A.V. Prokudin (Eds.), World Scientific (2000)

[14] E. Martynov, E. Predazzi and A. Prokudin, Eur. Phys. J. C **26** (2002) 271

[15] R. Fiore, L. Jenkovszky, F. Paccanoni and A. Papa, Phys. Rev. D **65** (2002) 077505