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NOVEL FEATURES
IN EXCLUSIVE VECTOR-MESON PRODUCTION

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Abstract

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It is shown that the universality of the initial and final state interactions responsible for the transition between the on- and off-mass shell states leads to the energy independence of the ratio of exclusive ρ electroproduction cross section to the total cross section. It is demonstrated that the above universality and explicit mass dependence of the exponent in the power-like energy behavior of the cross-section obtained in the approach based on unitarity is in a quantitative agreement with the high-energy HERA experimental data. We discuss also HERA results on angular distributions of vector-meson production.

Аннотация

Перфилов М.А., Трошин С.М., Тюрин Н.Е. Новые закономерности в эксклюзивном рождении векторных мезонов: Препринт ИФВЭ 2003-7. – Протвино, 2003. – 6 с., 4 рис., библиогр.: 16.

Показано, что универсальность взаимодействий в начальном и конечном состояниях, которые отвечают за переход от состояний вне массовой поверхности в состояния на массовой поверхности, приводит к независимости от энергии отношения сечения эксклюзивного электророждения к полному сечению. Показано также, что явная зависимость от массы показателя степени находится в хорошем согласии с высокоэнергетическими данными ГЕРЫ. Обсуждается также угловая зависимость сечений рождения векторных мезонов.

Introduction

Exclusive vector meson production is an important process which can provide information on hadronic structure at large and small distances and nature of soft and hard interaction dynamics. As it follows from the HERA data [1,2] the integral cross section of the elastic vector meson production $\sigma_{\gamma^*p}^V(W^2, Q^2)$ increases with energy in a way similar to the $\sigma_{\gamma^*p}^{tot}(W^2, Q^2)$ 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 takes also place when the virtuality Q^2 increases.

The preliminary data of ZEUS Collaboration [4] provide an indication for an energy independence of the ratio of the cross section of exclusive ρ electroproduction to the total cross section. 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 successes 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. Meanwhile, similar energy independence was obtained in the approach based on the off-shell extension of the s -channel unitarity [8]. In this note we provide an additional discussion pointing out to the origin of the above energy independence. We perform a quantitative comparison of the HERA data on vector-meson production with the results obtained in [8].

Vector-meson electroproduction

There is no universal, generally accepted method to obey unitarity of the scattering matrix. However, long time ago the arguments based on analytical properties of the scattering amplitude were put forward [9] in favor of the rational form of unitarization. Unitarity 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 and this pair can be treated as an effective virtual vector meson state. There were considered limitations the unitarity provides for the γ^*p -total cross-sections and geometrical effects in the energy

dependence of $\sigma_{\gamma^*p}^{tot}$. It was shown that the solution of the extended unitarity augmented by an assumption of the Q^2 -dependent constituent quark¹ interaction radius results in the following dependence at high energies:

$$\sigma_{\gamma^*p}^{tot} \sim (W^2)^{\lambda(Q^2)}, \quad (1)$$

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 asymptotical energies. Thus, power-like behavior of the cross-sections with the exponent dependent on virtuality could be of an asymptotical 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 a structure similar to the equation for the on-shell amplitude F but in the former case it relates the different amplitudes. We denoted in that way the amplitudes when 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 $\sigma_{\gamma^*p}^{tot}$ is determined by the imaginary part of the amplitude F^{**} , whereas $\sigma_{\gamma^*p}^V$ is determined by the square of another amplitude F^* . 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:

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

Eq. (2) reflects universality of the initial and final state interactions when transition between on- and off-mass shell states occurs. Despite that such 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 constituent quark Q from the virtual meson V^* increases with virtuality Q^2 . We use the same notation Q for the constituent quarks and virtuality, but it should not lead to misunderstanding. The dependence of the interaction radius

$$R_Q(Q^2) = \xi(Q^2)/m_Q. \quad (3)$$

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

$$R_Q(Q^2) = R_Q^0 + \frac{a}{m_Q} \ln(1 + Q^2/Q_0^2),$$

where $R_Q^0 = \xi/m_Q$ and parameters ξ , a and Q_0^2 are universal for all constituent quarks.

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

¹The concept of constituent quark has been used extensively since the very beginning of the quark era but has obtained just recently a possible direct experimental evidence at Jefferson Lab [10].

large values of W^2

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

where

$$\lambda(Q^2) = 1 - \xi/\xi(Q^2), \quad \xi(Q^2) = \xi + a \ln(1 + Q^2/Q_0^2). \quad (5)$$

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 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 a proton this state turns out into a real heavy vector meson.

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

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

where

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

In Eq. (7) \tilde{m}_Q denotes the mass of the constituent quarks from the vector meson and $\langle m_Q \rangle = (2\tilde{m}_Q + 3m_Q)/5$ 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

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

does not depend on energy for $V = \rho, \omega$. Eq. (6) and consequently (8) are in a good agreement (Fig. 1) with the experimental data of H1 and ZEUS Collaborations [1,2]. It should be noted, however, that the experimental definition of the ratio r_V adopted by the ZEUS Collaboration [4] considers cross-sections at the different virtualities² and does not directly correspond to (8).

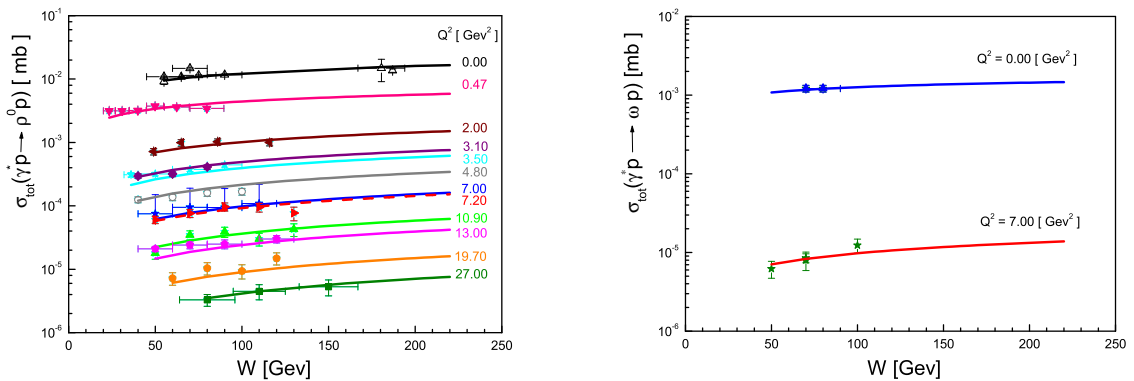


Figure 1. Energy dependence of the elastic cross-sections of exclusive ρ and ω -meson production.

²We are indebted to I. Ivanov for pointing out to this fact.

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.

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

Corresponding relations for the ϕ -meson production are the following

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

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

$$\lambda_V(Q^2) = 2.5\lambda(Q^2).$$

The quantitative agreement of Eq. (6) with experimental data for the case of ϕ and J/ψ production can be seen in Fig. 2.

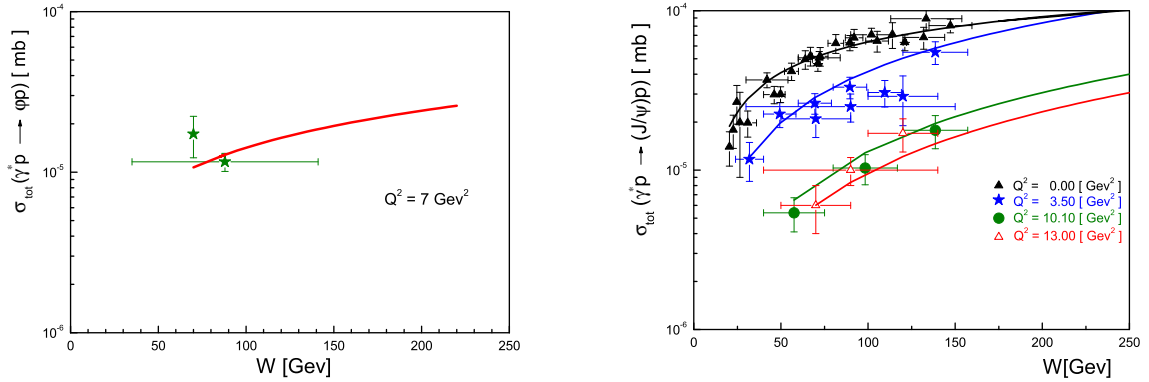


Figure 2. Energy dependence of the elastic cross-sections of exclusive ϕ and J/ψ -meson production.

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

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

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

The dependence of the constituent quark interaction radius (3) on its mass and virtuality gets an experimental support and the non-universal energy asymptotical dependence (6) and (7) and predicted in [8] does not contradict to 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 asymptotical Regge-type behavior with Q^2 -independent trajectories (cf. [13,14,15]), to treat the experimental regularities as transitory ones.

It seems, however, that the scattering of virtual particles reaches the asymptotics much faster than the scattering of the real particles and the Q^2 -dependent exponent $\lambda(Q^2)$ reflects

the asymptotical dependence and not the “effective” preasymptotical one. Despite that the relation between $\xi(Q^2)$ and $\lambda(Q^2)$ implies a 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 asymptotical energy values. 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 $r_\rho(W^2, Q^2)$ 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 (2) at the level of the U -matrix [8]. Under this the off-shell unitarity is the principal origin of the energy independence of the ratio $r_\rho(W^2, Q^2)$.

There are also other interesting manifestations of the off-shell unitarity effects, e.g. the behavior of the differential cross-sections at large t is to a large extent determined by the off-shell unitarity effects. Indeed, a smooth power-like dependence on t has been predicted [8]:

$$\frac{d\sigma_V}{dt} \simeq \tilde{G}(Q^2) [1 - \bar{\xi}^2(Q^2)t/\tilde{m}_Q^2]^{-3}, \quad (9)$$

where

$$\bar{\xi}(Q^2) = \xi\xi(Q^2)/[\xi - \xi(Q^2)]. \quad (10)$$

As it is seen from Fig. 3, Eq. (9) corresponds to experimental data for J/ψ vector meson even at the very moderate t -values. This fact is due to the effect of large mass of charmed quark which enhances in the model contribution of the region of small impact parameters.

It appears that differential cross section does not depend on energy and depends on t in a simple power-like way $(-t)^{-3}$. This dependence differs from the corresponding dependence in the case of on-shell exclusive scattering [11] which approximates the quark counting rule [16]. The ratio of differential cross-sections for the exclusive production of the different vector mesons

$$\frac{d\sigma_{V_1}/dt}{d\sigma_{V_2}/dt}$$

does not depend on the variables W^2 and t at large enough values of $-t$.

Meanwhile the Orear type behavior of the differential cross-section of the vector meson photoproduction obtained in [8]

$$\frac{d\sigma_V}{dt} \propto \exp\left[-\frac{2\pi\xi}{M}\sqrt{-t}\right]. \quad (11)$$

is in a good agreement with the HERA experimental data at moderate values of t (cf. Fig.4). Note, that the parameters ξ and $M = 2\tilde{m}_Q + 3m_Q$ are fixed.

Thus, we have shown that the model [8] which leads to the energy independence of the ratio of exclusive ρ -meson electroproduction cross-section to the total cross-section as the result of the adopted universality of the initial and final state interactions responsible for the transition

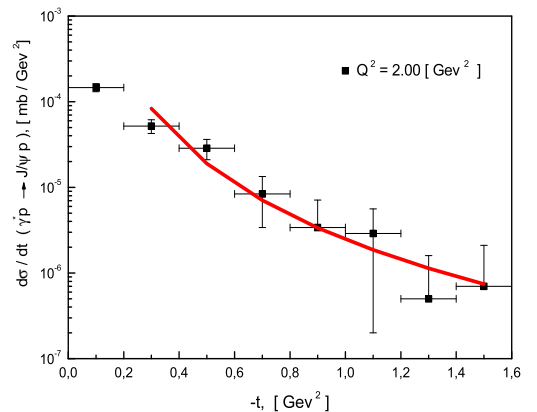


Figure 3. Angular dependence of the elastic cross-sections of exclusive J/ψ -meson electroproduction.

between the on- and off-mass shell states, is in a quantitative agreement with experimental data for the vector-meson production.

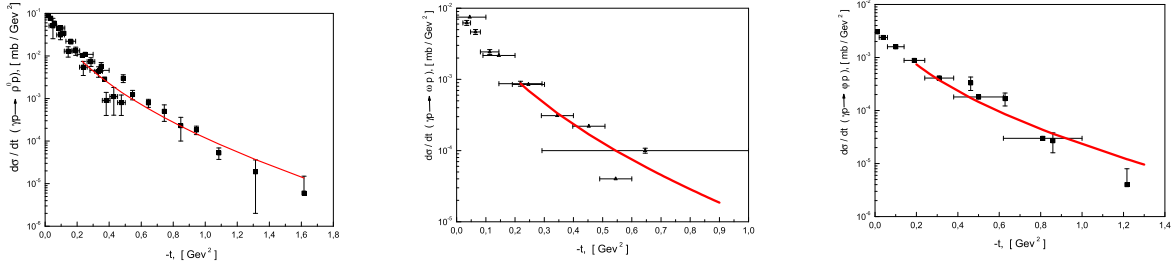


Figure 4. Angular dependence of exclusive ρ , ω and φ -meson production.

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