PHYSICAL REVIEW D **68**, 056008 (2003)

Novel features in exclusive vector-meson production

M. A. Perfilov
Physics Department, Moscow State University, Vorobiovy Gory, Moscow, 119 899 Russia

S. M. Troshin* and N. E. Tyurin
Institute for High Energy Physics, Protvino, Moscow Region, 142281, Russia
(Received 13 April 2003; revised manuscript received 16 June 2003; published 24 September 2003)

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

DOI: 10.1103/PhysRevD.68.056008 PACS number(s): 11.80.Fv, 12.40.Nn, 12.40.Vv

I. INTRODUCTION

Exclusive vector-meson production is an important process which can provide information on hadronic structure at large and small distances and the nature of soft and hard interaction dynamics. As follows from the DESY *ep* collider HERA data [1,2], the integral cross section of 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 appears also that the growth of the vector-meson electroproduction cross section with energy is steeper for heavier vector mesons. A similar effect also takes place when the virtuality Q^2 increases.

The preliminary data from the ZEUS Collaboration [4] provide an indication of the 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] and Regge and dipole approaches [4,6]. A 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 by fine-tuning the appropriate models. Meanwhile, a similar energy independence was obtained in the approach based on the off-shell extension of *s*-channel unitarity [8]. In this note we provide additional discussion about 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].

II. VECTOR-MESON ELECTROPRODUCTION

There is no universal, generally accepted method to obtain unitarity of the scattering matrix. However, long ago arguments based on the analytical properties of the scattering amplitude were put forward [9] in favor of a rational form of unitarization. Unitarity can be imposed for both the real and virtual external particle scattering amplitudes. However, the implications of unitarity are different for the scattering of real and virtual particles. The extension of the *U*-matrix unitarization scheme (the rational form of unitarization) for off-shell scattering was considered in [8]. It was supposed as usual that the virtual photon fluctuates into a quark-antiquark pair, and this pair can be treated as an effective virtual vector-meson state. The limitations that unitarity provides for the $\gamma^* p$ total cross sections were considered, and the role of geometrical effects in the energy dependence of $\sigma^{tot}_{\gamma^* p}$ was studied. It was shown that solution of the extended unitarity problem supplemented by the assumption of a Q^2-dependent constituent quark[1] 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 transform this powerlike dependence into a logarithmic one at asymptotic energies. Thus, powerlike behavior of the cross sections with the exponent dependent on virtuality could be of asymptotic nature and have a physical basis. 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 the mass shell, only the initial meson is off the mass shell, and both mesons are on the mass shell. Note that $\sigma^{tot}_{\gamma^* p}$ is determined by the imaginary part of the amplitude F^{**}, whereas $\sigma^V_{\gamma^* p}$ is de-

*Electronic address: troshin@mx.ihep.su

[1]We would like to note here that the concept of the constituent quark has been used extensively since the very beginning of the quark era, but just recently possible direct experimental evidence was obtained at the Jefferson Lab [10].

termined by the square of the amplitude F^*. Disregard of this fact is the main reason leading to the difficulties mentioned in the Introduction in explaining the energy independence of the ratio of the cross section of exclusive ρ electroproduction to the total cross section.

The important point in the solution of the extended unitarity problem is the factorization in the impact parameter representation at the level of the input dynamical quantity, the U matrix:

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

Equation (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 the unitarity equations are solved and the 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 with 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

$$R_Q(Q^2)=\xi(Q^2)/m_Q \tag{3}$$

on Q^2 comes through the dependence of the universal Q^2-dependent factor $\xi(Q^2)$ [in the on-shell limit $\xi(Q^2)\to\xi$]. The origin of the increasing interaction radius of the constituent quark Q with virtuality Q^2 might be of a dynamical nature, stemming from the emission of additional $q\bar{q}$ pairs in the nonperturbative structure of the 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 the 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 a cloud of quark-antiquark pairs of different flavors [11], is the main issue in the off-shell extension of the model, which at large values of W^2 provides

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

where

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

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

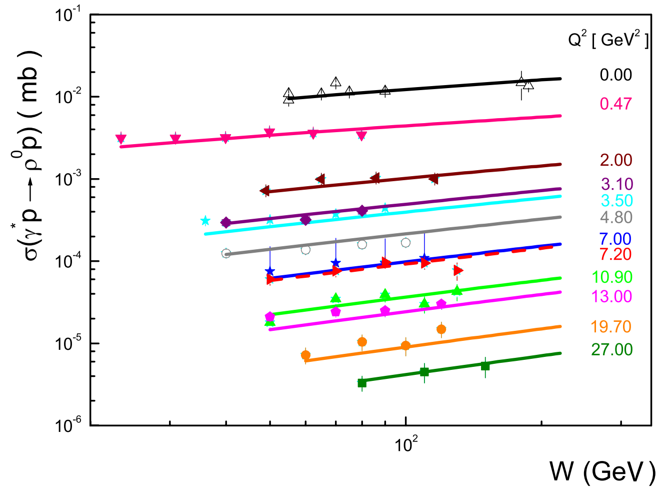

FIG. 1. Energy dependence of the elastic cross section of exclusive ρ-meson production. Experimental data are taken from [1,2]. Theoretical curves correspond to Eqs. (6) and (7).

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

The integral exclusive (elastic) cross section of vector-meson production in the process $\gamma^* p\to Vp$ when the vector meson in the final state does not necessarily contain 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

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

In Eq. (7) $\tilde{m}_Q$ denotes the mass of the constituent quarks from the vector meson and $\langle m_Q\rangle=(2\tilde{m}_Q+3m_Q)/5$ is the mean constituent quark mass of the vector-meson and proton system. The function $G_V(Q^2)$ in Eq. (6) at fixed values of Q^2 is considered as an overall constant to be fixed by the experimental data. Its dependence on Q^2 can then be described by the simple formula

$$G_V(Q^2)=G_0(1+Q^2/Q_0^2)^{-\alpha}.$$

Of course, for 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 light vector mesons, i.e., the ratio

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

does not depend on energy for $V=\rho,\omega$. Equation (6) and consequently Eq. (8) are in good agreement (Figs. 1 and 2) with the experimental data of the H1 and ZEUS Collabora-

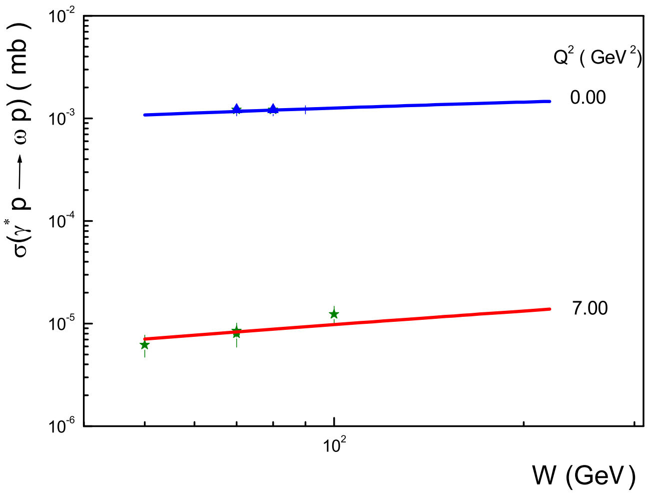

FIG. 2. Energy dependence of the elastic cross section of exclusive ω-meson production. Experimental data are taken from [13]. Theoretical curves correspond to Eqs. (6) and (7).

tions [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 different virtualities[2] and does not directly correspond to Eq. (8).

For the case of heavy vector-meson production J/ψ and Υ, the corresponding cross section increases 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.,

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

The corresponding relations for 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 meson production can be seen in Fig. 3. The corresponding cross section of J/ψ-meson production is presented in Fig. 4.

This agreement is in favor of relation (7), which provides explicit mass dependence of the exponent in the powerlike energy dependence of the cross sections. Thus, the powerlike parametrization of the ratio r_V,

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

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

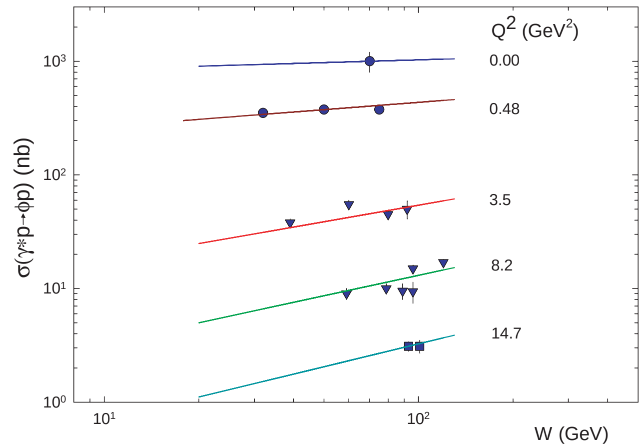

FIG. 3. Energy dependence of the elastic cross section of exclusive ϕ-meson production. Experimental data are taken from [14]. Theoretical curves correspond to Eqs. (6) and (7).

with an m_Q- and Q^2-dependent exponent, could also have a physical basis. It would be interesting 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 has experimental support, and the nonuniversal energy asymptotic dependence (6) and (7) and predicted in [8] does not contradict the high-energy experimental data on elastic vector-meson electroproduction. Of course, as already mentioned in the Introduction, the limited energy range of the available experimental data allows other parametrizations, e.g., universal asymptotic Regge-type behavior with Q^2-independent trajectories (cf. [16–18]), which 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 real particles, and the Q^2-dependent exponent $\lambda(Q^2)$ reflects the asymptotic dependence and not the "effective" preasymptotic one. Although the relation between $\xi(Q^2)$ and

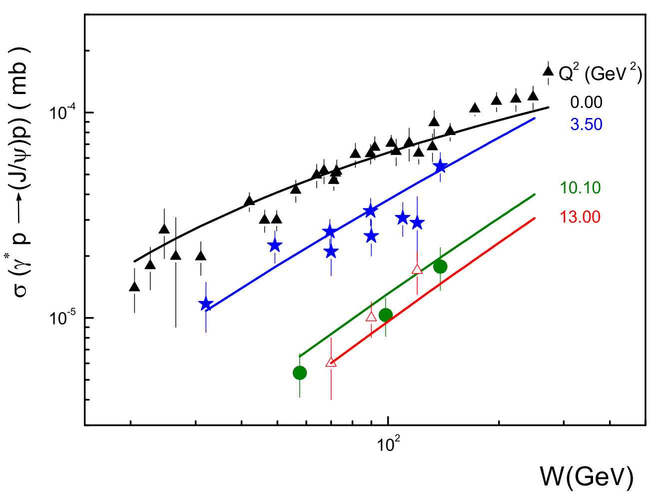

FIG. 4. Energy dependence of the elastic cross section of exclusive J/ψ-meson production. Experimental data are taken from [15]. Theoretical curves correspond to Eqs. (6) and (7).

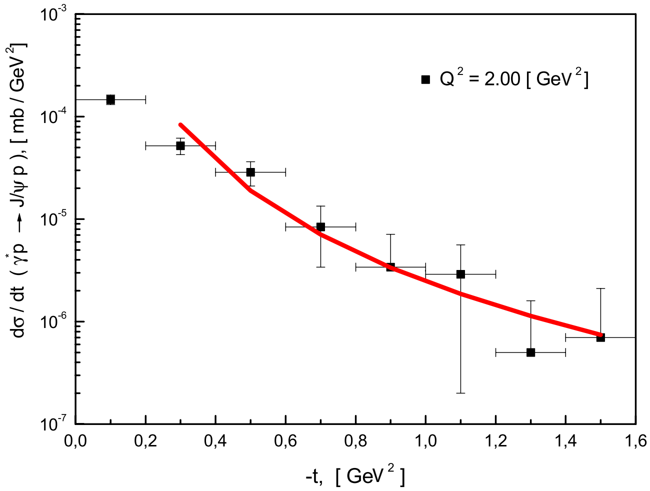

FIG. 5. Angular dependence of the elastic cross sections of exclusive J/ψ-meson electroproduction. Experimental data are taken from [22]. Theoretical curve corresponds to Eqs. (9) and (10).

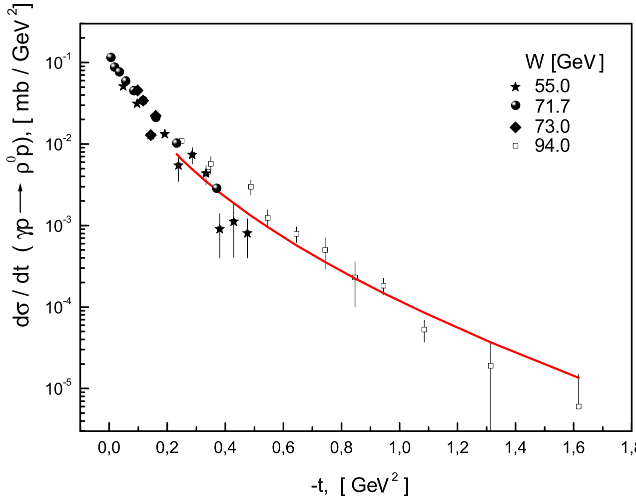

FIG. 6. Angular dependence of the elastic cross sections of exclusive ρ-meson electroproduction. Experimental data are taken from [25]. Theoretical curve corresponds to Eq. (11).

$\lambda(Q^2)$ implies a saturation of the Q^2 dependence of $\lambda(Q^2)$ at large values of Q^2, the powerlike energy dependence itself will survive at asymptotic 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 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 natural assumption leading to the factorization (2) at the level of the U matrix [8]. Under this condition, 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 powerlike dependence on t has been predicted [8]:

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

where

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

A smooth powerlike t dependence was also obtained in the approaches based on the perturbative QCD [19–21]. We expect that Eq. (9) should be applicable for J/ψ vector-meson elastic electroproduction not only at large but also at moderate values of t. This is due to the large mass of charmed quarks, which in this model enhances the contribution of the region of small impact parameters and suppresses the contribution from the region $b \sim R(s)$. As is seen from Fig. 5, Eq. (9) indeed corresponds to the experimental data for the J/ψ vector meson even at very moderate t values.

It appears that the differential cross section does not depend on energy and depends on t in a simple powerlike way, $(-t)^{-3}$. A similar powerlike behavior is expected for the differential cross section of processes with proton dissociation [23], which, however, will be dominant numerically at large t.

The above dependence differs from the corresponding dependence in the case of on-shell exclusive scattering [11], which approximates the quark counting rule [24]. The ratio of differential cross sections for the exclusive production of the different vector mesons

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

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 vector meson photoproduction obtained in [8],

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

is in a good agreement with the HERA experimental data at moderate values of t (cf. Figs. 6, 7, and 8). Note that the parameters ξ and $M = 2\tilde{m}_Q + 3m_Q$ are fixed.

It should be noted that at values of t close to forward scattering the behavior of the differential cross section is complicated. It is given by the sum of the series[3] [Eq. (39) from [8]]. The oscillating factors

[3]In case of on-shell scattering this series can be summed up [11] and leads to the well-known exponential dependence of the differential cross sections at values of t close to the forward direction.

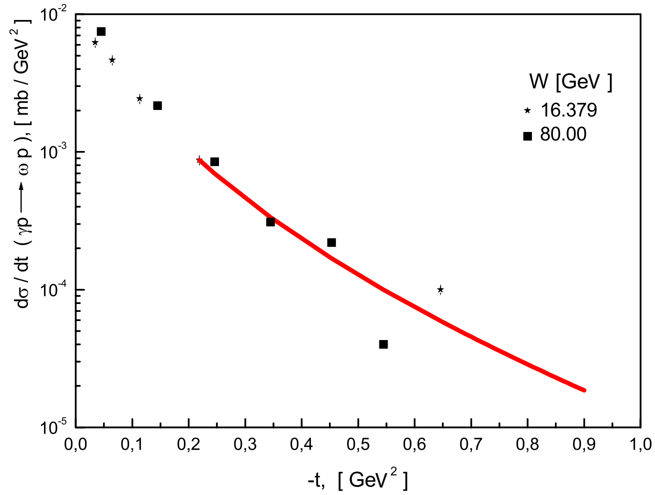

FIG. 7. Angular dependence of the elastic cross sections of exclusive ω-meson electroproduction. Experimental data are taken from [26] and [27]. Theoretical curve corresponds to Eq. (11).

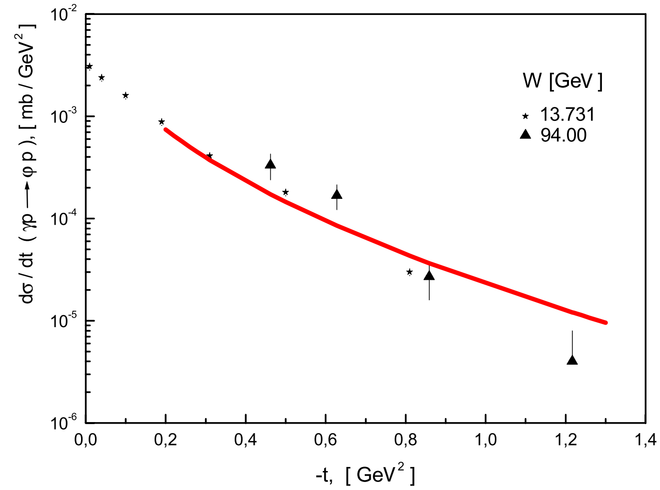

FIG. 8. Angular dependence of the elastic cross sections of exclusive ϕ-meson electroproduction. Experimental data are taken from [27] and [28]. Theoretical curve corresponds to Eq. (11).

$$\exp\left\{\frac{i\pi n}{N}\lambda_V(Q^2)\right\},$$

where $N=5$ is the total number of constituent quarks, which are absent in the on-shell scattering amplitude [11], play a significant role here. The presence of these factors leads at the same time to the suppression of terms with large values of n, and therefore we expect that the simple Orear type behavior will already occur at low values of t, and the differential cross section will have the dependence (11) at small as well as moderate values of t (but, of course, this is not valid for t values close to forward scattering).

Thus, we have shown that the model of [8], which leads to energy independence of the ratio of the exclusive ρ-meson electroproduction cross section to the total cross section as a result of the adopted universality of the initial and final state interactions responsible for the transition between the on- and off-mass-shell states, is in quantitative agreement with experimental data for vector-meson production.

ACKNOWLEDGMENTS

We are grateful to I. Ivanov and V. Petrov for interesting discussions of the results and experimental situation.

[1] J. Breitweg *et al.*, Eur. Phys. J. C **6**, 603 (1999); S. Chekanov *et al.*, *ibid.* **24**, 345 (2002).

[2] C. Adloff *et al.*, Phys. Lett. B **483**, 23 (2000); Eur. Phys. J. C **13**, 371 (2000).

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

[4] ZEUS Collaboration, S. Chekanov *et al.*, ICHEP02, Amsterdam, 2002, Paper 820; M. Capua, Acta Phys. Pol. B **33**, 3407 (2002); A. Levy, *ibid.* **33**, 3547 (2002); hep-ex/0301022.

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

[6] A. Bialas, Acta Phys. Pol. B **33**, 3983 (2002).

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

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

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

[10] R. Petronzio, S. Simula, and G. Ricco, Phys. Rev. D **67**, 094004 (2003).

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

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

[13] J. Breitweg *et al.*, Phys. Lett. B **487**, 273 (2000).

[14] M. Derrick *et al.*, Phys. Lett. B **380**, 220 (1996); C. Adloff *et al.*, *ibid.* **483**, 360 (2000).

[15] J. Breitweg *et al.*, Eur. Phys. J. C **6**, 603 (1999); C. Adloff *et al.*, Phys. Lett. B **483**, 23 (2000).

[16] V.A. Petrov and A.V. Prokudin, in *Proceedings of the 8th Blois Workshop, EDS'99*, Protvino, Russia, 1999, edited by V. A. Petrov and A.V. Prokudin (World Scientific, Singapore, 2000), p. 95, hep-ph/9912245.

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

[18] R. Fiore, L. Jenkovszky, F. Paccanoni, and A. Papa, Phys. Rev. D **65**, 077505 (2002); R. Fiore, L.L. Jenkovszky, F. Paccanoni, and A. Prokudin, *ibid.* **68**, 014005 (2003).

[19] D.Yu. Ivanov, Phys. Rev. D **53**, 3564 (1996); D.Yu. Ivanov, R. Kirschner, A. Schaäfer, and L. Szymanowski, Phys. Lett. B **478**, 101 (2000).

[20] J.R. Forshaw and G. Poludniowski, Eur. Phys. J. C **26**, 411 (2003).

[21] E. Gotsman, E. Levin, U. Maor, and E. Naftali, Phys. Lett. B **532**, 37 (2002).

[22] J. Breitweg *et al.*, Z. Phys. C **75**, 215 (1997).

[23] S.M. Troshin and N.E. Tyurin, Theor. Math. Phys. **132**, 1172 (2002).
[24] V.A. Matveev, R.M. Muradyan, and A.N. Tavkhelidze, Lett. Nuovo Cimento Soc. Ital. Fis. **7**, 719 (1973); S. Brodsky and G. Farrar, Phys. Rev. Lett. **31**, 1153 (1973).
[25] J. Breitweg *et al.*, Eur. Phys. J. C **2**, 247 (1998); **14**, 213 (2000); C. Adloff *et al.*, Phys. Lett. B **539**, 25 (2002); M. Derrick *et al.*, Z. Phys. C **73**, 253 (1996).
[26] M. Derrick *et al.*, Z. Phys. C **73**, 73 (1996); J. Breitweg *et al.*, Eur. Phys. J. C **14**, 213 (2000).
[27] J. Busenitz *et al.*, Phys. Rev. D **40**, 1 (1989).
[28] M. Derrick *et al.*, Phys. Lett. B **377**, 259 (1996).