Diffractive ϕ and ρ production in a perturbative QCD model

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The elastic leptoproduction of ϕ measured by the H1 Collaboration at DESY HERA is described by a perturbative QCD model, based on open $s\bar{s}$ production and parton hadron duality, proposed by Martin *et al.* We observe that both the total cross section and the ratio of the longitudinal and transverse cross sections are well reproduced with an effective strange-quark mass $m_s \sim 370-400$ MeV for various gluon distribution functions. The possible connection of the effective mass and the momentum dependent dynamical mass associated with dynamical breaking of chiral symmetry is discussed. The ρ leptoproduction data are also well reproduced with an effective quark mass ~ 315 MeV.

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I. INTRODUCTION

Recently the diffractive photoproduction and leptoproduction of vector mesons in electron proton collisions ($e+p \rightarrow e+\gamma^\star+p' \rightarrow e+V+p'$) has drawn considerable attention from experimental (see, e.g., Ref. [1]) as well as theoretical sides [2–9]. As the cross section for the diffractive vector meson production depends (quadratically) on the gluon distribution of the proton, it gives a unique opportunity to study the low x behavior of the gluons inside the proton and to investigate the transition from the perturbative to nonperturbative region. Experimental data for vector meson production at the DESY ep collider HERA [1,10] in the reaction $ep \rightarrow Vep$ are available over a wide range of the virtuality of the photon Q^2, the c.m. energy of $\gamma^\star p$ system W, the mass of the vector mesons m_V, and the square of the four momentum transfer t in the process. The physical picture for the vector meson production is demonstrated through the diagrams in Fig. 1. The virtual (or real) photon fluctuates to quark-antiquark ($q\bar{q}$) pairs, which interacts with the target proton via two gluons exchange. This interaction changes the transverse momenta of the pair, which subsequently hadronizes to a vector meson. It can be shown [11] that the time scale for the interaction of the $q\bar{q}$ with the proton is considerably smaller than the time scale for the $\gamma^\star \rightarrow q\bar{q}$ dissociation and vector meson formation. This leads to the following factorization for the amplitude of diffractive vector meson production:

$$A(\gamma^\star p \rightarrow Vp) = \psi^{\gamma^\star}_{q\bar{q}} \otimes A_{q\bar{q}+p} \otimes \psi^V_{q\bar{q}}, \tag{1}$$

where $\psi^{\gamma^\star}_{q\bar{q}}$ is the wave function of the virtual photon in $q\bar{q}$, $A_{q\bar{q}+p}$ is the amplitude for the $q\bar{q}$-p interaction and $\psi^V_{q\bar{q}}$ is the vector meson wave function.

The process under consideration is governed by the scale $K^2 \sim z(1-z)(Q^2+m_V^2)$, indicating that for large Q^2 and/or m_V^2 the perturbative QCD (PQCD) is applicable to describe the diffractive vector meson production [6,12]. For the production of heavier mesons (J/ψ or Υ) such a process is under control by PQCD even for $Q^2=0$ (photoproduction). A reliable description for the heavy vector meson production is obtained by using Eq. (1), which involves vector meson wave functions [4–6,13]. These wave functions can be obtained by solving Schrödinger equation with nonrelativistic potential model [14]. It has been argued in Ref. [15] that the main uncertainty to the description of the light vector mesons (ρ) production (particularly in the transverse cross section) originates from its wave function. To avoid this problem, Martin *et al.* [15] proposed a model based on the open $q\bar{q}$ production and parton-hadron duality to describe various features of ρ production in diffractive processes. Subsequently the same approach has been used to study the diffractive J/Ψ [16] and Υ production [17]. In Ref. [18] it has been shown that the x and Q^2 behavior of the cross section for diffractive dissociation into $q\bar{q}$ pair and the exclusive vector meson production is similar for $Q^2/(Q^2+M^2) \rightarrow 1$, i.e., when the invariant mass of the pair M is small.

Very recently the experimental data for elastic leptoproduction of ϕ mesons at HERA have been made available by the H1 Collaboration [19]. In the present article we follow Ref. [17] to study the ϕ production at HERA energies. In this approach one first calculates the amplitude for the open

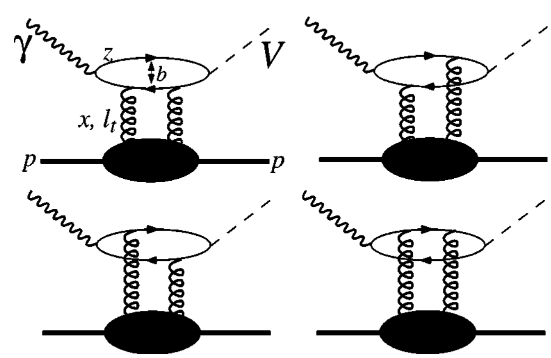

FIG. 1. The diffractive vector meson production in ep collisions. b is the separation between the quark and the antiquark. x and l_t (x' and $-l_t$, not shown in the figure) are the Bjorken-x and transverse momentum of the left (right) gluon, respectively.

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$q\bar{q}$ production, then takes the projection of the amplitude on the $J^P=1^-$ state appropriate for the vector meson quantum numbers and finally integrating over an invariant mass interval such that it contains the resonance peak for the vector meson. The sensitivity of the results on the quark mass is examined. It is found in our analysis that the experimental data for ϕ are well reproduced with effective quark mass, interpolated between the current and the constituent mass. The description of ρ data is reasonably good with quark mass ~ 315 MeV.

The paper is organized as follows. In the next section we discuss the model used in the present work. Section III is devoted to present the results and finally in Sec. IV we give summary and conclusions.

II. PQCD MODEL

The differential cross section for the open $q\bar{q}$ production from a longitudinally (L) or transversely (T) polarized photon can be written as [16,20] (see also Refs. [21,22]),

$$\frac{d\sigma^{L(T)}}{dM^2\,dt}=\frac{2\pi^2 e_q^2\alpha}{3(Q^2+M^2)^2}\int dz\sum_{i,j}|B_{ij}^{L(T)}|^2, \tag{2}$$

where e_q is the charge of the quark flavor q, α is the fine structure constant, M is the invariant mass of the $q\bar{q}$ pair, $z(1-z)$ is the light cone fraction of the photon momentum carried by the quark (antiquark) and $B_{ij}^{L(T)}$ is the helicity amplitude for the dissociation of a $L(T)$ polarized photon into a $q\bar{q}$ pair with helicities i and j, respectively. For transversely and longitudinally polarized photon the amplitudes (for $t=0$) are given by [16]

$$\begin{aligned}
&\mathrm{Im}\,B_{++}^T=\frac{m_q I_L}{2h(z)},\quad \mathrm{Im}\,B_{+-}^T=\frac{-zk_T I_T}{h(z)},\\
&\mathrm{Im}\,B_{-+}^T=\frac{(1-z)k_T I_T}{h(z)},\quad B_{--}^T=0,\\
&\mathrm{Im}\,B_{+-}^L=-\mathrm{Im}\,B_{-+}^L=\sqrt{\frac{Q^2}{2}}h(z)I_L,\\
&B_{++}^L=B_{--}^L=0,
\end{aligned} \tag{3}$$

where $h(z)=\sqrt{z(1-z)}$ and

$$I_L=K^2\int^{K^2}\frac{dl_t^2}{l_t^4}\alpha_s(l_t^2)f(x,x',l_t^2)\left(\frac{1}{K^2}-\frac{1}{K_l^2}\right), \tag{4}$$

$$I_T=\frac{K^2}{2}\int^{K^2}\frac{dl_t^2}{l_t^4}\alpha_s(l_t^2)f(x,x',l_t^2)\left(\frac{1}{K^2}-\frac{1}{2k_T^2}+\frac{K^2-2k_T^2+l_t^2}{2k_T^2K_l^2}\right). \tag{5}$$

m_q is the mass of the quark, $k_T(-k_T)$ is the transverse momentum of the quark (antiquark), $K^2=z(1-z)Q^2+k_T^2+m_q^2$, is the scale probed by the process, $K_l^2=\sqrt{(K^2+l_t^2)^2-4k_T^2l_t^2}$, and α_s is the strong coupling constant. $f(x,x',l_t^2)$ is the skewed (off-diagonal) gluon distribution unintegrated over its transverse momentum l_t. $x\simeq(Q^2+M^2)/(W^2+Q^2)$ and $x'\simeq(M^2-m_V^2)/(W^2+Q^2)(\ll x)$, which indicates that the heavier the mesons the more important is the skewness. In the present article we use diagonal gluon distribution $g(x,l_t^2)$ related to $f(x,l_t^2)$ as follows:

$$f(x,l_t^2)=\frac{\partial[xg(x,l_t^2)]}{\partial\ln l_t^2}. \tag{6}$$

The skewness of the gluon distribution has been taken into account by multiplying the amplitudes by a factor R_g [16]

$$R_g=\frac{2^{2\lambda+3}\Gamma\left(\lambda+\frac{5}{2}\right)}{\sqrt{\pi}\Gamma(\lambda+4)}, \tag{7}$$

where $\lambda\sim\partial\ln[xg(x,Q^2)]/\partial\ln(1/x)$.

The contribution from the infrared region has been obtained by introducing an infrared separation scale l_0^2 [20]:

$$I_L=\alpha_s(l_0^2)xg(x,l_0^2)\left(\frac{1}{K^2}-\frac{2k_T^2}{K^4}\right)+K^2\int_{l_0^2}^{K^2}\frac{dl_t^2}{l_t^4}\alpha_s(l_t^2)f(x,x',l_t^2)\left(\frac{1}{K^2}-\frac{1}{K_l^2}\right), \tag{8}$$

and similarly

$$I_T=\alpha_s(l_0^2)xg(x,l_0^2)\left(\frac{1}{K^2}-\frac{k_T^2}{K^4}\right)+\frac{K^2}{2}\int_{l_0^2}^{K^2}\frac{dl_t^2}{l_t^4}\alpha_s(l_t^2)f(x,x',l_t^2)\left(\frac{1}{K^2}-\frac{1}{2k_T^2}+\frac{K^2-2k_T^2+l_t^2}{2k_T^2K_l^2}\right). \tag{9}$$

The amplitudes $B_{ij}^{L(T)}$ given above are evaluated in the proton rest frame. As the formation of the vector meson takes place in the rest frame of the $q\bar{q}$, it is required to transform the helicity amplitude from the proton rest frame to the $q\bar{q}$ rest frame through the transformation

$$A_{kl}=\sum_{i,j}c_{ik}c_{lj}B_{ij}, \tag{10}$$

where

$$c_{++}=c_{--}=c_{+-}=-c_{-+}=\sqrt{(1-ab)/2}, \tag{11}$$

a_μ is the quark polarization vector in the $q\bar{q}$ rest frame and b_μ is the corresponding quantities in the proton rest frame [17].

Having obtained these values for the amplitudes in the $q\bar{q}$ rest frame we take the projections of these amplitudes in the $J^P=1^-$ states by the following equation:

$$A_{jk}^{L(T)}=\sum_J e_J^{L(T)} d_{1\beta}^J, \tag{12}$$

where $d_{1\beta}^J$ are the spin rotation matrices [23] and $e_J^{L(T)}$ could be obtained by inverting the above relation. The helicity amplitude for diffractive leptoproduction of both light and heavy vector mesons has been performed in Refs. [24,25] and a radically different spin dependence of S and D wave amplitude has been obtained [26]. However, in the present work we will confine ourselves to the S-wave amplitude of open $q\bar{q}$ production only.

The amplitudes given in Eqs. (3) contain only the imaginary part, while the real parts are obtained by using the relation $\mathrm{Re}\,A=\tan(\pi\lambda/2)\,\mathrm{Im}\,A$ [17]. In the present work the next-leading order (NLO) correction has been taken into account by multiplying the amplitudes by a $\mathcal{K}$ factor, $\mathcal{K}=\exp(\pi C_F\alpha_s)$, where the scale used as the argument of α_s is $2K^2$ and $C_F=4/3$. The absolute normalization of the vector meson production cross section depends on the value of the $\mathcal{K}$ factor and the invariant mass window one selects for the integration over dM in Eq. (2). There is some degree of freedom in the choice of these two quantities. However, a reasonably good Q^2 behavior of the cross section and the ratio $R=\sigma_L/\sigma_T$, has been obtained here by constraining these quantities to reproduce the data at a large value of Q^2 ($=14$ and 40 GeV^2 for ϕ and ρ, respectively, where the results are less sensitive to quark mass and infrared scale l_0) and kept fixed for all other values of Q^2. It is also important to mention at this point that for $Q^2\sim 14$ GeV^2 and the invariant mass window for ϕ $[1\leqslant M(\mathrm{GeV})\leqslant 1.04]$ here, the quantity, $\beta[\equiv Q^2/(Q^2+M^2)]\sim 0.9$, where the duality type relationship between the exclusive vector meson production and the diffractive dissociation to $q\bar{q}$ continuum holds good as shown in Ref. [18].

III. RESULTS

The cross section for the ϕ production from longitudinally and transversely polarized photon are obtained by integrating Eq. (2) (with the amplitudes projected in the $J^P=1^-$ state) over an mass interval $1.0\ \mathrm{GeV}\leqslant M\leqslant 1.04$ GeV, as the ϕ meson has been experimentally observed in this invariant mass interval through $\phi\to K\bar{K}$ decay [19]. The t integration has been performed by assuming a t dependence of the cross section $\sim\exp(bt)$, with an average slope, $b=5.2$ GeV^{-2}, taken from experiment [19].

The typical value of x sampled in diffractive ϕ production for $W=75$ GeV is $x\sim 2\times 10^{-4}$. For such a low value of x there is a large ambiguity among various parametrizations of the gluon distributions [27–29]. Therefore, we will show the sensitivity of our results on the gluon distributions. We start with the Glück-Reya-Vogt (GRV98) 1998 (NLO) gluon distribution. In Fig. 2, the Q^2 dependence of the cross section is depicted. For the strange quark mass $m_s=390$ MeV, and the infrared scale $l_0^2=1$ GeV^2, the agreement between the QCD based description and the experimental data is reasonably good. The sensitivity of the cross section on the strange quark mass is evident from the figure. The data can be fitted by appropriately increasing (decreasing) the invariant mass interval for $m_s=400(380)$ MeV, but in the present work we prefer to fix the window in the range $1\leqslant M\leqslant 1.04$ GeV because of the reason mentioned earlier. With current quark mass, $m_s\sim 150$ MeV, it is observed that the theoretical results overestimate the data by a large amount with the above invariant mass window. It is also observed that the data can be well reproduced by a constant $\mathcal{K}$ factor ~ 3.5 with the above invariant mass window and the strange quark mass ~ 390 MeV.

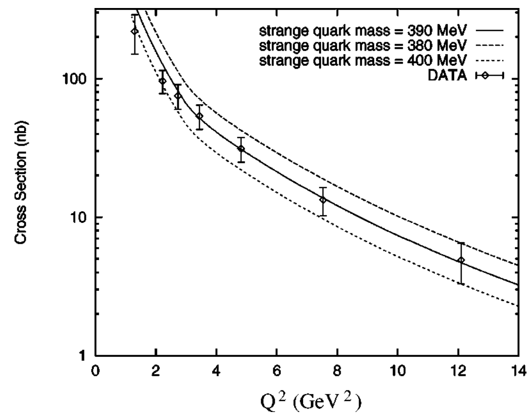

FIG. 2. Diffractive ϕ production cross section as a function of Q^2 at HERA for GRV98(NLO) gluon distribution and for three values of the strange quark masses, $m_s=380$, 390, and 400 MeV. The c.m. energy of the $\gamma^\star p$ system is $W=75$ GeV and $l_0^2=1$ GeV^2.

We note that the experimental data is well reproduced with the strange quark mass $m_s\sim 390$ MeV which is intermediate between the constituent mass ($M_s\sim 500$ MeV) and the current mass ($m_{s,0}\simeq 120$ MeV). At this point we recall the momentum-dependent effective strange-quark mass $m_s(p)$, which interpolates between the constituent mass and the current mass, may be realized through the dynamical breaking of chiral symmetry [30–32]. In particular, for large spacelike momentum $p^2=-P^2<0$ (P^2: large), the operator product expansion for the quark propagator yields the asymptotic behavior [31]

$$m_s(P)=m_{s,0}(\mu)\left(\frac{\alpha_s(P)}{\alpha_s(\mu)}\right)^d+\frac{16\pi\alpha_s(P)}{P^2}|\langle\bar{\psi}\psi(\mu)\rangle|\left(\frac{\alpha_s(P)}{\alpha_s(\mu)}\right)^{-d}, \tag{13}$$

where $d(=12/27$ for $N_f=3)$ is the mass anomalous dimension, μ is the renormalization point and $\langle\bar{\psi}\psi(\mu)\rangle$ is the chiral vacuum condensate.

In Fig. 3, the asymptotic form of $m_s(P)$ as a function of the spacelike momentum P is shown, where $m_{s,0}(2\ \mathrm{GeV})=118.9\pm 12.2$ MeV, $m_{u,0}(2\ \mathrm{GeV})=3.5\pm 0.4$ MeV, $m_{d,0}(2\ \mathrm{GeV})=6.3\pm 0.8$, and $m_\pi^2 f_\pi^2\simeq-(m_u+m_d)\langle\bar{\psi}\psi\rangle$ are

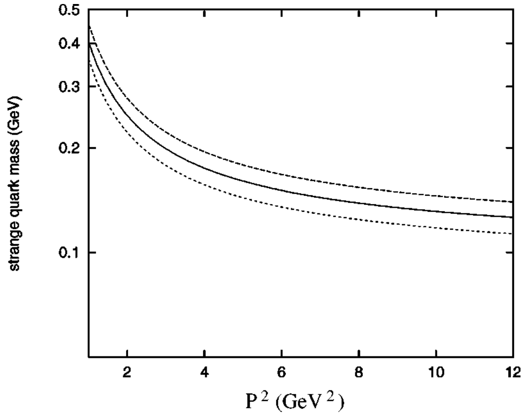

FIG. 3. The variation of the strange quark mass as a function of P^2 in the spacelike domain taking into account the uncertainty of the current masses $m_{u,0}$(2 GeV) $=3.5\pm0.4$ MeV, $m_{d,0}$(2 GeV) $=6.3\pm0.8$ MeV, and $m_{s,0}$(2 GeV) $=118.9\pm12.2$ MeV (see text). These current masses are taken from Ref. [33].

taken from Narison [33]. To obtain $m_s(P)$ for an entire domain of spacelike and timelike momenta, one needs to solve the Schwinger-Dyson equation for quark propagator with suitable assumption on the gluon propagator and the quark-gluon vertex at low energies (see, e.g., Refs. [32,34,35]). In that case, $m_s(P)$ is expected to be a smooth interpolation between the asymptotic behavior Eq. (13) at large P^2 and the constituent mass $M_s \simeq 500$ MeV at $P\sim 0$. In our diffractive process, we need $m_s(P)$ in the entire domain of P in principle, since the quarks with spacelike momentum are initially produced by the spacelike photon ($Q^2<0$) and they eventually become timelike after the *kick* by the gluons inside the proton (see Fig. 1). The quark mass, we have found in our analysis, $m_s \sim 390$ MeV, which is smaller than M_s but is larger than $m_{s,0}$, may thus be interpreted as an effective mass averaged over momentum relevant for the diffractive process shown in Fig. 1.

In Fig. 4 we show the ratio $R=\sigma_L/\sigma_T$ as a function of Q^2. The theoretical calculation shows the correct trend. Putting the constraint on the strange quark mass and the infrared scale from the experimental data shown in Fig. 2, we evalu-

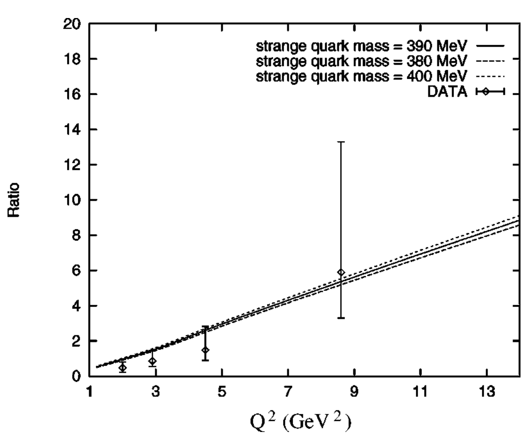

FIG. 4. The ratio $R=\sigma_L/\sigma_T$ as a function of Q^2 for GRV98(NLO) gluon distribution for $l_0^2=1$ GeV^2.

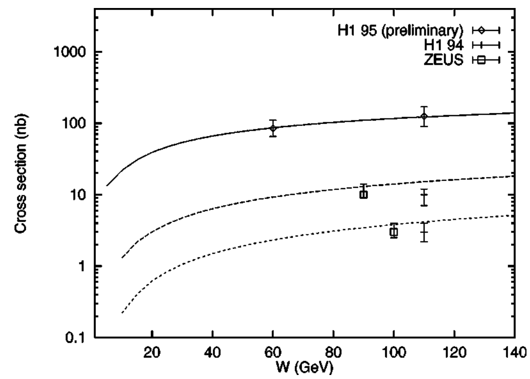

FIG. 5. The cross section for ϕ production as a function of W for $Q^2=$ 2.5 (solid line), 8.3 (dashed line), and 14.6 GeV^2 (dotted line) for GRV98(NLO) gluon distribution with $l_0^2=1$ GeV^2 and $m_s=390$ MeV.

ate the W dependence of the cross section for various values of Q^2. The agreement between the experimental data (taken from Ref. [1]) and the theoretical calculation is satisfactory, as shown in Fig. 5. In Fig. 6 we show the results for various values of l_0^2 with $m_s=390$ MeV. Results obtained for $l_0^2=1.5$ and 2 GeV^2 start deviating from the experimental value at small Q^2.

In Fig. 7 we show the Q^2 behavior of the cross section for different gluon distribution functions. The value of the infrared scale l_0^2 and strange quark mass m_s are 1.5 GeV^2 and 370 MeV, respectively. Although GRV98(NLO) gluon distribution overestimates, the predictions with Martin-Roberts-Stirling-Thorne 1999 (MRST99) and CTEQ5M gluon distributions are in agreement with the experimental results.

With smaller values of $m_s \sim 150$ MeV, however, we fail to describe the data provided the invariant mass window is kept fixed at $1\leqslant M\leqslant 1.04$ GeV, where the ϕ has been measured experimentally. Figure 8 indicates the variation of σ_L/σ_T as function of Q^2 for CTEQ5M, GRV98(NLO), and MRST gluon distributions, the ratio seems to be less sensitive to the parametrization of the gluon distributions.

In Fig. 9 we show the elastic leptoproduction cross section of ρ meson for $W=75$ GeV as a function of Q^2. The

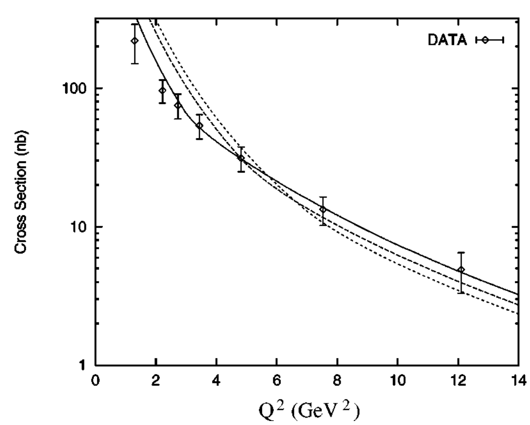

FIG. 6. The cross section for ϕ production as a function of Q^2 for $W=75$ GeV with GRV98 (NLO) gluon distribution for $l_0^2=1$ (solid line), 1.5 (dashed line), and 2 GeV^2 (dotted line) with $m_s=390$ MeV.

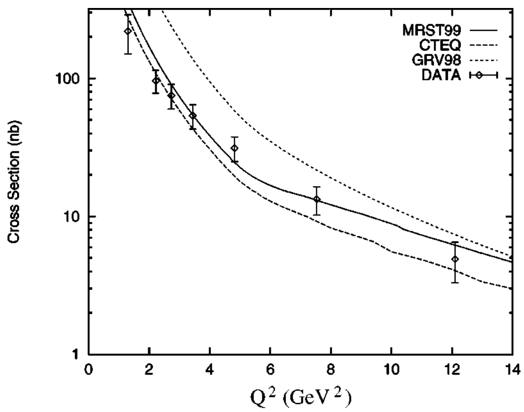

FIG. 7. Diffractive production of ϕ at HERA for various parametrizations of gluon distribution function. $m_s = 370$ MeV and $l_0^2 = 1.5$ GeV^2 are adopted.

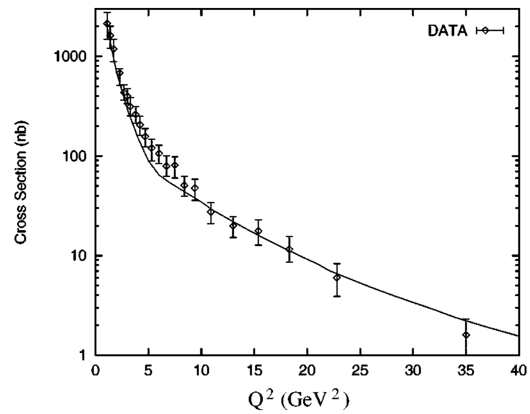

FIG. 9. ρ production cross section as function of Q^2, for MRST gluons for $m_q = 315$ MeV and $l_0^2 = 1.5$ GeV^2. Data taken from Ref. [36].

theoretical result is obtained by integrating over the invariant mass window $0.63 \leqslant M(\mathrm{GeV}) \leqslant 1.08$ with effective quark mass, $m_u = m_d \equiv m_q = 315$ MeV and $l_0^2 = 1.5$ GeV^2. The slope parameter for the t dependence is taken as 5.5 GeV^{-2} [36]. The theoretical prediction describe the data well up to a value of Q^2 as low as ~ 1 GeV^2. It is observed that the data cannot be reproduced with quark mass $m_q \sim 100$ MeV or below for low value of Q^2. For $Q^2 > 5$ GeV^2 the cross section is not sensitive to the value of l_0^2 which is in agreement with Ref. [15], but for lower Q^2 the result is sensitive to l_0^2.

In Fig. 10 we depict the ratio σ_L/σ_T for ρ. Although experimental data [36] shows a tendency of saturation at higher Q^2, the theoretical results indicate a slow growth. However, inclusion of quark off-shellness and Fermi motion lead to the saturation at higher Q^2 [7]. It is also evident from Fig. 10 that for low Q^2, current quark mass cannot reproduce the data. We recall that an effective quark mass ~ 280 MeV has recently been used to extract the dipole cross section from photo and leptoproduction data [37] and the importance of an effective quark mass has been emphasized for low value of Q^2.

IV. SUMMARY AND CONCLUSIONS

We have studied the diffractive ϕ production at HERA energies measured by the H1 Collaboration within the ambit of PQCD model based on parton hadron duality. The effects of the off-diagonal gluon distribution and the NLO corrections through the $\mathcal{K}$ factor have been incorporated. The sensitivity of the results on the infrared separation scale and the various parametrizations of the gluon distribution have been discussed. It is found that, with reasonable choice of the infrared scale, the total cross section and the ratio σ_L/σ_T are well described in the present framework with an effective strange quark mass $m_s \sim 370 - 400$ MeV. Such a value of the strange quark mass, which lies between constituent and current quark masses may be closely related to the momentum-dependent dynamical mass associated with the dynamical breaking of chiral symmetry in QCD. For the leptoproduction of ρ, at low values of Q^2, the effects of quark mass have also been emphasized.

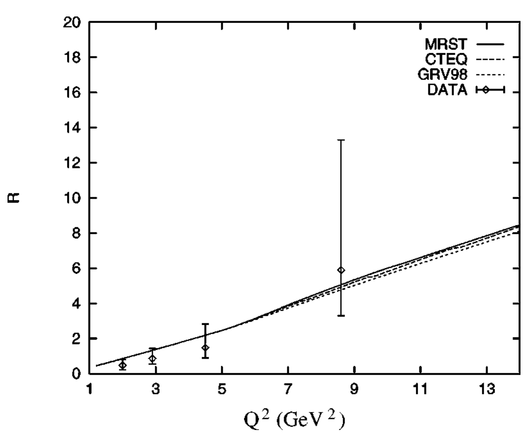

FIG. 8. The ratio $R = \sigma_L/\sigma_T$ as a function of Q^2 for various parametrizations of the gluon distribution function with $m_s = 370$ MeV and $l_0^2 = 1.5$ GeV^2.

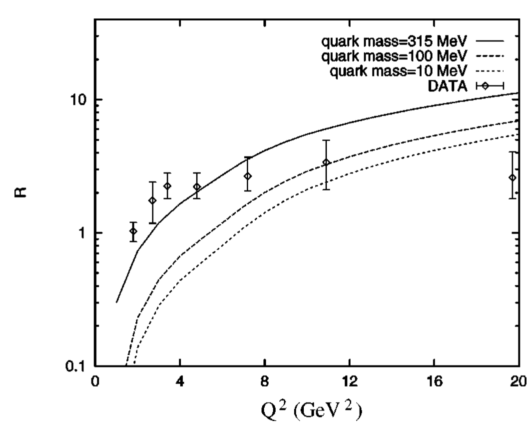

FIG. 10. The ratio $R = \sigma_L/\sigma_T$ for ρ as a function of Q^2 for MRST parametrization of the gluon distribution function with $m_q = 315$, 100, and 10 MeV for $l_0^2 = 1.5$ GeV^2. Data taken from Ref. [36].

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[1] H. Abramowicz and A. Caldwell, Rev. Mod. Phys. **71**, 1275 (1999).
[2] A. Hebecker, Phys. Rep. **331**, 1 (2000).
[3] A. Donnachie and P. V. Landshoff, Phys. Lett. B **185**, 403 (1987); **198**, 590(E) (1987); Nucl. Phys. **B311**, 509 (1989).
[4] B. Z. Kopeliovich, J. Nemchick, N. N. Nikolaev, and B. G. Zakharov, Phys. Lett. B **309**, 179 (1993).
[5] J. Nemchick, N. N. Nikolaev, E. Predazzi, and B. G. Zakharov, Z. Phys. C **75**, 71 (1997).
[6] S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller, and M. Strikman, Phys. Rev. D **50**, 3134 (1994).
[7] I. Royen and J. R. Cudell, Nucl. Phys. **B545**, 505 (1999).
[8] K. Suzuki, A. Hayashigaki, K. Itakura, J. Alam, and T. Hatsuda, Phys. Rev. D **62**, 031501 (2000).
[9] P. Hoyer and S. Peigne, Phys. Rev. D **61**, 031501(R) (2000).
[10] H1 Collaboration, C. Adloff *et al.*, Eur. Phys. J. C **10**, 373 (1999).
[11] M. Wüsthoff and A. D. Martin, J. Phys. G **25**, R309 (1999).
[12] J. C. Collins, L. Frankfurt, and M. Strikman, Phys. Rev. D **56**, 2982 (1997).
[13] L. Frankfurt, W. Koepf, and M. Strikman, Phys. Rev. D **57**, 512 (1998).
[14] E. J. Eichten and C. Quigg, Phys. Rev. D **52**, 1726 (1995).
[15] A. D. Martin, M. G. Ryskin, and T. Teubner, Phys. Rev. D **55**, 4329 (1997); **56**, 3007 (1997).
[16] A. D. Martin, M. G. Ryskin, and T. Teubner, Phys. Rev. D **62**, 014022 (2000).
[17] A. D. Martin, M. G. Ryskin, and T. Teubner, Phys. Lett. B **454**, 339 (1999).
[18] M. Genovese, N. N. Nikolaev, and B. G. Zakharov, Phys. Lett. B **380**, 213 (1996).
[19] H1 Collaboration, C. Adloff *et al.*, Phys. Lett. B **483**, 360 (2000).
[20] E. M. Levin, A. D. Martin, M. G. Ryskin, and T. Teubner, Z. Phys. C **74**, 671 (1997).
[21] M. Genovese, N. N. Nikolaev, and B. G. Zakharov, Phys. Lett. B **378**, 347 (1996).
[22] J. Bartels, H. Lotter, and M. Wüsthoff, Phys. Lett. B **379**, 239 (1996); **382**, 449 (1996).
[23] A. R. Edmonds, *Angular Momentum in Quantum Mechanics* (Princeton University Press, Princeton, 1957).
[24] D. Yu. Ivanov and R. Kirschner, Phys. Rev. D **58**, 114026 (1998).
[25] E. V. Kuraev, N. N. Nikolaev, and B. G. Zakharov, Pis'ma Zh. Eksp. Teor. Fiz. **68**, 667 (1998) [JETP Lett. **68**, 696 (1998)].
[26] I. P. Ivanov and N. N. Nikolaev, JETP Lett. **69**, 294 (1999).
[27] H. L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).
[28] M. Glück, E. Reya, and A. Vogt, Eur. Phys. J. C **5**, 461 (1998).
[29] A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Eur. Phys. J. C **14**, 133 (2000).
[30] H. Georgi and H. D. Politzer, Phys. Rev. D **14**, 1829 (1976).
[31] H. D. Politzer, Nucl. Phys. **B117**, 397 (1976).
[32] K. Higashijima, Phys. Rev. D **29**, 1228 (1984); Prog. Theor. Phys. Suppl. **87**, 441 (1992).
[33] S. Narison, Nucl. Phys. B (Proc. Suppl.) **86**, 242 (2000); J. Gasser and H. Leutwyler, Phys. Rep. **87**, 77 (1982).
[34] R. Fukuda and T. Kugo, Nucl. Phys. **B117**, 250 (1976); A. Bender and R. Alkofer, Phys. Rev. D **53**, 446 (1996).
[35] C. Roberts and A. G. Williams, Prog. Part. Nucl. Phys. **33**, 477 (1994).
[36] H1 Collaboration, C. Adloff *et al.*, Eur. Phys. J. C **13**, 371 (2000).
[37] J. R. Forshaw, G. Kerley, and G. Shaw, Phys. Rev. D **60**, 074012 (1999).