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Vector meson J/ψ, ϕ electro-production in QCD *

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Abstract We study the vector meson electro-production off the proton in a QCD inspired model. A calculation of the differential cross section is performed for the J/ψ, ϕ meson off the proton. The theoretical results are consistent with the experimental data, and remind us to consider the contribution from the tensor glueball and Odderon to the differential cross section. Since gluons interact among themselves via self-interaction, the gluons can form a glueball with quantum numbers I^G, $J^{PC}=0^+$, 2^{++}, with a decay width $\Gamma_t=100$ MeV and mass of $m_{\rm G}=2.23$ GeV. The three gluons can form a three gluon color bound state with charge conjugation quantum number $C=-1$. This study is quite important to verify the validity of QCD and to search for new particles (tensor glueball and Odderon) as well as quest for new physics.

Key words vector meson electro-production, quark, gluon, Odderon

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1 Introduction

Vector meson electro-production provides an interesting laboratory for studying the interplay between perturbative and nonpertubative QCD. A microscopic understanding of vector meson electro-production remains an elusive goal of hadronic physics. Two experiments at the H1 [1] and Zeus [2, 3] have measured the high energy γ^*p differential cross section. In recent years many more data have been obtained in HERA experiments with high accuracy and statistics and their comparison with theoretical calculation provides an opportunity to understand and describe important general features of the dynamics governing these processes. We can learn about the quark gluon structure of hadrons and it offers an opportunity to search for new physics and new particles such as the quest for the H-particle, Higgs, Glueball and Odderon.

Various models have been proposed to describe the dynamics of vector meson electro-production. Among them, the Pomeron theory [4] is one of the most successful descriptions of the high energy vector meson dynamics and produces a successful understanding of the existing data. It investigates the virtual photon-proton interaction by studying general properties of the S-matrix for vector meson electro-production off the proton. Based on the Pomeron exchange model, vector meson electro-production off the proton is investigated with both a linear and a non-linear Pomeron trajectory. It should be emphasized that unlike the Raggeon trajectory for known particles, which would provide the resonances for integer values of $\alpha(t)$ for positive t, the pomeron has not been conclusively identified. But the Pomeron exchange model can not describe the experimental differential cross sections if the energy becomes too high a range, where new experimental data recently became available. The origin and nature of the Pomeron has not been known so far and the Pomeron coupling to the proton has a vector form, γ^μ, similar to that of the $C=+1$ isoscalar photon, which is in contradiction to the vacuum property of the Pomeron. It is just a phenomenological object to describe the diffractive processes.

Within Quantum ChromoDynamics (QCD) hadrons are described in terms of quarks, anti-quarks and gluons. Correctly speaking, the quantum numbers of the meson are the same as those of the photon. The usual, well-known vector mesons are supposed to

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contain quarks and anti-quarks which, produced by the virtual photon, leads to a description of the vector meson electro-production off the proton in QCD via the virtual photon and the proton interaction.

The principles of analyticity, unitarity and crossing symmetry are truly fundamental to our understanding of particle physics. A requirement of analyticity is that the forward scattering amplitudes for vector meson electro-production off the proton come from the same analytic function as $J(s,t)$, $F_{\gamma^*\mathrm{p}}(s,t)=\lim_{\varepsilon\to 0}J(s+\mathrm{i}\varepsilon,t)$ [5]. Further, unitarity provides a relationship between the total cross section and the imaginary part of the forward scattering amplitude - the optical theorem. Cheng and Wu [6] proposed initialy that eikonalization should properly unitarize Regge models. Now we used a QCD-inspired eikonal model to predict the differential cross section for the vector meson J/ψ and ϕ appropriate to the energies of Zeus and H1. Using the impact parameter representation, the QCD-inspired model predicts the experimental data in terms of the elementary scattering theory of non relativistic quantum mechanics.

Our paper consists of 5 parts. In Sect. 2 we explain the QCD inspired model. In Sect. 3 we describe the QCD mechanism of the vector meson electro-production off the proton $\gamma^*+\mathrm{p}\to\mathrm{V}+\mathrm{p}$. The differential cross sections for the vector meson J/ψ, ϕ electro-production is calculated in Sect. 4. The summary and concluding remarks are reserved for Sect. 5.

2 QCD inspired model

2.1 Amplitude $F_{\gamma^*\mathrm{p}}(s,t)$, total cross section $\sigma_{\mathrm{tot}}^{\gamma^*\mathrm{p}}(s)$ and differential cross section $[\frac{\mathrm{d}\sigma}{\mathrm{d}t}]_{\gamma^*\mathrm{p}}$ of $\gamma^*\mathrm{p}$ elastic scattering

We start our investigations by considering the following two body elastic scattering process

$$\mathrm{a}+\mathrm{b}\to\mathrm{a}+\mathrm{b} \tag{1}$$

in the s-channel with amplitude $F^{\mathrm{ab}}(s,t)$. The related two body elastic scattering process in the u-channel

$$\mathrm{a}+\bar{\mathrm{b}}\to\mathrm{a}+\bar{\mathrm{b}}, \tag{2}$$

with its amplitude $F^{\mathrm{a}\bar{\mathrm{b}}}(s,t)$ can be obtained from the former, Eq. (1), by crossing to the u-channel, Eq. (2), via the crossing symmetry relationship

$$F^{\mathrm{a}\bar{\mathrm{b}}}(s,t,u)=F^{\mathrm{ab}}(u,s,t), \tag{3}$$

where s,t,u are the Mandelstam variables. It is important to notice the order of variables s, t, and u in both side of Eq. (3).

Let us now define two new amplitudes $F_\pm$ by $F^{\mathrm{ab}}(s,t)$ and $F^{\mathrm{a}\bar{\mathrm{b}}}(s,t)$ in such a way that

$$F_\pm(s,t)=\frac{1}{2}[F^{\mathrm{ab}}(s,t)\pm F^{\mathrm{a}\bar{\mathrm{b}}}(s,t)]. \tag{4}$$

Under the crossing from the s-channel process, Eq. (1), to the u-channel, Eq. (2), the amplitude $F_+(s,t)$ evidently remains unchanged whereas the amplitude $F_-(s,t)$ changes its sign. Accordingly, they are called even under-crossing and odd under-crossing amplitudes, respectively.

So the amplitude of the proton-proton elastic scattering at high energies is defined as:

$$F_{\mathrm{pp}}(s,t)=F_+(s,t)+F_-(s,t). \tag{5}$$

Since we study vector meson electro-production off a proton at high energies, the amplitude $F_{\gamma^*\mathrm{p}}(s,t)$ is similarly defined

$$F_{\gamma^*\mathrm{p}}(s,t)=F_+^{\gamma^*\mathrm{p}}(s,t)+F_-^{\gamma^*\mathrm{p}}(s,t). \tag{6}$$

Assuming that $F_{\gamma^*\mathrm{p}}(s,t)$ is a general scattering amplitude, the total cross section $\sigma_{\mathrm{tot}}^{\gamma^*\mathrm{p}}(s)$ and the differential cross section $\left[\frac{\mathrm{d}\sigma(s,t)}{\mathrm{d}t}\right]_{\gamma^*\mathrm{p}}$ can be normalized in such a way that [7]

$$\sigma_{\mathrm{tot}}^{\gamma^*\mathrm{p}}(s)=\frac{P_{\mathrm{had}}^{\gamma^*\mathrm{p}}}{s}\mathrm{Im}F_{\gamma^*\mathrm{p}}\ (s,t=0), \tag{7}$$

$$\left[\frac{\mathrm{d}\sigma(s,t)}{\mathrm{d}t}\right]_{\gamma^*\mathrm{p}}=\frac{P_{\mathrm{had}}^{\gamma^*\mathrm{p}}}{16\pi s^2}\,|\,F_{\gamma^*\mathrm{p}}(s,t)\,|^2, \tag{8}$$

where $P_{\mathrm{had}}^{\gamma^*\mathrm{p}}$ is an appropriate probability for the virtual photon to turn into a vector meson. Eqs. (7,8) are the fundamental formulae of our present study of vector meson electro-production off proton at high energies. According to Eq. (6), to calculate the scattering amplitudes $F_{\gamma^*\mathrm{p}}(s,t)$ we have, at first, to work out the amplitudes $F_\pm^{\gamma^*\mathrm{p}}(s,t)$.

2.2 Crossing even and odd eikonal profile functions $\chi_\pm(b,s)$

Eq. (5) indicates that to calculate $F_{\mathrm{pp}}(s,t)$, one must figure out the $F_\pm(s,t)$ at first. According to Glauber multiple scattering theory [8], which is an accurate, simple approximation to describe high energy hadron scattering, the $F_\pm(s,t)$ can be expressed by their corresponding eikonal profile functions $\chi_\pm$. Therefore, let us now set up the relationship of $F_\pm(s,t)$ with the eikonal profile functions $\chi_\pm$, and then we study $\chi_\pm(b,s)$ instead of $F_\pm(s,t)$ in this subsection. The total eikonal profile function χ is defined in such a way that the complex interacting amplitude $A(b,s)$ in the impact parameter space $\vec{b}$ is formulated as

$$A(b,s)=\frac{\mathrm{i}}{2}(1-\mathrm{e}^{\mathrm{i}\chi})\cong\frac{1}{2}\chi\ . \qquad (9)$$

Therefore, according to Ref. [6], if $A(b,s)$ is given, the scattering amplitude $F_{\pm}(s,t)$ in the center-of-mass system can be written as

$$F_{\pm}(s,t)=\frac{k}{\pi}\int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{b}}A(b,s)\mathrm{d}^2\vec{b}\cong\frac{k}{2\pi}\int \mathrm{d}^2\vec{b}\mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{b}}\chi_{\pm}. \quad (10)$$

Eq. (10) is the relationship between $F(s,t)$ and $\chi_{\pm}$ that we wanted to set up. With $\chi_{\rm even}=\chi_{+}$, $\chi_{\rm odd}=\chi_{-}$ and $\chi_{\rm pp}=\chi_{\rm even}+\chi_{\rm odd}$, where $\chi_{\rm even}$ ($\chi_{\rm odd}$) denotes the crossing even (odd) profile function of the scattering. k in Eq. (10) is the momentum in the center-of-mass system of the incident proton and target nucleon system. To guarantee unitarity, we introduce in Eq. (10) the eikonal formulism in the two-dimensional transverse impact parameter space $\vec{b}$. Here $\mathrm{d}^2\vec{b}=2\pi b\mathrm{d}b$ and $\vec{q}$ is a two-dimensional vector in space $\vec{b}$ and $q^2=-t$ with $t=-2k^2(1-\cos\theta)$ being the invariant four-momentum transfer. θ is the scattering angle in the center-of-mass system.

2.3 Even eikonal profile function $\chi_{\rm even}$ in the QCD inspired model

"By QCD inspired model" [7] here means that we study profile functions $\chi_{\pm}(b,s)$ by consideration of quark and gluon degrees of freedom and the contributions from color-balls to hadronic interactions. A detailed description of pp and $\bar{\rm p}$p scattering eikonal profile functions of $\chi_{\rm even}(b,s)$ and $\chi_{\rm odd}(b,s)$ is now necessarily required. The scattering amplitude must be analytic, unitary, and satisfies crossing symmetry as well as the Froissart bounding [9]. Let us now at first figure out the expression of $\chi_{\rm even}(b,s)$ theoretically. The QCD inspired theory of high energy baryon-baryon scattering [7] tells us that the even eikonal profile functions $\chi_{\rm even}$ for pp and $\bar{\rm p}$p elastic scattering in QCD can be given by summing three contributions from the quark-quark and the gluon-gluon interactions and the quark-gluon interference terms. They are individually factorized into a product of a cross section $\sigma(s)$ times an impact parameter space distribution function $W(b,\mu)$, that is

$$\begin{aligned}\chi_{\rm even} &= \chi_{\rm qq}(b,s)+\chi_{\rm gg}(b,s)+\chi_{\rm qg}(b,s)=\\ &\mathrm{i}[\sigma_{\rm qq}(s)W(b;\mu_{\rm qq})+\sigma_{\rm gg}(s)W(b;\mu_{\rm gg})+\\ &\sigma_{\rm qg}(s)W(b;\sqrt{\mu_{\rm qq}\mu_{\rm gg}})]. \qquad (11)\end{aligned}$$

The factor i has been inserted in the second line of Eq. (11) since the high energy eikonal profile function is largely imaginary. The impact parameter space distribution functions $W(b,\mu)$ used in Eq. (11) are taken to be convolutions of two dipole form factors, i.e. we parameterize $W(b;\mu)$ as the Fourier transform of two dipole form factors of the nucleon [10]:

$$W(b;\mu)=\frac{\mu^2}{96\pi}(b\mu)^3K_3(b\mu), \qquad (12)$$

where $K_3(x)$ is a modified Bessel function of the second kind. In the QCD inspired model it allows us to reformulate the Froissart bounding from axiomatic field theory. We found that the asymptotic total cross section contributed from the gluon-gluon interaction term can be given by [7]

$$\sigma_{\rm gg}=2\pi\left(\frac{\varepsilon}{\mu_{\rm gg}}\right)^2\lg^2\frac{s}{s_0}. \qquad (13)$$

The quark-quark interaction is simulated by a constant cross section plus a Regge-even falling cross section which can be approximated by

$$\sigma_{\rm qq}=\Sigma_{\rm gg}\left(C+C^{\rm even}_{\rm Regge}\frac{m_0}{\sqrt{s}}\right), \qquad (14)$$

where m_0 is the threshold mass which is determined by experiment and has the value of $m_0=0.6$ GeV. The contribution from the quark-gluon interference term is also simulated by

$$\sigma_{\rm qg}(s)=\Sigma_{\rm gg}C^{\rm log}_{\rm qg}\lg\frac{s}{s_0}\ . \qquad (15)$$

2.4 Odd eikonal profile function $\chi_{\rm odd}$ in the QCD inspired model

The odd eikonal profile function $\chi_{\rm odd}=-\mathrm{i}\sigma_{\rm odd}W(b,\mu)$ accounts for the difference between pp and p$\bar{\rm p}$ elastic scattering, $\chi_{\rm pp}=\chi_{\rm even}+\chi_{\rm odd}$ and $\chi_{p\bar{p}}=\chi_{\rm even}-\chi_{\rm odd}$, and must vanish at high energies. A Regge behaved analytic odd eikonal profile function $\chi_{\rm odd}(b,s)$ can be well parameterized as follows [5]

$$\begin{aligned}\chi_{\rm odd}(b,s) &= -\mathrm{i}\sigma_{\rm odd}(s)W(b,\mu_{\rm odd})=\\ &-\mathrm{i}C_{\rm odd}\Sigma_{\rm gg}\frac{m_{\rm o}}{\sqrt{s}}W(b,\mu_{\rm odd}), \qquad (16)\end{aligned}$$

where $W(b;\mu_{\rm odd})$ is determined by experiments and the normalization constant $C_{\rm odd}$ has to be fitted.

Table 1. The parameters used in our calculations to fitted experimental data [11].

fixed	fitted
$m_0=0.6$ GeV	$C=5.65\pm0.14$
$\epsilon=0.3$	$C^{\rm log}_{\rm qg}=0.0167\pm0.0037$
$\mu_{\rm qq}=0.89$ GeV	$\Sigma_{\rm gg}=9\pi\alpha_{\rm s}^2/m_0^2$
$\mu_{\rm gg}=0.73$ GeV	$C^{\rm even}_{\rm Regge}=25.3\pm2.0$
$\mu_{\rm odd}=0.53$ GeV	$C_{\rm odd}=-(7.62\pm0.28)$
$\alpha_{\rm s}=0.5$	$s_0=1.0$ GeV^2

The parameters in the above equations, Eqs. (13, 14, 15, 16), are given in Table 1. It should be emphasized that the physical meaning of the odd eikonal profile function is completely different from the even one.

3 QCD mechanism of $\gamma^*+\mathrm{p}\rightarrow\mathrm{V}+\mathrm{p}$

3.1 Generalized vector meson dominance theory

Ref. [12] simply defines the diffraction in the following way: "every reaction in which no quantum numbers are exchanged between high energy colliding particles is dominated asymptotically by diffraction". According to the above definition of diffraction, vector meson electro-production, as shown in Fig. 1(a), is a purely diffractive process. We take the vector meson electro-production off the proton shown in Fig. 1(a) as an example. In this case we have in fact $J_{\mathrm{V}}^{PC}=1^{--}$ for the outgoing vector meson and like for the incoming virtual photon γ^*, $J_{\gamma^*}^{PC}=1^{--}$. Therefore, no quantum numbers are exchanged between the virtual photon (γ^*) and the target proton and this process is manifestly diffractive. In Fig. 1(a) the virtual photon -proton interaction is replaced by the interaction of a quark-antiquark pair with the target proton. What is the reason? We answer this question by simply introducing the vector meson dominance model for the virtual photon and proton interaction.

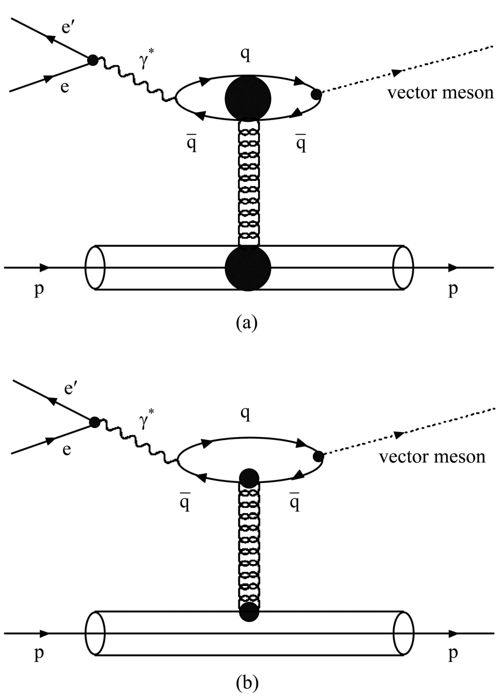

Fig. 1. (a) QCD mechanism of vector meson electro-production in the $\gamma^*+\mathrm{p}\rightarrow\mathrm{V}+\mathrm{p}$ reaction. (b) Vector meson electro-production in the $\gamma^*+\mathrm{p}\rightarrow\mathrm{V}+\mathrm{p}$ reaction with quark-quark interaction contribution.

Gribov [13] was the first one to observe that a photon (even a virtual photon) fluctuates into a hadron system with a life time (coherence length)

$$\tau=l_{\mathrm{c}}=\frac{1}{mx_{\mathrm{B}}},\quad x_{\mathrm{B}}=\frac{Q^2}{s}\ ,\tag{17}$$

where Q^2 is the photon virtuality (momentum) and m is the mass of the target nucleon. We can consider the virtual photon-hadron interaction as a process which proceeds in two stages as shown in Fig. 1(a).

(1) Transition γ^* into hadrons is not affected by the target hadron, therefore, it looks similar to electron-positron annihilation;

(2) Hadron–target interaction, which can be treated as standard hadron-hadron interaction, for example, in the Odderon exchange approach.

In $\mathrm{e}^+\mathrm{e}^-$ the annihilation the hadron total cross section, defines:

$$R(M^2)=\frac{\sigma(\mathrm{e}^+\mathrm{e}^-\rightarrow\mathrm{allhadrons})}{\sigma(\mathrm{e}^+\mathrm{e}^-\rightarrow\mu^+\mu^-)}.\tag{18}$$

Experimentally $R(M^2)$ can be described in a two-component picture: The contribution of resonances such as ρ, ω, J/ψ, ϕ, ϒ and so on, and the contribution from quarks which give a more or less constant term that changes abruptly with every new open quark-antiquark channel. $R(M^2)\approx 3\Sigma_{\mathrm{q}}e_{\mathrm{q}}^2$, where e_{q} is the charge of the quark and the summation extends over all active quark terms. If we take into account only the the contribution of the ρ-meson, ω-meson, J/ψ-meson, ϕ meson in $R(M^2)$, it is the so-called vector meson dominance model (VMD).

The VMD model expresses the virtual photon-hadron scattering cross section in terms of the vector meson-hadron scattering cross section. In VMD language the virtual photon fluctuates into a quark-antiquark pair which can be though of as the superposition of various vector meson states $\mathrm{V}(\rho,\omega,\phi,\mathrm{J}/\psi,\Upsilon\cdots)$. The model assume that the hadronic components of the vacuum polarization of the photon consist exclusively of the known vector mesons $(\rho,\omega,\phi,\mathrm{J}/\psi,\Upsilon)$.

3.2 Vector meson electro-production in the QCD inspired model

The vector meson electro-production in the $\gamma^*+\mathrm{p}\rightarrow\mathrm{V}+\mathrm{p}$ reaction is a pure diffractive process and offers a variety of insights into the diffractive mechanism. The QCD inspired theory of high energy baryon-baryon scattering [6] tells us that the mechanism of the proton-proton interaction in QCD can be given by the summation of three contributions, the quark-quark, gluon-gluon interactions and quark-gluon interference terms. Thus we can assume that the QCD mechanism of the vector meson electro-production consists of quark-quark, gluon-gluon interactions and quark-gluon interference contributions. We assume that the virtual photon behaves like a quark and antiquark system when it interacts strongly.

Based on QCD theory and vector meson dominance, we propose a QCD inspired model here. The diagrammatic representation of the model is illustrated in Fig. 1(a). The virtual photon-proton interaction will in fact be replaced by the interaction of a quark-antiquark pair with the proton target which consists of three valence quarks. The wiggle line stands for the virtual photon with quantum number 1^{--}, the solid line denotes the quark-antiquark as a symbol in the figure, the dashed line represents the produced vector meson in the figure. The whirly line stands for the gluon which carries whimsical particles(tensor glueball or Odderon) and finally the three-solid line represents the proton and V stands for vector mesons such as $\rho, \omega, \phi, J/\psi, \Upsilon$ produced by the $\gamma^* + p$ interaction.

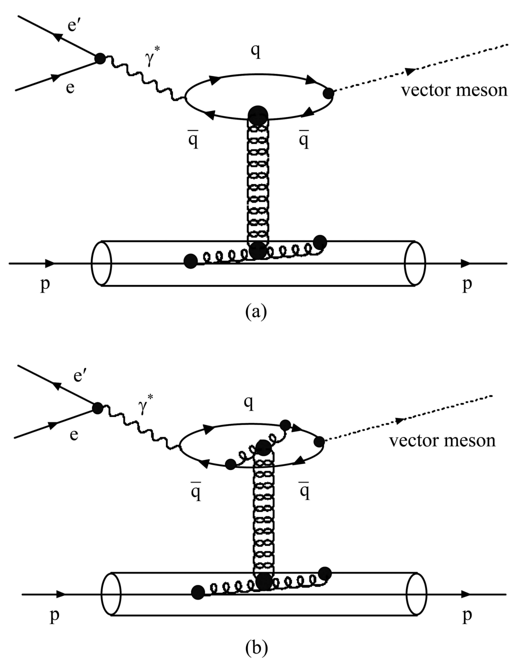

Fig. 2. (a) Vector meson electro-production in the $\gamma^* + p \to V + p$ reaction with quark-gluon interference contribution. (b) Vector meson electro-production in the $\gamma^* + p \to V + p$ reaction with gluon-gluon interaction contribution.

The vector meson electro-production in the $\gamma^* + p \to V + p$ reaction with quark-quark interaction contribution is given in Fig.1(b) and the contribution from the quark-gluon interference in the $\gamma^* + p \to V + p$ reaction is shown in Fig. 2(a). We also estimate the gluon-gluon contribution to the differential cross section from diagrams as shown in Fig. 2(b). Since gluons interact among themselves via self-interaction, the gluons can form a glueball with quantum numbers I^G, $J^{PC} = 0^+$, 2^{++}, with a decay width $\Gamma_t = 100$ MeV and mass of $m_G = 2.23$ GeV. The three gluons can form a three gluon color bound state with a charge conjugation quantum number $C = -1$. As shown in Fig. 2(b), vector meson electro-production in the $\gamma^* + p \to V + p$ reaction with a gluon-gluon interaction contribution contains two terms, the gluon-gluon interaction and a term with particle (tensor gluonball or Odderon) exchange.

Next we derive a theoretical expression for the differential cross section for $\gamma^* p$ elastic scattering. Now the eikonal phase $\chi_{\gamma^* p}$ for $\gamma^* p$ elastic scattering clearly reads as

$$\chi_{\gamma^* p} = \chi_{\text{even}}^{\gamma^* p} + \chi_{\text{odd}}^{\gamma^* p} . \tag{19}$$

The $\gamma^* p$ scattering amplitude $F_{\gamma^* p}$ can evidently be expressed by

$$F_{\gamma^* p}(s,t) = \frac{k}{2\pi} \int d^2\vec{b} e^{i\vec{q}\cdot\vec{b}} (\chi_+^{\gamma^* p} + \chi_-^{\gamma^* p}) \cong \frac{k}{2\pi} \int d^2\vec{b} e^{i\vec{q}\cdot\vec{b}} (\chi_{\text{even}}^{\gamma^* p} + \chi_{\text{odd}}^{\gamma^* p}). \tag{20}$$

Using the vector meson dominance and the QCD inspired model, the virtual photon-proton total cross section can then be written as

$$\sigma_{\text{tot}}^{\gamma^* p}(s) = 2P_{\text{had}}^{\gamma^* p} \int \left[1 - e^{-\chi_I^{\gamma^* p}(b,s)} \cos(\chi_R^{\gamma^* p}(b,s))\right] d^2\vec{b}, \tag{21}$$

where $P_{\text{had}}^{\gamma^* p}$ is the probability that a virtual photon splits into a quark- antiquark pair. The differential scattering cross section is given by

$$\frac{d\sigma^{\gamma^* p}}{dt}(s,t) = \frac{P_{\text{had}}^{\gamma^* p}}{4\pi} \left| \int J_0(qb)(1 - e^{i(\chi_{\text{even}}^{\gamma^* p} + \chi_{\text{odd}}^{\gamma^* p})(b,s)}) d^2\vec{b} \right|^2 . \tag{22}$$

In the spirit of the VMD, the virtual photon is a two-quark state, in contrast to the proton, which is a three-quark state. The $\gamma^* p$ total cross section is obtained from the even eikonal for pp and $\bar{p}p$ by the substitutions $\sigma_{ij} \to \frac{2}{3}\sigma_{ij}$ and $\mu_{ij} \to \sqrt{\frac{2}{3}}\mu_{ij}$, so that Eq. (11) becomes

$$\chi_{\text{even}}^{\gamma^* p} = \chi_{qq}^{\gamma^* p}(b,s) + \chi_{gg}^{\gamma^* p}(b,s) + \chi_{qg}^{\gamma^* p}(b,s) = i\left[\frac{2}{3}\sigma_{qq}(s) W(b; \sqrt{\frac{2}{3}}\mu_{qq}) + \right.$$

$$\frac{2}{3}\sigma_{gg}(s)W\left(b;\sqrt{\frac{2}{3}}\mu_{gg}\right)+$$

$$\frac{2}{3}\sigma_{qg}(s)W\left(b;\sqrt{\frac{2}{3}}\sqrt{\mu_{qq}\mu_{gg}}\right)\Bigg]. \quad (23)$$

By the same way we obtain the γ^*p scattering amplitudes by performing the substitutions $\sigma_{ij}\to\frac{2}{3}\sigma_{ij}$ and $\mu_{ij}\to\sqrt{\frac{2}{3}}\,\mu_{ij}$ in the odd eikonal for nucleon-nucleon scattering. So that Eq. (16) becomes

$$\chi_{\rm odd}^{\gamma^*\rm p}(b,s) = -{\rm i}\frac{2}{3}\sigma_{\rm odd}(s)W\left(b,\sqrt{\frac{2}{3}}\mu_{\rm odd}\right) = -{\rm i}\frac{2}{3}C_{\rm odd}\Sigma_{gg}\frac{m_o}{\sqrt{s}}W\left(b,\sqrt{\frac{2}{3}}\mu_{\rm odd}\right). \quad (24)$$

In the next section the numerical calculations for J/ψ and ϕ electro-production in the QCD inspired model will be performed by use of Eq.(22).

4 Numerical calculations of $\gamma^*+\rm p\to V+p$

4.1 Theoretical predictions for J/ψ electro-production

In terms of Eqs. (20, 22, 23, 24), with all eikonal parameters fixed by the nucleon-nucleon data of table 1, we can calculate the differential cross section $\mathrm{d}\sigma^{\gamma^*\rm p}/\mathrm{d}t$ as a function of the momentum transfer $|t|$. We use the value $P_{\rm had}^{\gamma^*\rm p}=1/200$ as the appropriate probability for a virtual photon to turn into a J/ψ. The differential cross section $\mathrm{d}\sigma^{\gamma^*\rm p}/\mathrm{d}t$ for the reaction $\gamma^*+\rm p\to J/\psi+p$ is plotted in Fig. 3. The solid curve is our theoretical prediction of the t dependence of the differential cross section for J/ψ electro-production. The square black points are the H1 [1] electro-production data at $\sqrt{s}=90$ GeV.

From Fig. 3 we can conclude that the calculated results of the differential cross section for the vector meson J/ψ electro-production in the QCD inspired model at $\sqrt{s}=90$ GeV fits the corresponding experimental measurements successfully. Therefore, the QCD inspired theory of J/ψ electro-production tells us that the differential cross section for the $\gamma^*+\rm p\to J/\psi+p$ reaction can be given by a sum of four contributions, namely from quark-quark, gluon-gluon interactions, quark-gluon interference and Odderon exchange terms. The quark-quark term makes the dominant contribution to the total differential cross section $\mathrm{d}\sigma^{\gamma^*\rm p}/\mathrm{d}t$. The contributions from the gluon-gluon interaction and the quark-gluon interference term reduce rapidly as $|t|$ increasing. The Odderon contribution decreases slowly as $|t|$ increasing.

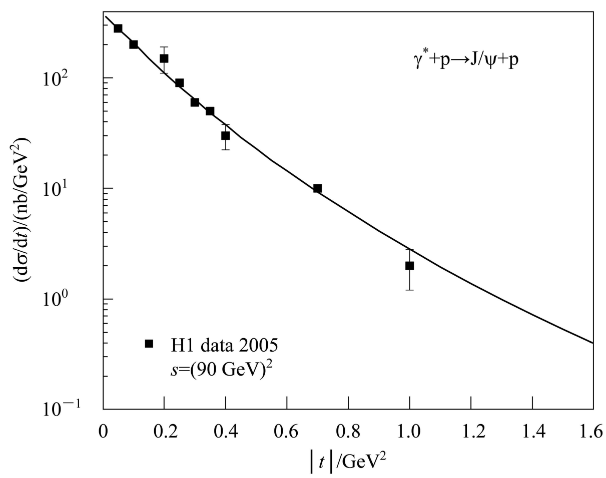

Fig. 3. The t dependence of the differential cross section for J/ψ electro-production. The solid curve is our theoretical prediction. The square black points are from H1 [1].

4.2 Theoretical predictions for ϕ electro-production

Based on Eqs. (20, 22, 23, 24) the numerical calculations for ϕ electro-production in electro-proton interactions at energies $\sqrt{s}=94$ GeV are performed in the QCD inspired model. We use the value $P_{\rm had}^{\gamma^*\rm p}=1/115000$, with all eikonal parameters from Table 1. The numerical prediction is shown in Fig. 4 for differential cross section of ϕ electro-production off the proton.

In Fig. 4, we show our theoretical prediction for the differential cross section of ϕ electro-production off the proton in the QCD inspired model with energy $\sqrt{s}=94$ GeV. The solid curve is our theoretical prediction. The square black points are from the Zeus collaboration at low t [2]. The white circles are from the Zeus collaboration at larger t [3]. Clearly, we have gotten good fits to the experimental data for ϕ electro-production off the proton at energy $\sqrt{s}=94$ GeV. ϕ electro-production tells us that the differential cross section in the $\gamma^*+\rm p\to\phi+p$ reaction also can be given by a summation of four contributions from quark-quark, gluon-gluon interactions, quark-gluon interference and Odderon exchange terms. Just as we have done for J/ψ electro-production, the quark-quark term also makes the dominant contribution to the total differential cross section $\mathrm{d}\sigma^{\gamma^*\rm p}/\mathrm{d}t$ in the $\gamma^*+\rm p\to\phi+p$ reaction. The contribution coming from the gluon-gluon interaction and the quark-gluon interference term decrease quickly as $|t|$ is increasing. At the same time, the Odderon contribution falls slowly as $|t|$ increases.

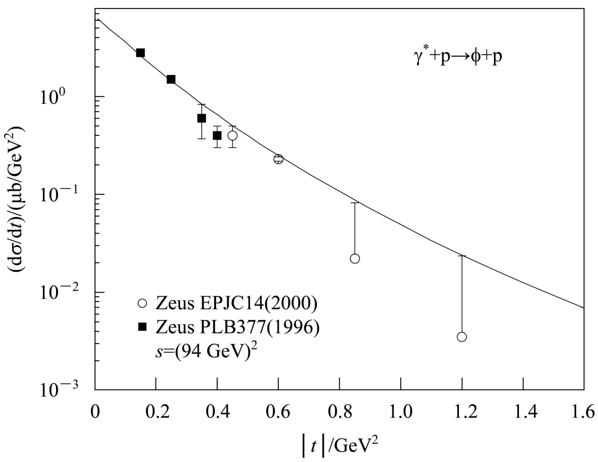

Fig. 4. The t dependence of differential cross section of ϕ electro-production at $\sqrt{s}$ = 94 GeV. The solid curve is our theoretical prediction. The square black points are from the Zeus collaboration [2], the white circles are from the Zeus collaboration [3].

5 Summary and calculational remarks

We study vector meson electro-production off the proton in the QCD inspired model. Vector meson electro-production is a purely diffractive process in which there are no quantum numbers exchanged between the two colliding particles. In QCD the hadrons are described in terms of quarks, anti-quarks and gluons. Correctly speaking, the quantum numbers of the meson are the same as those of the virtual photon. The usual, well-known vector mesons are supposed to contain quarks and anti-quarks which, produced by the virtual photon, leads to a description vector meson electro-production off the proton in QCD via virtual photon and proton interaction. We use the QCD inspired model to calculate J/ψ and ϕ electro-production.

The present model provides a good description of the available experimental data. When linking the factor 2/3 exclusively to the quark composition of our eikonal in Eqs. (23,24), we found that the differential cross section of the J/ψ and ϕ electro-production in the $\gamma^*+p \rightarrow J/\psi+p$ and $\gamma^*+p \rightarrow \phi+p$ reactions can be given by a sum of four contributions coming from quark-quark, gluon-gluon interactions, quark-gluon interference terms and Odderon exchange terms. During the calculation we found that the quark-quark interaction makes a dominant contribution to $\gamma^*+p \rightarrow V+p$ as compared with the other contributions. The Odderon contribution decreases slowly, but is not negligible. From the calculation we also found that the differential cross section strongly depends on the momentum transfer.

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