Charmonium photoproduction.

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The available data on $J/\Psi$ photoproduction are analyzed in terms of pomeron exchange, two gluon exchange and photon-gluon fusion models. Allowing the pomeron-quark interaction to be flavour dependent and introducing the soft and hard pomerons it is possible to reproduce the data at $\sqrt{s}>10$ GeV and small $|t|$. The two gluon exchange calculations indicate strong sensitivity to the gluon distribution function. The results obtained with the most modern MRST2001 and DL PDF reproduce the forward $J/\Psi$ photoproduction cross section at $\sqrt{s}>10$ GeV. The calculations with the photon-gluon fusion model and with MRST2001 and DL PDF are also in reasonable agreement with the data on the total $J/\Psi$ photoproduction cross section. We allocate the $J/\Psi$ photoproduction at low energies and large $|t|$ to the mechanism different from pomeron or two gluon exchanges. We consider that this might be axial vector trajectory exchange that couples to the axial form factor of the nucleon.

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I. INTRODUCTION

$J/\Psi$ production by real and virtual photons provides an effective way to test QCD dynamics at short distances and to verify QCD inspired models. The pomeron exchange model is one of the nonperturbative QCD approaches traditionally applied to vector meson photoproduction at high energies. The crucial point of the model is the flavour independence of the pomeron-quark interaction, which can be studied through systematic analysis of the photoproduction of light, strange, charm and beauty quarks.

The perturbative QCD models, such as two gluon exchange and photon-gluon fusion, provide a direct access to the gluon distribution function. The $J/\Psi$ electro and photoproduction is an excellent tool to test the gluon parton distribution function (PDF).

$J/\Psi$ electroproduction has been systematically studied within these different approaches. Most modern gluon distribution functions, such as MRST2001 and CTEQ6, became available just recently through the analysis of $J/\Psi$ electroproduction at large $Q^2$. Very recently the data on $J/\Psi$ electro production were analyzed with the photon-gluon fusion model.

Here we present a systematic analysis of $J/\Psi$ production by real photons. We collect old data available at low energies as well as data at high energies from H1 and ZEUS. We also include very recently published results.

Our aim is to investigate whether $J/\Psi$ photoproduction can be understood in terms of a certain model, which is also applicable to the photoproduction of other vector mesons. It is also a crucial line of our study whether the QCD or pQCD models are able to explain the mechanism of $J/\Psi$ photoproduction close to the reaction threshold, i.e. at $\sqrt{s}<10$ GeV.

II. THE DIFFERENCE BETWEEN $\omega$ AND $J/\Psi$ PHOTOPRODUCTION.

The $\omega$, $\phi$ and $J/\Psi$ vector mesons, which are the mixtures of $uu$, $dd$, $s\bar{s}$ and $c\bar{c}$ quarks states, have the same quantum numbers. For ideal mixing, $\theta_V$ is near $35^\circ$, $\phi=s\bar{s}$ and $J/\Psi=c\bar{c}$, while the $\omega$ meson is built up with $uu$ and $dd$. However, the mixing is not ideal and both the $\phi$ and $J/\Psi$ vector mesons contain a certain fraction of light quarks.

Systematic Regge theory analysis of $\omega$ meson photoproduction shows that at large invariant collision energies, $\sqrt{s}>10$ GeV, the reaction is dominated by soft pomeron exchanges, while at $\sqrt{s}>100$ GeV additional small contribution might come from the hard pomeron. At low energies, $\sqrt{s}<10$ GeV, the $\omega$ photoproduction is dominated by the meson exchanges. The Regge model with contributions from $\pi$ and $f_2$ trajectories reasonably describes the data as well as the standard meson exchange model with $\pi$, $\eta$ and $\sigma$ contributions. Particularly large contribution from $\pi$ meson exchange to $\omega$ photoproduction at low energies can be understood through the large $\omega \rightarrow \pi^+\pi^-$ partial decay width, which dominates the $\omega$ meson radiative decay mode.

An absolutely different situation holds for the $J/\Psi$ meson. Following the Regge theory it is believed that at high energies the $J/\Psi$ meson is produced through soft and hard pomeron exchanges, where the last dominates at $\sqrt{s}>50$ GeV. It is hard to classify what mechanism is responsible for $J/\Psi$ photoproduction at low energies, below $\sqrt{s}=10$ GeV. The $J/\Psi$ mass $m\approx 3.097$ GeV is below the $D\bar{D}$ threshold $\approx 3.739$ GeV and OZI allowed $J/\Psi\rightarrow D+\bar{D}$ decay cannot be realized in vac-
uum. Instead there are large amount of OZI suppressed decay channels involving stable hadrons, hadronic resonances and radiative decays. A large fraction of radiative $J/\Psi$ decay proceeds through the production of multi mesonic resonant and non resonant states. The $J/\Psi\rightarrow n+\gamma$ and $J/\Psi\rightarrow \eta+\gamma$ both constitute a negligible part of the total radiative decay modes, thus the single meson exchanges contribution to $J/\Psi$ photoproduction are expected to be very small.

However, it might be that the mesonic or multi mesonic exchange contribution to $\gamma+N\rightarrow J/\Psi+N$ is negligible and the soft pomeron exchange dominates already starting from the reaction threshold.

The difference between $\omega$ and $J/\Psi$ total photoproduction cross section is illustrated by Fig. 1 where the reduced total photoproduction cross section $\sigma_f/\sqrt{s}$ is shown as a function of photon energy, $E_\gamma$. The upper axis of Fig. 1 indicates the invariant collision energy $\sqrt{s}$, where $s=m_N^2+2m_NE_\gamma$ with $m_N$ being the nucleon mass.

The $\omega$ photoproduction data are shown by squares and were collected in Ref. [6]. The circles show the $J/\Psi$ photoproduction data were taken from Ref. [22], where the results available until 1985 were reviewed. The part of the $J/\Psi$ photoproduction data from Ref. [22] were obtained with the nuclear target and therefore should be considered as an average between the proton and neutron. The $J/\Psi$ photoproduction threshold is $E_\gamma \approx 8.15$ GeV. The Cornell measurement [20] is the only result available now for $J/\Psi$ photoproduction close to the reaction threshold. We note that the $J/\Psi$ photoproduction data measured at $9.0 \leq E_\gamma \leq 11.8$ GeV at Cornell were incorrectly reviewed in Ref. [22]. The original experimental numbers for the differential $J/\Psi$ photoproduction cross section were published [20] in the form $d\sigma/dt=(1.01\pm0.20)\exp[(1.25\pm0.20)t] \text{nb/GeV}^2$. The total photoproduction cross section is therefore $\sigma=0.48\pm0.12 \text{nb}$, taking into account the minimal four momentum transfer squared.

The triangles in Fig. 1 show the $J/\Psi$ photoproduction data, which appeared after 1985 and are published in Refs. [24, 25, 26, 27, 29]. The $J/\Psi$ photoproduction data at high energies are shown by triangles and are taken from Refs. [24, 25, 26, 27, 29]. The dashed lines show the calculations with soft pomeron exchange alone, while the solid lines are the sum of soft and hard pomeron contributions. The upper axis indicates the invariant collision energy $\sqrt{s}$.

FIG. 1: Reduced $\omega$ (squares) and $J/\Psi$ (circles and triangles) total photoproduction cross section as a function of photon energy. The $\omega$ photoproduction data are collected in Ref. [6]. The $J/\Psi$ photoproduction data available before 1985 are shown by circles and taken from Ref. [22]. The $J/\Psi$ photoproduction data at high energies are shown by triangles and are taken from Refs. [24, 25, 26, 27, 29]. The dashed lines show the calculations with soft pomeron exchange alone, while the solid lines are the sum of soft and hard pomeron contributions.

FIG. 2: Reduced $\omega$ (squares) and $J/\Psi$ (circles and triangles) forward photoproduction cross sections as a function of photon energy. The $\omega$ photoproduction data are collected in Ref. [6]. The circles show $J/\Psi$ photoproduction data from Refs. [27, 29]. The triangles show $J/\Psi$ photoproduction data from Refs. [24, 25, 26, 27, 29]. The dashed lines show the calculations with soft pomeron exchange alone, while the solid lines are the sum of soft and hard pomeron contributions.
Another value of interest is the exponential slope $b$ of $t$ dependence of the differential photoproduction cross section, which is defined as

$$
\frac{d\sigma}{dt} = \frac{d\sigma}{dt} \bigg|_{t=0} \times \exp(b t),
$$

and is shown in Fig. 3. The data on $\omega$ photoproduction can be well fitted with a constant slope $b=7.6\pm0.1$ GeV$^{-2}$ over a wide range of available photon energies. In contrast, the $J/\Psi$ photoproduction data show a strong energy dependence of the exponential slope. At $E_\gamma<100$ GeV the data can be well reproduced with a constant slope $b=2.6\pm0.4$ GeV$^{-2}$, while at high energies $b=5.1\pm0.2$ GeV$^{-2}$.

Finally, the available experimental results on $\omega$ and $J/\Psi$ meson photoproduction might indicate a rather different mechanism for their production. Although, the quantum numbers of $\omega$ and $J/\Psi$ are the same, they have different quark structures. The difference between the $\omega$ and $J/\Psi$ photoproduction data can be attributed to the difference between the properties of light and charm quarks, such as their interaction through the gluon exchange, confinement and fusion into real hadrons and photon quark-antiquark fluctuation. Therefore, currently available theoretical models for $\omega$ and $J/\Psi$ meson photoproduction are inspired by QCD.

In the next section we review some of the models that recently were successfully applied to the $J/\Psi$ electroproduction off the nucleon. We will compare these models with data on $J/\Psi$ photoproduction by real photons. Furthermore, we consider all available data on $J/\Psi$ photoproduction in order to make our study in a more systematic way.

### III. POMERON EXCHANGE MODEL.

The basis of the model is the factorization of the exclusive vector meson production amplitude in terms of the product of $\gamma\rightarrow q\bar{q}$ fluctuation, the scattering of the $qq$ system by the proton and finally the $qq$ hadronization into a vector meson. The interaction between the $qq$ state confined in the vector meson and the nucleon is taken to be given by pomeron exchange. The pomeron propagator $G(s,t)$ is parameterized as

$$
G(s,t) = i \left( \frac{s}{s_0} \right)^{\alpha(t)-1} \exp(-\frac{i\pi}{2}[\alpha(t)-1]),
$$

and therefore the pomeron trajectory $\alpha(t)$ drives the $\sqrt{s}$ energy dependence of the reaction amplitude. The evolution of $t$ dependence with energy is controlled by pomeron exchange trajectory as well.

The interaction between the pomeron and quark is considered to be a flavour independent. The flavour independence of the quark-pomeron interaction might provide a unique way to construct a unified model for vector meson photoproduction.

#### A. Soft pomeron.

The pomeron exchange amplitude $T$ for vector meson photoproduction is depicted in Fig. 4a) and is explicitly given \[1,2,4,5\] in the form

$$
T = 3iF_1(t) \frac{8\sqrt{6} m_q e_q f_V^2 \beta_q^2}{4m_q^2 - t} (\varepsilon \cdot \varepsilon_V) \left( \frac{s}{s_0} \right)^{\alpha(t)-1} \times \exp(-\frac{i\pi}{2}[\alpha(t)-1]) \frac{\mu_q^2}{2m_q^2 + 4m_q^2 - t},
$$

where $e_q$ and $m_q$ are the charge and mass of the quark, $\varepsilon$ and $\varepsilon_V$ are the polarization vectors of the photon and $J/\Psi$ meson.
vector meson, respectively and \( f_V \) is the meson decay constant given by \( V \rightarrow e^+e^- \) radiative decay width \( \Gamma_{e^+e^-} \) as

\[
\Gamma_{e^+e^-} = \frac{8\pi\alpha'^2e_q^2}{3m_V}f_V^2,
\]

where \( \alpha \) is the electromagnetic coupling constant and \( m_V \) is the vector meson mass.

Furthermore, \( t \) is the squared four momentum transfer and \( F_1(t) \) is the proton isoscalar EM form factor given as

\[
F_1(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t} \frac{1}{(1-t/t_0)^2},
\]

with \( m_p \) being the proton mass and \( t_0=0.71 \) GeV\(^2 \). The \( F_1(t) \) was introduced assuming the pomeron resembles an isoscalar photon.

The pomeron trajectory \( \alpha(t) \) for soft pomeron exchange is given as

\[
\alpha(t) = 1.08 + \alpha' t, \tag{6}
\]

with \( \alpha'=0.25 \) GeV\(^{-2} \). The constant \( s_0 \) is not well defined theoretically and can be taken as \( s_0=1/\alpha' \) following the dual model prescription \( 35 \).

The free model parameter, \( \beta_q \), determines the strength of the effective pomeron coupling to the quark, while \( \mu_q \) accounts for the possibility that the coupling to an off-shell quark is not pointlike but dressed with the form factor given by the last term of Eq. (5). Both \( \beta_q \) and, in principle, \( \mu_q \) might depend on the flavour of the quark and can be fixed by experimental data.

The phase of the soft pomeron exchange amplitude was not written explicitly in Refs. 1, 2, 3, 4, 5 since no interference with other exchanges was considered.

The amplitude is normalized so that \( d\sigma/dt = |T|^2 \). Finally, the differential \( \gamma+p\rightarrow V+p \) cross section due to soft pomeron exchange is given for a real photon as,

\[
\frac{d\sigma}{dt} = \frac{81m_p^4\beta_q^4\mu_q^4}{4\pi s_0} \Gamma_{e^+e^-} \left( \frac{s}{s_0} \right)^{2\alpha_p(t) - 2} \times \frac{F_1^2(t)}{(m_V^2 - t)^2(2\mu_q^2 + m_V^2 - t)^2}, \tag{7}
\]

where it was assumed that \( m_V=2m_q \).

The coupling constant \( \beta_q \) and the form factor \( \mu_q \) were fitted \( 30 \) through the systematical analysis of \( \omega \) meson photoproduction as

\[
\beta_q = 2.35 \text{ GeV}^{-1}, \quad \mu_q^2 = 1.1 \text{ GeV}.
\]

It was found \( 30 \) that the parameter \( \beta_q \) evaluated from \( \omega \) photoproduction was different from \( \beta_q=2.0 \) GeV\(^{-1} \) needed in the description \( 37, 38 \) of \( \rho \) photoproduction data. This discrepancy could not be explained in a satisfactory way, since once the parameters of the pomeron exchange are fixed by \( \rho \) meson photoproduction, they should be applicable to the other vector mesons as well. Moreover, at this stage we still do not discuss the flavour dependence of the quark-pomeron interaction, because we are dealing with \( \rho \) and \( \omega \) photoproduction, i.e. light \( q\bar{q} \) states.

An ideal illustration of this finding is given by the ratio of the \( \gamma+p\rightarrow\omega+p \) and \( \gamma+p\rightarrow\rho+p \) cross sections, shown in Fig. 9 as a function of photon energy \( E_\gamma \) and invariant collision energy \( \sqrt{s} \). Following Eq. (7) the ratio of \( \omega \) and \( \rho \) meson photoproduction is given by the ratio of \( \omega\rightarrow e^+e^- \) and \( \rho\rightarrow e^+e^- \) decay widths

\[
R = \frac{\Gamma_{\omega\rightarrow e^+e^-}}{\Gamma_{\rho\rightarrow e^+e^-}} = \frac{0.60\pm0.02 \text{ keV}}{6.77\pm0.32 \text{ keV}} = 0.088\pm0.005,
\]

which is shown by the solid line in Fig. 9 and considerably underestimates the experimental results.

The dashed line in Fig. 9 shows the fit to the data by a constant value \( R=0.115\pm0.003 \), which is close to the SU(3) estimates for the \( \omega \) and \( \rho \) coupling to the photon. Finally the difference between the Regge model and the data accounts for a factor of \( \simeq 1.3 \). It is already clear that both \( \rho \) and \( \omega \) photoproduction data could not be reproduced by the soft pomeron exchange simultaneously with the same set of parameters \( \beta_q \) and \( \mu_q \).

Now, the dashed line in Fig. 1 shows the contribution from soft pomeron exchange to the total reduced \( \omega \) meson photoproduction cross section. The calculations were done with the parameters given by Eq. (5). The comparison to differential \( \gamma+p\rightarrow\omega+p \) cross section at different photon energies is given in Ref. 33. The contribution from soft pomeron exchange to forward \( \omega \) meson photoproduction is shown in Fig. 2 by the dashed line.

Obviously, the soft pomeron exchange alone will reproduce the \( \omega \) photoproduction data at \( \sqrt{s}\geq6 \) GeV. At lower energies the dominant contribution to the \( \gamma+p\rightarrow\omega+p \) reaction comes from meson exchanges.

The diagrams for pomeron exchange (a), two gluon exchange c,d) and photon-gluon fusion model b) are shown in Fig. 4.
The slope dependence of the photoproduction cross section arising from the soft pomeron exchange is given by the proton EM form factor squared $F_1^2(t)$, the quark-pomeron form factor squared and by the pomeron exchange trajectory $(s/s_0)^2\alpha(t)^{-2}$. The exponential slope, $b$, of the $t$ dependence can be evaluated as

$$b = \frac{d}{dt} \ln \left( \frac{d\sigma}{dt} \right),$$  \hspace{1cm} (10)$$
from the differential photoproduction cross section given by Eq. (11).

The slope due to the proton isoscalar EM form factor is

$$b_1 = -\frac{5.6}{4m_p^2 - 2.8t} + \frac{2}{4m_p^2} + \frac{4}{t_0 - t},$$  \hspace{1cm} (11)$$
and since it depends on $t$ it can be considered as a local slope. At $t=0$ the slope from proton EM form factor is $\simeq 4.6$. The slope due to the quark-pomeron form factor squared is given as

$$b_2 = \frac{t}{m_V^2} + \frac{2}{2\mu_q^2 + m_V^2 - t},$$  \hspace{1cm} (12)$$
and depends on the cutoff parameter $\mu_q$ and mass of the produced vector meson $m_V$. For $\omega$ meson photoproduction at $t=0$ the slope associated with the quark-pomeron form factor is $\simeq 4.0$. The energy dependence of the slope comes from pomeron trajectory and is given for soft pomeron exchange as

$$b_3 = 0.5 \ln(0.25s).$$  \hspace{1cm} (13)$$

Finally, the total exponential slope, $b$, of the $t$ dependence for $\omega$ meson photoproduction at $t=0$ has a minimum value of $b=8.6$ GeV$^{-2}$ and increases logarithmically with energy. This result is in excellent agreement with the data shown in Fig. 5. Here we also show the local slope $b$ at different squared four momentum transfers $t$. It is also clear that the appearance of the proton EM form factor in the reaction amplitude dictates quite a large value of the minimal available $b$ at $t=0$.

The contribution from soft pomeron exchange to $J/\Psi$ photoproduction is given by Eq. (7). Taking the parameters $\beta_q$ and $\mu_q$ as determined from the data on $\omega$ meson photoproduction one can easily estimate the ratio of forward $J/\Psi$ and $\omega$ photoproduction cross section as

$$R \left( \frac{J/\Psi}{\omega} \right) = \frac{\Gamma_{J/\Psi \to e^+e^-} m_\omega (m_\omega^2 + 2\mu_q^2)}{\Gamma_{\omega \to e^+e^-} m_J (m_J^2 + 2\mu_q^2)} = 0.13,$$  \hspace{1cm} (14)$$
with $\Gamma_{J/\Psi \to e^+e^-} = 5.26$ keV. The experimental results shown in Fig. 2 indicate that this ratio is of order 0.005 at $\sqrt{s} \approx 10$ GeV. Therefore the soft pomeron exchange with fixed parameters for the quark-pomeron interaction substantially overestimates the data on $J/\Psi$ photoproduction. However, since it was already realized that a simultaneous description of both $\rho$ and $\omega$ photoproduction data requires a different coupling constant $\beta_q$, one might proceed in a similar way and readjust $\beta_q$ to the $J/\Psi$ photoproduction data.

Considering the flavour dependence of the interaction between the pomeron and quark one might distinguish the light quark coupling $\beta_q = 2.35$ GeV$^{-1}$, which is taken to be the same as evaluated from $\omega$ meson photoproduction, and the pomeron coupling to charm quark $\beta_c$. In that case the $b_3$ term in the amplitude given by Eq. (13) should be replaced by product $b_3 b_c$. In addition the differential cross section of Eq. (13) must also be corrected.

We found that the choice of $\beta_c = 0.45$ GeV$^{-1}$ provides a reasonable description of the data around $\sqrt{s} \approx 10$ GeV. The dashed lines in Figs. 123 show our calculation of the soft pomeron contribution to the reduced total and forward $J/\Psi$ photoproduction cross section.

However, resolving the problem with the reduction of the soft pomeron contribution to $J/\Psi$ photoproduction leaves one far short of a description of the $J/\Psi$ meson data collected in Figs. 123.

First, although the soft pomeron seems to reproduce the total $J/\Psi$ photoproduction cross section starting just from the reaction threshold, the model absolutely fails to describe the forward cross section and slope $b$ of the $t$ dependence at low energies. Recall, that the minimal value of the slope is given by the proton scalar EM form factor and this is already larger than the experimental results at low energies.
Second, the energy dependence of the total and forward $J/\Psi$ photoproduction cross section and the slope $b$ at high energies cannot be reproduced by soft pomeron exchange.

### B. Hard pomeron.

There are different attempts to reproduce the energy dependence of the total $J/\Psi$ photoproduction cross section without introducing a new pomeron trajectory. The strategy is to readjust the $t$ dependence in such a way that it becomes flatter, providing the correct total cross section after integration over the large $t$ region accessible at high energies. One of the more natural ways is to introduce a trajectory that is nonlinear in $t$, instead of that given by Eq. (6). Obviously the $J/\Psi$ photoproduction data at $t=0$, shown in Fig. 2 do not support such solution.

Instead, the forward $J/\Psi$ photoproduction cross section requires that at $t=0$ the cross section is proportional to $\sqrt{s}$, because the reduced cross section in Fig. 2 is almost independent of energy for $\sqrt{s}>10$ GeV. From Eq. (2) one can show that the trajectory necessary to reproduce the data has an intercept $\alpha(t=0)\approx 1.25$. Moreover, since the energy dependence of the slope, $b$, is proportional to $\alpha'\ln(s)$, the data shown in Fig. 3 support the value of $\alpha'\approx 0$ GeV$^{-2}$.

The hard pomeron trajectory was introduced in Ref. [4] as

$$\alpha(t) = 1.44 + 0.1t. \quad (15)$$

The calculations with both hard and soft pomeron exchanges, including their interference, are shown by the solid lines in Figs. 4 and 5. The coupling constant between the hard pomeron and charm quark was fitted as $\beta_c=0.05$ GeV$^{-1}$. The calculations reproduce quite well the data on total and forward $J/\Psi$ photoproduction cross section and slope $b$ of $t$ dependence at $\sqrt{s}>10$ GeV. Note that for both soft and hard pomeron exchanges the partial slope $b_1$, coming from the form factor in the upper pomeron-quark vertices, is $b_1>0.37$, because of the large $J/\Psi$ mass appearing in Eq. (11). It is clear that the hard pomeron dominates at high energies.

Figs. 6 shows the differential cross section for $J/\Psi$ photoproduction at high energies. The data available at small $t$ can be described well by the model.

The most crucial data are shown in Fig. 7 where we collect available data on differential $\gamma+N\rightarrow J/\Psi+N$ cross section at relatively small energies, $\sqrt{s}<23$ GeV. The solid lines show the calculations with soft and hard pomeron contributions. The dashed lines show the fit to the soft part of the differential spectra.

The comparison between the differential spectra and calculations at $\sqrt{s}<10$ GeV illustrates that both slope and extrapolated cross section at $t=0$ could not be reproduced by the model. The rough agreement between the integrated theoretical and experimental cross sections shown in Fig. 8 should be considered as an accident. The pomeron exchange model is far from describing the data at $\sqrt{s}<10$ GeV.

The comparison at $\sqrt{s}>20$ GeV shows that pomeron exchange allows one to describe the steep dependence of the differential $\gamma+N\rightarrow J/\Psi+N$ cross section at small $t$. At large four momentum transfer squared there are additional contributions resulting in a soft component of the spectrum. It is worthwhile to note the slope of the soft component observed at $\sqrt{s}>20$ GeV is close to that measured at lower energies and is around $0.7\pm 2.8$ GeV$^{-2}$.

Fig. 9 shows recent data on differential $\gamma+N\rightarrow J/\Psi+N$ cross section collected by ZEUS Collaboration [28] at $30\leq \sqrt{s}\leq 170$ GeV. The solid lines show the calculations with soft and hard pomeron contributions, which well describe the data at low $|t|$. At large four momentum transfer squared we detect a soft component of the spectrum [28, 10, 11].
IV. TWO GLUON EXCHANGE MODEL.

The exclusive vector meson photoproduction amplitude is again factorized in terms of the $\gamma\rightarrow q\bar{q}$ fluctuation, the scattering of the $q\bar{q}$ system by the proton and finally the $q\bar{q}$ hadronization into the vector meson. The $q\bar{q}$ system interacts with a nucleon through two gluon exchange.

In lowest order perturbative QCD the photoproduction amplitude is given by the sum of two diagrams depicted in Fig 4b,c) and can be written as

$$
T = \frac{i 2 \sqrt{2} \pi^2}{3} m_q \alpha_s e_q f V F_2(t) \times \int d^2 D_g(l) [D_+(l) - D_-(l)] G(l),
$$

where the integration is performed over the gluon transverse momentum, $e_q$ and $m_q$ are the charge and mass of the quark, respectively, while $\alpha_s$ is the QCD coupling constant \(\frac{3}{\pi}\). The meson decay constant is given by Eq(4). The gluon propagator $D_g(l)$ is taken as $1/l^2$, the $D_-(l)$ is the propagator of the off-shell quark in the diagram where each gluon couples to a different quark of

![Diagram](image.png)

FIG. 8: The $\gamma+p\rightarrow J/\Psi+p$ differential cross section as a function of four momentum transfer squared $t$ measured at different invariant collision energies $\sqrt{s}$ by ZEUS Collaboration \[29\]. The solid lines show the calculations including both soft and hard pomeron exchanges.

C. Short comment.

It is clear that assuming the appropriate flavour dependence of the interaction between pomeron and quark the Regge model allows an excellent description of the high energy data on vector meson photoproduction.

There are attempts to recover flavour independence by accounting for the mass-dependent corrections, such as Fermi motion and quark off-shellness in the $q\bar{q}$ loop. Indeed the vector meson coupling to $q\bar{q}$ introduced through Eq(4) was obtained within an on-shell approximation, which is not correct in the case of diffractive photoproduction. However, it was found that calculations \[12, 43, 44\] with realistic vector meson wave functions do not allow one to describe simultaneously the $\rho$ and $J/\Psi$ meson electroproduction, similar to what we have found in the present study of $\omega$ and $J/\Psi$ photoproduction by real photons. It was proposed to use a Gaussian wave function instead and to regulate its mean value individually for each vector meson. It is not clear whether such degree of freedom is better than the individual choice of coupling constant $\beta_q$. 
the vector meson and is given as
\[ D_-(l) = (-2m_q^2 - 2l^2)^{-1}. \] (17)

When the two gluons couple to the same quark the off-shell quark propagator is
\[ D_+(l) = (-2m_q^2)^{-1}. \] (18)

Furthermore, \( F_{2g}(t) \) accounts for the \( t \) dependence of the amplitude given by a two gluon correlation in the proton. The form factor \( F_{2g}(t) \) is not defined by the model and, as proposed in Ref. 8, can be taken to be the proton isoscalar EM form factor, \( F_1(t) \), given by Eq. 8.

Function \( G(l) \) defines the probability of catching the two gluons with momenta \( l \) from the proton and it is related to the conventional gluon distribution function \( g(x) \) as
\[ xg(x, Q^2) = \int dl^2 \frac{G(l)}{l^2}. \] (19)

Finally the two gluon exchange amplitude becomes
\[ \mathcal{T} = \frac{i \sqrt{2} \pi^2}{3} m_q \alpha_s \epsilon_q \epsilon_{\Psi} F_{2g}(t) \times \left[ \frac{xg(x, Q_0^2)}{m_q^2} + \int_{Q_0^2}^{+\infty} \frac{dl^2}{l^2} \frac{\partial xg(x, l^2)}{\partial l^2} \right] \] (20)

The amplitude is normalized so that \( d\sigma/dt = \alpha |\mathcal{T}|^2 \) and in lowest order the \( J/\Psi \) photoproduction cross section is given as
\[ \frac{d\sigma}{dt} = \frac{\pi^3 \Gamma_{\Psi^-} \alpha_s^2}{6 \omega_m^5} \left[ xg(x, Q_0^2) \right]^2, \] (21)

where \( x = m_j^2/s \) and \( Q_0 \approx m_V \). The cross section depends on the gluon distribution function squared and the energy dependence of \( d\sigma/dt \) is directly given by the \( x \) dependence of \( xg(x) \).

To compare the two gluon exchange model with data on \( J/\Psi \) photoproduction we need to specify the gluon parton distribution function. The PDF used in the following calculations are shown in Fig. 9 as a function of \( x \) and for \( Q^2 = m_j^2 \). The upper axis of Fig. 9 indicates the relevant invariant collision energy, \( \sqrt{s} = m_j / \sqrt{x} \). The old GRV98 15 and MRSG 16 functions show a very steep dependence at small \( x \), while the most modern MRST2001 17 and CTEQ6 18 functions are almost flat in \( x \). The DL 19 structure function shows some average dependence between the two extreme GRV98 and MRST2001 cases.

The PDF shown in Fig. 9 are very similar for \( x \geq 0.01 \), which corresponds to the invariant collision energy of \( \sqrt{s} < 30 \text{ GeV} \). That means that the data available before H1 and ZEUS measurement are not sensitive to the choice of PDF. One might expect that the differences between the different gluon functions in reproducing the \( \gamma + p \rightarrow J/\Psi + p \) reaction should appear only at high energies. Since \( xg(x, Q_0^2) \) enters the photoproduction cross section as an unintegrated function squared, the sensitivity of the energy dependence of \( J/\Psi \) photoproduction to the type of PDF should be extremely high.

The calculations were done for two extreme cases given by GRV98 and MRST2001 and for the DL function. The energy dependence of the QCD coupling constant \( \alpha_s \) was taken from Ref. 33. The mass of the charm quark allows for additional freedom in the absolute normalization of the calculations and we used \( m_q = 1.3 \text{ GeV} \).

Fig. 9 shows the forward \( \gamma + p \rightarrow J/\Psi + p \) cross section as a function of photon energy in comparison to the two gluon exchange model calculations by Eq. 21 with different gluon distribution functions.

As expected, the different PDF equally well reproduce the data around \( \sqrt{s} \approx 10 \text{ GeV} \). The GRV98 function is too steep at small \( x \) to describe the \( J/\Psi \) photoproduction at high energies. The DL function reasonably well reproduces the data over a wide range of photon energies, but it has incorrect threshold dependence, because of its asymptotic behaviour at large \( x \approx 1 \), as can be seen from Fig. 9.

The modern MRST2001 gluon distribution function describes the energy dependence of the forward \( J/\Psi \) photoproduction cross section very well, providing as well the correct threshold behaviour. It is also important to note that the two gluon model calculations with MRST2001...
leave some room for contribution from other processes at \( \sqrt{s}<8 \) GeV. As is illustrated by Figs. 12 and 8 the data actually require a different photoproduction mechanism close to threshold, which certainly can be added to the two gluon exchange contribution.

The \( t \) dependence of the two gluon exchange is introduced artificially through the proton EM form factor \( F_1 \) providing the slope \( b=4.6 \) GeV\(^{-2} \) at \( t=0 \). Although this result is in agreement with the data shown in Fig. 9 one may consider this agreement as a reasonable guess.

V. PHOTON GLUON FUSION MODEL.

In the photon-gluon fusion model (PGF) the photon fuses with a gluon from the nucleon and forms a \( c\bar{c} \) pair, as is shown in diagram in Fig. 8. Since a gluon transforms as a color octet, the production and the photon-gluon cross section \( \sigma_{\gamma g \rightarrow c\bar{c}} \) of the final nucleon.

The PGF model convoluted the gluon momentum distribution and the photon-gluon cross section \( \sigma_{\gamma g \rightarrow c\bar{c}} \), which is given as

\[
\sigma_{\gamma g \rightarrow c\bar{c}} = \frac{2\pi\alpha s}{\sqrt{s}} \frac{e_c^2 \alpha_s}{8^3} \left( [s^2 + 4m_c^2(s^2 - 2m_c^2)] \right) \times \ln \left[ \frac{1 + \beta}{1 - \beta} - \beta (s^2 + 4sm_c^2) \right],
\]

where \( e_c \) and \( m_c \) are the charge and mass of the charm quark, respectively, \( \alpha_s \) is the QCD coupling constant, \( \alpha \) is electromagnetic coupling constant, \( \tilde{s} \) is squared invariant mass of the photon-gluon system and

\[
\beta^2 = 1 - \frac{4m_c^2}{s}.
\]

The PGF does not consider explicitly the formation of the final state, which should enter through the \( J/\Psi \) wave function as in the case of two gluon exchange model. Instead the convolution of photon-gluon cross section with the gluon momentum distribution is performed over the range from charmonium production threshold, \( 2m_c \), up to the open charm production threshold \( 2m_D \), given by the mass of \( D \) meson. Finally the charmonium photoproduction cross section is

\[
\sigma = f \int_{4m_D^2}^{s} \frac{d\tilde{s}}{8} \sigma_{\gamma g \rightarrow c\bar{c}} g(x=\frac{\tilde{s}}{s}, Q_0^2),
\]

where the factor, \( f \), is an adjustable parameter that accounts for the fraction of the specific charmonium bound states available in the mass region between \( 2m_c \) and \( 2m_D \). For the \( J/\Psi \) meson we fit it as \( f=0.062 \) with \( m_c=1.3 \) GeV. Furthermore, we take \( Q_0^2=m_J^2 \).

The PGF calculations with different gluon distribution functions are shown in Fig. 10 together with data on the total \( \gamma+p \rightarrow J/\Psi+p \) reaction cross section. Obviously, the PGF is less sensitive to the type of gluon distribution functions in comparison to the two gluon exchange model. The calculations with MRST2001 [17] and DL [19] reproduce the data better than the results obtained with GRV98 [12], which indicates a much steeper energy dependence. However the MRST2001 and GRV98 distributions both have correct threshold behaviour, while DL - not. In principle, the DL gluon distribution function can be corrected in order to get the correct asymptotic behaviour as \( x \rightarrow 1 \), by multiplying it with \((1-x)^5 \). However, then the agreement with the data disappears.

The PGF model does not contain a \( t \) dependence and in the best case it can be artificially introduced through the proton EM form factor. Although the PDF calculations are able to reproduce the cross section for \( J/\Psi \) photoproduction starting from threshold we would not claim that pQCD is able to describe the data at \( \sqrt{s} \leq 10 \) GeV. We consider this good agreement between the data and PGF calculations due to the correct asymptotic behaviour of the gluon distribution function as \( x \rightarrow 1 \), given by \( \simeq (1-x)^5 \) dependence. Fig. 11 shows this function alone.
in order to illustrate its threshold dependence. Furthermore, in the two gluon exchange model the PDF enters squared and the near threshold behaviour of the $J/\Psi$ photoproduction cross section is then given by function \( \simeq (1-x)^{10} \), which is shown in Fig.10. However, now the dependence is too steep to reproduce the data near the threshold.

VI. CONCLUSION.

We have analyzed the available data on $J/\Psi$ photoproduction in terms of pomeron exchange, two gluon exchange and photon-gluon fusion models.

Allowing the pomeron-quark interaction to be flavour dependent and introducing the soft and hard pomerons it is possible to reproduce almost all available data on $J/\Psi$ photoproduction at $\sqrt{s}>10$ GeV. At the same time, the model reproduce well the data on $\omega$ meson photoproduction, again taking into account that the interaction of the pomeron with light and charm quarks is very different. However the pomeron exchange model cannot not reproduce the data at $\sqrt{s}<10$ GeV and differential spectra at large $|t|$. The agreement between the calculations and total $J/\Psi$ photoproduction cross section near threshold should be considered as accidental, because both the slope $b$ of the $t$ dependence and the forward extrapolated cross section are in strong systematic disagreement with the pomeron exchange model at $\sqrt{s}<10$ GeV.

The two gluon exchange pQCD calculations indicate strong sensitivity to the gluon distribution function. The results obtained with the most modern MRST2001 and DL PDF reproduce the forward $J/\Psi$ photoproduction cross section at $\sqrt{s}>10$ GeV quite well. The calculations with MRST2001 show correct threshold dependence of the cross section and leave room for a contribution from other mechanisms at low energies. The two gluon exchange model does not contain any $t$ dependence. Its artificial introduction through the isoscalar EM proton form factor allows one to reproduce the slope of the $t$ dependence at high energies, but fails at $\sqrt{s}<10$ GeV.

The calculations with the photon-gluon fusion model again show sensitivity to the gluon distribution function. The PGF results calculated with MRST2001 and DL PDF are in reasonable agreement with the data on the total $J/\Psi$ photoproduction cross section. The PGF does not constrain the $t$ dependence.

Although the PGF calculations with MRST2001 reproduce the threshold behaviour of the total $\gamma+p\rightarrow J/\Psi+p$ cross section it does not prove that pQCD is able to describe the reaction at $\sqrt{s}<10$ GeV. It is just an artifact of the correct PDF asymptotic behaviour at $x\to 1$, given by $\simeq (1-x)^5$ dependence. For instance it is not a case for two gluon exchange model, where the PDF enters as squared and finally the $\simeq (1-x)^{10}$ dependence is too steep to reproduce the $J/\Psi$ photoproduction data near the threshold.

We allocate the $J/\Psi$ photoproduction at low energies and large $|t|$ to the mechanism different from pomeron or two gluon exchanges. The energy dependence of the differential cross section, $d\sigma/dt$, indicates that this mechanism does not depend on $s$. Furthermore, small slope $b$ of the $t$ dependence indicates that the exchange does not couple to the isoscalar EM proton form factor. We consider that this might be axial vector trajectory exchange that couples to the axial form factor of the nucleon. However, a definite conclusion requires more detailed study.

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