Two-gluon form factor of the nucleon and $J/\psi$ photoproduction.

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ABSTRACT

We argue that the $t$-dependence of the two-gluon form factor of the nucleon should be given by $\Gamma(t) = (1 - t/m^2_g)^{-2}$ with $m^2_g \approx 1 GeV^2$. We demonstrate that this form provides a good description of the $t$-dependence of the cross section of the elastic photoproduction of $J/\psi$-mesons between the threshold region of $E_\gamma = 11 GeV$ (Cornell), $E_\gamma = 19 GeV$ (SLAC) and $E_\gamma = 100 GeV$ (FNAL) including the strong energy dependence of the $t$-slope. It is also well matched with the recent HERA data. The same assumption explains also the $t$-dependence of $\phi$-meson electroproduction near threshold at $W = 2.3 GeV, Q^2 = 1.0 GeV^2$.

1 Theoretical expectations

It was demonstrated in [1] for the case of small $x$ and in [2] in a general case that in the limit of large $Q^2$ the $t$-dependence of the process $\gamma^*_L + N \rightarrow V + N$ at fixed $x$ is factorized into the convolution of a hard interaction block calculable in perturbative QCD, the short-distance $q\bar{q}$ wave function of the meson, and the generalized/skewed parton distribution (GPD) in the nucleon.

In the scaling limit the $t$-dependence is originating solely from the GPD’s since the meson wave function is highly squeezed in the direction transverse to the reaction axis. In the case of the valence quark exchanges these $t$-dependences are constrained by the sum rules for unpolarized [3] and polarized quarks [4] and could be also modeled in the chiral soliton models, see review in [5]. The $t$-dependence of GPD’s provides unique information about the impact parameter distribution of the partons in nucleons. The knowledge of the transverse gluon distribution is especially important since it provides a key ingredient for the understanding of relative importance of soft and hard physics for high energy nucleon-nucleon interactions at different impact parameters and has to be implemented in realistic Monte Carlo generators of nucleon-nucleon collisions at collider energies.

In this paper we will first discuss theoretical expectations for the $t$-dependence of gluon GPD’s. Next we will use the $11 \leq E_\gamma \leq 100 GeV$ data to check these expectations and hence
to explain the strong variation with energy of the t-slope (extracted from the data using exp $B(t - t_{\text{min}})$ fits) close to the threshold.

First let us summarize the theoretical expectations for the t-dependence of the two gluon form factor:

$$\Gamma(x_1, x_2, t, \mu^2) = \frac{g(x_1, x_2, t, \mu^2)}{g(x_1, x_2, 0, \mu^2)},$$

(1)

where $x_1, x_2$ are the light-cone fractions carried by the gluons in the gluon GPD. The fractions are measured relative to the incoming nucleon + component, $t$ is usual invariant momentum transfer variable, and $\mu^2$ is the renormalization scale.

If $\mu^2$ is sufficiently large ($\mu^2 \geq 2 \text{GeV}^2$) we expect three distinctive regimes of the behavior of $\Gamma$. At moderate $0.05 \leq x_1, x_2 \leq 0.3$ the form factor should be universal and practically $\mu^2$ independent since it is determined by the interaction with the average configurations in the nucleon.

The t-dependence in this case could be guessed based on the comparison with other nucleon form factors. The difference between the t-dependence of the electric and magnetic form factors and the axial form factor is naturally interpreted as due to the contribution of the photon scattering off the soft pion cloud, see e.g. [6]. In the case of gluon GPD’s with $0.05 \leq x_1, x_2 \leq 0.3$ the pions are not important since they carry a small fractions of the nucleon momentum and also contribute very little to the gluon density of the nucleon. Hence a natural guess is that

$$\Gamma(x_1, x_2, t, \mu^2) \approx G_A(t),$$

(2)

for $0.05 \leq x_1, x_2 \leq 0.3$. In following analysis we will make a natural assumption that

$$\Gamma(x_1, x_2, t, \mu^2) = \frac{1}{(1 - t/m_{2g}^2)^2},$$

(3)

for $|t| \leq 1 \div 2 \text{GeV}^2$, with $m_{2g}^2$ expected to be $\sim 1 \text{GeV}^2$. Similar parameterizations works well in the case of soft physics for the Pomeron coupling with the nucleon [15]. However in this case the mass scale is close to the electromagnetic one, most likely because the soft Pomeron interaction with the pion cloud is not suppressed as compared to the case of the electromagnetic form factor.

For significantly smaller $x_1, x_2$ we expect a gradual increase of the slope [1], which for fixed $x_1 - x_2$ should become weaker with increasing $\mu^2$ (as implicitly discussed above). In the region of large $x_1, x_2 \to 1$ a qualitatively different regime is expected when the form factor should become a very weak function of $x$. This is because the transverse momentum is shared between the partons in proportion of the longitudinal fractions (this feature of the Lorentz kinematics plays a critical role in the Feynman mechanism for the nucleon form factor). In practice this region is hard to reach experimentally except very close to the photoproduction threshold (see discussion below).

One of the important predictions of the QCD factorization theorems is that for processes dominated by two gluon exchange in the t-channel, the t-dependence at large $Q^2$ and fixed $x$ should reach a universal limit which is independent of the flavor of the quark constituents of the meson [1]. The mechanism for such universality is the transverse squeezing of the meson wave function ($r_t \propto 1/Q$). Hence in this limit the t-dependence of the amplitude is given solely by the two-gluon form factor of the nucleon. The extension of the analysis of
In [4], to account for the finite transverse size effects for $J/\psi$ production the squeezing starts already from $Q^2 \sim 0$. The difference of the t-dependences of $\rho$ and $J/\psi$ production was calculated in [8] in the dipole approximation. In that case, for $J/\psi$ production the meson size contributes $\Delta B \sim 0.3 GeV^{-2}$ at low $Q^2$ and does not change over experimentally covered range of $Q^2$. On the other hand, for $\rho$ production the slope strongly depends on $Q^2$. The $B_{\mu}(Q^2) - B_{J/\psi}$ difference observed at HERA is in reasonable agreement with the [8] prediction for $Q^2 \geq 3 GeV^2$ (see comparison in [4]).

Another prediction of [4] was that the rate of change of the t-dependence with energy should decrease with increase of the hardness of the diffractive process due to suppression of the Gribov diffusion in the hard processes, at least at moderate $x$. The HERA data appear to support this expectation [10, 11, 12]. If one uses a Reggeon type fit one finds for the case of $J/\psi$ production [12]:

$$B(W) = B_0 + 2\alpha' \cdot \ln(W/90 GeV)^2.$$  \hspace{1cm} (4)

where

$$B_0 = 4.30 \pm 0.08(stat)^{+0.16}_{-0.41}(syst) GeV^{-2}$$
$$\alpha' = 0.122 \pm 0.033(stat)^{+0.012}_{-0.032}(syst) GeV^{-2}.$$  \hspace{1cm} (5)

Somewhat smaller values of $\alpha'$ were observed for electroproduction of $\rho$-mesons[13]. $\alpha'$ in Eq. 5 is a factor of $\sim 2$ smaller than $\alpha'_{soft} \approx 0.25 GeV^2$ measured for the soft processes[4]. Moreover the $J/\psi$-production analysis of [14] suggests that the observed value of $\alpha'$ can be explained naturally by the contribution of the large size configurations to the production amplitude for which diffusion is not suppressed.

Based on the above discussion it appears natural to use the $J/\psi$ photoproduction at energies $E_\gamma \leq 100 GeV$ where Gribov diffusion effects are not important in the extraction of the two-gluon form factor of the nucleon.

The important effect which we encounter here is that the t-dependence of the cross section which follows from Eq. 3,

$$\frac{d\sigma}{dt} \propto \Gamma^2(x_1, x_2, t, \mu^2) = \frac{1}{(1 - t/m_{2g}^2)^4},$$  \hspace{1cm} (6)

does not exactly match an exponential form. As a result we expect that the effective exponential slope would depend on the t-interval used in the data analysis. This is especially true for low energies where $-t_{min}$ is not equal to zero.

If defines the slope as the logarithmic derivative of the cross section, then the fit to Eq. 3 becomes:

$$B_{eff}(t) = \frac{4}{m_{2g}^2 - t}.$$  \hspace{1cm} (7)

The slope of the exponential fit, $B$, corresponds roughly to $B_{eff}$ calculated for the average t of the experiment. In the case of HERA data for the lowest end of the energy interval the data give $B \sim 3 GeV^{-2}$. We checked that this corresponds to

$$m_{2g} \approx 1 GeV.$$  \hspace{1cm} (8)

\.___1\A word of caution is in order here. At HERA $\alpha'$ was determined by fitting $\alpha(t)$ over a large range of $|t|$. At the same time a number of measurements of elastic hadron-hadron scattering indicate that $\alpha'_{soft}$ decreases with increase of $-t$.\n
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Since we neglected in Eq. 6 the contribution of the \( J/\psi \) size which contributes \( \Delta B \approx 0.3 \text{GeV}^{-2} \) to the slope, we expect the value of \( m_{2g}^2 \) should be larger than the result of our fit by about 0.1 \( \text{GeV}^{-2} \).

## 2 Comparison with the data

Let us now check the consistency of Eqs. 6, 8 with the data obtained at lower energies. We want to emphasize here that we do not feel that the accuracy of the data and information available about the systematics justifies at that stage performing a \( \chi^2 \) fit. We simply fix the value of \( m_{2g}^2 \) and check whether a reasonable description can be achieved.

First we consider the FNAL data of Binkley et al. [16] at \( \langle E_\gamma \rangle = 100 \text{ GeV} \) which appear to be the only data where the recoil proton was detected. In other measurements the elastic sample was contaminated (especially at large \( |t| \)) by the inelastic diffractive events. The comparison of the t-dependence is presented in Fig. 1. One can see that a good agreement with the shape of these data is reached.

Next we consider the photoproduction data at energies close to the threshold. In this case \( t_{\text{min}} \) is not negligible. If the form factor t-dependence is indeed a power law it would result in a decrease of the slope of the exponential fits of the form \( \exp(B(t - t_{\text{min}})) \). Two experiments reported the t-dependence in this range. The SLAC data [17] at \( E_\gamma = 19 \text{ GeV} \) correspond to \( -t_{\text{min}} = 0.087 \text{ GeV}^2 \). We find them in a good agreement with Eq. 3, see Fig. 2. The Cornell experiment [18] measured \( J/\psi \) photoproduction at \( \langle E_\gamma \rangle = 11 \text{ GeV} \). Because \( -t_{\text{min}} = 0.41 \text{ GeV}^2 \), we expect a significant change of the slope. The data presented in Fig. 3 indeed correspond to a very weak t-dependence. It is probably somewhat weaker than the expectation based on Eq. 3. However one should remember that in this case the value of longitudinal light-cone fraction transfered from the nucleon to \( J/\psi \): \( x_1 - x_2 = 1 - (E_{p,N}^+ + E_{n,N}^+)/(E_{p,N} + E_{n,N}) \) becomes large (it is equal to 0.48 for \( \langle E_\gamma \rangle = 11 \text{ GeV} \)). It was suggested in [19] that photoproduction of charm near threshold is dominated by a three gluon exchange with the nucleon rather than by a two -gluon exchange as at high energies. The observed connection of the t-dependence of \( J/\psi \) production at 11 GeV and at higher energies indicates that at least for 11 GeV the dominant contribution remains a two gluon exchange.

Hence we conclude that the current data are in a reasonable agreement with the suggested form Eq. 3. Clearly new much more accurate data close to threshold are necessary. The planned SLAC experiment E160 [20] may contribute here as well as the Jlab 12 GeV upgrade. Another critical test will be a measurement of the t-dependence of the \( \Upsilon \) photoproduction at HERA which should be very close to the genuine two-gluon form factor. Note in passing that the t-slope of the elastic \( \Upsilon \) photoproduction entered in the calculation of the total cross section of the \( \gamma + p \to \Upsilon + p \) reaction in [21]. Since at that time the data on the energy dependence of the slope of \( J/\psi \) production did not allow determination of \( \alpha' \) for \( J/\psi \) we took it to be equal to zero. Taking \( \alpha' \) from Eq. 3 leads to renormalization of our prediction in [21] by a factor \( \sim 1.3 \).

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2The paper [18] in addition to the plot of the data presents also a fit to the data \( B = 1.25 \pm 0.2 \) which corresponds to a significantly slower t-dependence than indicated by the plot. Reasons for this are not clear.

3Often \( x_1 - x_2 \) for \( J/\psi \) photoproduction is calculated as \( m_{J/\psi}^2/s \). This expression is not valid very close to the threshold. However it does a good job even for \( E_\gamma = 11 \text{ GeV} \).
It is natural also to ask a question whether a large part of the variation of the t-slope of the exclusive electroproduction of light vector mesons near threshold could be due to a similar effect. The cleanest case is the \( \phi \)–meson production for which the quark exchange contribution is strongly suppressed. Naturally in this case the size of the meson cannot be as safely neglected as in the \( J/\psi \) case. At the same time the threshold region corresponds to large values of \( x_1 - x_2 \approx 0.4 \) which work in the direction of slowing down the t-dependence of the cross section. Hence we performed a comparison of Eq. \( \ref{eq:6} \) with the most recent data on electroproduction of \( \phi \)–meson which were reported in the Jlab experiment \([22]\) (the Cornell data \[23]\) are pretty similar). Surprisingly enough we find reasonable agreement with the data - Fig.4. This suggest a common origin of the dynamics of the \( \phi \)-meson and \( J/\psi \) electroproduction near threshold.

In conclusion, we have demonstrated that the current data are consistent with the dipole dependence of the two-gluon form factor with the mass scale \( \mu_{2g}^2 \approx 1 \text{ GeV}^2 \), which is a lower bound due to the contribution of the finite \( J/\psi \) size which is of the order \( 0.1 \text{ GeV}^2 \). This corresponds to a significantly smaller radius of the distribution of the gluon field in the nucleon than for the electromagnetic charge where \( \mu^2 \approx 0.7 \text{ GeV}^2 \). It is close to the mass scale in the axial form factor which reflects the distribution of the valence quarks. A more narrow space distribution at \( x \geq 0.05 \), especially when combined with a small value of \( \alpha' \) for virtualities \( \geq 2 \text{ GeV}^2 \), has many implications for diffractive studies as well as for modeling the structure of final states at high energies in pp collisions with high \( p_t \) jets.

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Figure 1: Comparison of the dipole parameterization of the $d\sigma^{\gamma+p\rightarrow J/\psi+p}/dt$ with the data of [16] at $\langle E_\gamma \rangle = 100$ GeV.
Figure 2: Comparison of the dipole parameterization of the $d\sigma^{\gamma+p\to J/\Psi+p}/dt$ with the data of [17] at $E_\gamma = 19 \text{ GeV}$
Figure 3: Comparison of the dipole parameterization of the $d\sigma^{\gamma+p\rightarrow J/\psi+p}/dt$ with the data of [18] at $\langle E_\gamma \rangle = 11$ GeV.
Figure 4: Comparison of the dipole parameterization of the $d\sigma^{\gamma^*p\rightarrow\phi+p}/dt$ with the data of [22] at $\langle W \rangle = 2.3$ GeV, $\langle Q^2 \rangle = 1$ GeV$^2$. 