The $Q^2$ dependence of the hard diffractive photoproduction of vector meson or photon and the range of pQCD validity

I.F. Ginzburg*, D.Yu. Ivanov†

Institute of Mathematics, 630090 Novosibirsk, Russia

(February 1, 2008)

Abstract

We consider two coupled problems.

We study the dependence on photon virtuality $Q^2$ for the semihard quasi-elastic photoproduction of neutral vector mesons on a quark, gluon or real photon (at $s \gg p^2 \perp, Q^2; p^2 \perp \gg \mu^2 \approx (0.3 \text{ GeV})^2$). To this end we calculate the corresponding amplitudes (in an analytical form) in the lowest nontrivial approximation of perturbative QCD. It is shown that the amplitude for the production of light meson varies very rapidly with the photon virtuality near $Q^2 = 0$.

We estimate the bound of the pQCD validity region for such processes. For the real incident photon the obtained bound for the $\rho$ meson production is very high. This bound decreases fast with the increase of $Q^2$, and we expect that the virtual photoproduction at HERA gives opportunity to test the pQCD results. The signature of this region is discussed. For the hard Compton effect the pQCD should work good at not too high $p_\perp$, and this

*e-mail: ginzburg@math.nsk.su
†e-mail: d-ivanov@math.nsk.su
effect seems measurable at HERA.

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I. INTRODUCTION

The diffractive photoproduction of neutral vector mesons or photon was investigated in many theoretical [1–16] and experimental [17–19] papers.

Below we study the photoproduction of light vector meson or photon (hard Compton effect) on a quark or gluon, initiated by both real and virtual photon $\gamma^*$ (having virtuality $Q^2$):

$$\gamma^* q \rightarrow V q, \quad \gamma^* g \rightarrow V g \quad (V = \rho, \phi, \ldots, \gamma, \ldots)$$

(1)

in the region of parameters where the perturbative QCD (pQCD) validity is beyond doubts:

$$s \gg p_{\perp}^2, Q^2; \quad p_{\perp}^2 \gg \mu^2 \quad (\mu \approx 0.2 \div 0.3 \text{ GeV}).$$

(2)

The transverse momentum of produced meson relative to collision axis $p_{\perp}$ is small as compared to the energy but it is large as compared to the QCD scale $\mu \approx 0.3 \text{ GeV}$.

Besides, we consider the similar photoproduction of heavy vector mesons on a quark, gluon or other photon:

$$\gamma^* q \rightarrow \tilde{V} q, \quad \gamma^* g \rightarrow \tilde{V} g, \quad \gamma^* \gamma \rightarrow \tilde{V} \tilde{V}' \quad (\tilde{V}, \tilde{V}' = J/\Psi, \ldots).$$

(3)

The photoproduction on quarks and gluons can be studied as that on a proton in the events with the rapidity gap $\eta > \eta_0$ between produced meson and other produced hadrons X. The photon–photon processes can be studied at the future photon colliders [19].

The cross section of the process $\gamma^* p \rightarrow VX$ with rapidity gap is related with that for the photoproduction on a quark and a gluon via the gluon and quark densities in a proton $G(x, t)$ and $q(x, t)$:

$$\frac{d^2\sigma(\gamma^* p \rightarrow VX)}{dtdx} = \sum_f (q(x, t) + \bar{q}(x, t)) \frac{d\sigma(\gamma^* q \rightarrow Vq)}{dt} +$$

$$+ G(x, t) \frac{d\sigma(\gamma^* G \rightarrow VG)}{dt}; \quad x > \frac{4p_{\perp}^2}{s} \cosh^2 \frac{\eta_0}{2}.$$

(4)

The main object, studied in these processes, is called the perturbative Pomeron (pP). Its theoretical and experimental study is of great interest, since this object should be common
for different reactions and it is sensitive to the inner structure of pQCD. Only the results in the Leading Log Approximation (LLA) are known until now, that is the BFKL Pomeron [25].

To estimate the bounds of the pQCD validity region, we simulate the nonperturbative effects near these bounds by the specific model. The idea of this model is to use the pQCD equations, in which quark mass is considered as a parameter (which is near the constituent quark mass). We also use this model for the qualitative description of some phenomena outside this bound.

Our efforts are focused on the problems: *What are the main features of $Q^2$-dependence in these processes within pQCD, without any phenomenological hypotheses? What are the bounds of pQCD validity at the description of diffractive processes?* To this end we restrict our consideration by the calculation in the lowest nontrivial approximation of pQCD — two–gluon exchange in the $t$-channel (see Fig. 1). We obtain that the cross sections of light meson photoproduction decrease very fast with virtuality near mass shell. Besides, for these processes and for hard Compton effect with real incident photon the influence of nonperturbative effects is very essential in the very large interval of $p_\perp$, the pQCD become valid at very large values of $p_\perp$ only. We present some arguments, why these features could be reproduced in the entire amplitude (beyond two–gluon approximation). We give the definite signature for the pQCD validity in the photoproduction of light mesons, which is independent on the validity of two–gluon approximation.

In this respect, the calculations with heavy mesons are presented mainly for the comparison to make clearer some details. Both our calculations here and the comparison of LLA results [10,13] show that the naive extension of the results obtained for heavy mesons to the photoproduction of light mesons or photons is dangerous procedure.

Additionally, the obtained results provide the opportunity to discuss a relation between the point–like and the hadron–like components of a photon.

The known for us papers, treated the similar problems, are discussed in the end of paper.

The study of pQCD validity in the discussed processes is on line with that in the other
exclusive reactions. The relation between perturbative and nonperturbative contributions to the amplitudes of exclusive processes was discussed widely (see refs. [20][21] and references therein). The advantage of processes considered is the possibility to study this subject by the two probes simultaneously — via investigation of the dependence on both the produced meson transverse momentum \( p_\perp \) and the photon virtuality \( Q^2 \).

II. BASIC RELATIONS

The process discussed can be described as two stage one. At the first stage, a photon decays into a \( q\bar{q} \) pair, the quarks with energies \( \varepsilon_i \) move along the photon momentum. Their transverse momenta are relatively small and the total energy of quark’s pair is close to the energy of the photon, \( \varepsilon_1 + \varepsilon_2 \approx E \). This first stage describes also the processes with the production of jet–like hadron system (both resolved for the two quark jets and unresolved one) with the rapidity gap.

At the second stage the quarks are glued into meson.

The basic kinematical notations are presented in Fig. 1. We denote also the virtuality of photon by \( Q^2 \equiv -p_1^2 > 0 \), the quark mass — by \( m \), the transverse momentum of produced meson (relative to the collision axis) — by \( p_\perp \). For the description of the photon fragmentation into quarks, we use quark spinors \( u_1 = u(q_1) \) and \( u_2 = u(-q_2) \). The relative motion of the quark and antiquark is described by the variable \( \xi \):

\[
\xi = \frac{2(q_1 - q_2)p_2}{s} = \frac{\varepsilon_1 - \varepsilon_2}{E}; \quad -1 \leq \xi \leq 1.
\]

Next, we denote

\[
\mathbf{n} = \frac{p_\perp}{|p_\perp|}; \quad \delta = \frac{2m}{p_\perp}; \quad u = \frac{Q^2}{p_\perp^2}; \quad v = \delta^2 + (1 - \xi^2)u = \frac{4m^2 + (1 - \xi^2)Q^2}{p_\perp^2}. \tag{5}
\]

Besides, \( e = (0, e, 0) \) and \( e_V = (0, e_V, 0) \) are the polarization vectors of the transverse photon and the transversely polarized vector meson.

As usually, \( \alpha_s = g^2/4\pi, \quad \alpha = e^2/4\pi = 1/137 \), \( Q_q e \) is the quark charge, \( N = 3 \) is the number of colors.
Impact representation

The amplitude of the process in the lowest nontrivial pQCD order is described by the diagrams of Fig. 1 (with the accuracy $\sim p_\perp^2/s, Q_\perp^2/s$). Just as in refs. [2,3,22], the sum of these diagrams is transformed with the same accuracy to the integral over the gluon transverse momentum — the impact representation:

$$M_{\gamma^*Vq} = is \int \frac{J_{\gamma^*V}(k_\perp, p_\perp) J_{qq}(-k_\perp, -p_\perp) d^2k_\perp}{k_\perp^2 (k_\perp - p_\perp)^2 (2\pi)^2}. \quad (6)$$

Impact–factors $J_{\gamma^*V}$ and $J_{qq}$ correspond to the upper and the lower blocks in Fig. 1. They are $s$–independent. The entire dependence on the photon virtuality is concentrated in the impact–factor $J_{\gamma^*V}$. For colorless exchange the impact–factors contain factors $\delta_{ab}$, where $a$ and $b$ are the color indices of the exchanged gluons.

The impact–factors, which describe the transition between two colorless states vanish when the gluon momenta tend to zero: [2]:

$$J_{\gamma^*V}(k_\perp, p_\perp) \rightarrow 0 \quad \text{at} \quad \begin{cases} k_\perp \rightarrow 0, \\ (p - k)_\perp \rightarrow 0. \end{cases} \quad (7)$$

This general property ("dipole shielding" or "quark coherence") takes place independent on the validity of perturbation expansion. In the coordinate space this property can be treated as zero’s color charge of an object.

The derivation of impact representation and impact–factors repeats in the main features that given in Appendices to ref. [2] (see refs. [23], [24] also) with two variations.

First, one should consider separately the impact–factors of a photon to meson transitions for the transverse ($\gamma^*_T$) and scalar (or longitudinal) ($\gamma^*_S$) initial off–shell photons.

Second, Sudakov variables are introduced for the reaction with "massive" collided particles. All momenta are decomposed over the plane perpendicular to the reaction axis and over the light-like four–vectors combined from the initial ones: $p'_1 = p_1 - (p_1^2/s)p_2 = p_1 + (Q^2/s)p_2$, $p'_2 = p_2 - (p_2^2/s)p_1$. It leads to the single replacement

$$m^2 \rightarrow m^2 + Q^2(1 - \xi^2)/4. \quad (8)$$
in the denominators of quark propagators.

**Relation to the BFKL Pomeron.**

Let us discuss briefly the relation with the entire pQCD series in LLA (the BFKL Pomeron \[25\]). The modern using of BFKL for the diffractive processes at high \(p_\perp\) was initiated by the paper \[26\].

In the LLA the impact representation transforms to the form (see Fig.X):

\[
M_{\gamma^*q \to Vq} = is \int J_{\gamma^*V}(k_\perp, p_\perp) J_{qq}(-k'_\perp, -p_\perp) \mathcal{P}(s; p_\perp, k_\perp, k'_\perp) \frac{d^2k_\perp d^2k'_\perp}{(2\pi)^4}. \tag{9}
\]

The discussed lowest nontrivial approximation of pQCD (6) corresponds to

\[
\mathcal{P}(s; p_\perp, k_\perp, k'_\perp) = \frac{(2\pi)^2 \delta(k_\perp - k'_\perp)}{k_\perp^2 (k_\perp - p_\perp)^2} \delta_{aa'} \delta_{bb'}. \tag{8}
\]

The kernel \(\mathcal{P}\) of eq. (8) corresponds to the LLA for the pP.

In accordance with predictions of refs. \[2,3\], the amplitude (8) in its asymptotic form (the high energy asymptotic of LLA result) is Regge–like:

\[
M = isG_{\gamma^*V}(p_\perp, Q^2) \cdot K(s/p_\perp^2) \cdot G_{qq}(p_\perp). \tag{10}
\]

At \(p_\perp^2 \gtrsim Q^2\) the LLA is governed by the unique large logarithm \(\ln(s/p_\perp^2)\), and the lowest nontrivial approximation for the impact–factors is valid. In this case the vertex \(G_{\gamma^*V}\) is the convolution of our \(\gamma^* \to V\) impact–factor with some factor from \(\mathcal{P}\). The corresponding integration is similar to that in our case, and the \(Q^2\) dependence near mass shell is expected to be roughly the same.

At \(Q^2 \gg p_\perp^2\) the additional large logarithm \(\ln(Q^2/p_\perp^2)\) appear. In this case the (unknown now) higher order corrections should be taken into account even at the description of the impact–factors. It is the first reason, why the \(Q^2\) dependence in this region cannot be predicted definitely now.

The kernel \(K\) is pP itself, it is obtained in refs. \[25\], one can write for \(\rho \gg 1\)

\[
K = \frac{e^{\rho \ln 4}}{(7\zeta(3)\rho)^{3/2}}; \quad \rho = \frac{6\alpha_s(c_1 p_\perp^2)}{\pi} \ln \frac{s}{c_2 p_\perp^2}. \tag{11}
\]
The quantities $x_i$ here cannot be determined within LLA (even at $Q^2 \ll p^2_\perp$ and for light mesons or photons). At $Q^2 \gg p^2_\perp$ these coefficients are completely unknown [28]. It is the second reason, why the $Q^2$ dependence in this region cannot be predicted definitely now.

The real influence of BFKL corrections is different for different processes even for real incident photons (due to important numerical factors). For the $J/\Psi$ production the BFKL Pomeron enhances the two–gluon result already at not too small $\rho > 0.8$ and pure two–gluon approximation practically lacks range of validity [10]. On the other hand, the Regge–like contribution (11) is larger than the two–gluon result only at $\rho > 3.4$ for the $\rho$ production with real photon [13] and at $\rho \sim 1$ for the hard Compton effect ($\gamma q \rightarrow \gamma q$) [14]. At smaller $\rho$ values the calculations in the discussed two–gluon approximation seems more adequate for the description of data.

III. IMPACT–FACTORS

Quark and gluon impact–factors

The impact–factors of $q \rightarrow q$ (from [3]) and $g \rightarrow g$ transitions through the colorless exchange are similar:

$$J_{qq} = g^2 \delta_{ab} \frac{2N}{N^2 - 1}; \quad J_{gg} = -g^2 \delta_{ab} \frac{N}{N^2 - 1}.$$  \hspace{1cm} (12)

The helicity and color state of the quark or gluon target are conserved in these vertices.

The relations (12) show that the cross section for the photoproduction of vector meson on a gluon is about 5 times larger than that on a quark:

$$d\sigma_{\gamma^* g \rightarrow V g} \left( \frac{2N^2}{N^2 - 1} \right)^2 d\sigma_{\gamma^* q \rightarrow V q} = \frac{81}{16} d\sigma_{\gamma^* q \rightarrow V q}.$$  \hspace{1cm} (13)

It means that the photoproduction of vector meson on a proton with the rapidity gap can be used for the study of the gluon content of a proton.

Besides, this relation allows us to present below the formulae for the photoproduction on a quark only.
Impact–factor $J_{\gamma^* \rightarrow q\bar{q}}$

The impact–factor for a transverse photon has the same form as for the on shell photon \[2\] but with the replacement \[8\] in denominators:

$$J_{\gamma^* \rightarrow q\bar{q}} = e Q g^2 \frac{\delta_{ab}}{2 N} \bar{u}_1 \left[ m R(m) \hat{e} - (1 + \xi) P(m) e - \hat{P}(m) \hat{e} \right] \frac{\hat{p}_2}{s} u_2. \quad (14)$$

Here transverse vector $P(m) = (0, P(m), 0)$ and scalar $R(m)$ are:

$$P(m) = \left[ \frac{q_{1\perp}}{q_{1\perp}^2 + m^2 + (1 - \xi^2) Q^2 / 4} + \frac{k_{\perp} - q_{1\perp}}{(k_{\perp} - q_{1\perp})^2 + m^2 + (1 - \xi^2) Q^2 / 4} \right] - [q_{1\perp} \leftrightarrow q_{2\perp}]; \quad (15)$$

$$R(m) = \left[ \frac{1}{q_{1\perp}^2 + m^2 + (1 - \xi^2) Q^2 / 4} - \frac{1}{(k_{\perp} - q_{1\perp})^2 + m^2 + (1 - \xi^2) Q^2 / 4} \right] + [q_{1\perp} \leftrightarrow q_{2\perp}]. \quad (16)$$

To describe the impact–factor for a scalar photon, it is necessary to define the polarization vector of scalar photon $e_S$. Taking into account the gauge invariance, in our kinematical region one can use a reduced form of this vector $e_S = 2 \sqrt{Q^2} \left( p'_2 / s \right)$. Then the calculations similar to those for $T$ photon:

$$J_{\gamma S q\bar{q}} = -e Q g^2 \frac{\delta_{ab}}{2 N} \frac{1 - \xi^2}{2} \sqrt{Q^2} R(m) \bar{u}_1 \frac{\hat{p}_2}{s} u_2. \quad (17)$$

It is easily seen that these impact–factors obey eq. (7).

Impact–factors for a meson production

To produce a meson, the relative transverse momenta of quarks should be small ($\lesssim \mu$). With our accuracy ($\mu^2 / p_{\perp}^2 \ll 1$) the transverse momenta of quarks relative to collision axis are proportional to their energies $\varepsilon_i$, i.e.

$$q_{1\perp} = \frac{1}{2} (1 + \xi) p_{\perp}, \quad q_{2\perp} = \frac{1}{2} (1 - \xi) p_{\perp}, \quad \varepsilon_{1,2} = \frac{1}{2} (1 \pm \xi) E.$$ 

The $q\bar{q} \rightarrow V$ transition is described, as usual (see [27]), by the change of product $\bar{u}_1 ... u_2$ for meson wave function $\varphi_V(\xi)$:
\[ Q_q \bar{u}_1 \ldots u_2 \to \frac{Q_V}{4N} \int_{-1}^{1} d\xi \begin{cases} f^L_V \phi^L_V(\xi) \text{Tr}(\ldots \hat{p}_3) & \text{for } V_L \\ f^T_V \phi^T_V(\xi) \text{Tr}(\ldots \hat{e}^T_V \hat{p}_3) & \text{for } V_T. \end{cases} \] (18)

(The trace over vector and color indices is assumed). The quantity \( Q_V \) relates to the quark charges in the meson \( V \). The specific form for these wave functions is given in eq. \( 28 \), eq. \( 34 \). We use the coupling constants from refs. \[29\], \[30\], see Table I.

The impact–factors \( J_{\gamma^*V} \) are obtained by the substitution of eq. \( (18) \) into eqs. \( (14) \), \( (17) \):

a) For a \textit{transverse photon} we have two opportunities:

\[
J_{\gamma^*V}(k_\perp, p_\perp) = \frac{1}{2} eQ_V g^2 \frac{\delta_{ab}}{2N} \int_{-1}^{1} d\xi \begin{cases} (-f^L_V) \phi^L_V(\xi) \xi (\text{Pe}) & \text{for } V_L \\ f^T_V \phi^T_V(\xi) mR (\text{ee}_V^*) & \text{for } V_T. \end{cases} \] (19)

b) A \textit{scalar photon} produces a longitudinal vector meson only:

\[
J_{\gamma^*V_L}(k_\perp, p_\perp) = -\frac{1}{2} eQ_V g^2 \frac{\delta_{ab}}{2N} \int_{-1}^{1} d\xi f^L_V \phi^L_V(\xi) \frac{1 - \xi^2}{2} \sqrt{Q^2 R}. \] (20)

Below we neglect the difference between \( \phi^L \) and \( \phi^T \), \( f^L \) and \( f^T \).

It is useful to introduce dimensionless vector \( r \) via equation \( k_\perp = (r + n)p_\perp / 2 \). Then the above impact–factors get the forms:

\[ J_{\gamma^*V} = eQ_V g^2 \frac{\delta_{ab}}{2N} \frac{f^L_V}{p_\perp} \left\{ \begin{array}{ll} (\text{eF}_{T\to V_L}) & \text{for } T\text{-photon} \to \text{meson } V_L \\ (\delta (\text{ee}_V^*) \text{F}_{T\to V_T}) & \text{for } T\text{-photon} \to \text{meson } V_T \\ \text{F}_{S\to V_L} & \text{for } S\text{-photon} \to \text{meson } V_L. \end{array} \right. \] (21)

\[ \text{F}_{T\to V_L} = -\int_{-1}^{1} d\xi \phi_V(\xi) \cdot \xi \left\{ \frac{(1 + \xi) n}{v + (1 + \xi)^2} + \frac{r - n\xi}{v + (r - n\xi)^2} \right\} - [\xi \leftrightarrow -\xi]; \] (22)

\[ \text{F}_{T\to V_T} = \int_{-1}^{1} \phi_V(\xi) d\xi \cdot \mathcal{R}; \quad \text{F}_{S\to V_L} = -\int_{-1}^{1} d\xi \sqrt{u(1 - \xi^2)} \phi_V(\xi) \cdot \mathcal{R} \] (23)

\[ \mathcal{R} = \left[ \frac{1}{v + (1 + \xi)^2} - \frac{1}{v + (r + n\xi)^2} \right] + [\xi \leftrightarrow -\xi]. \]

The impact–factor for \( \gamma \to \gamma \) transition (for the hard Compton effect) with on shell initial photon was obtained in fact for a long time ago in refs. \[24\], \[23\] and written in the convenient form in ref. \[2\] neglecting quark mass.

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IV. NEUTRAL VECTOR MESON PHOTOPRODUCTION ON A QUARK OR A GLUON

To calculate the amplitudes under interest we substitute these impact–factors into eq. (3). The result for the meson production on a quark is

\[ M_{\gamma^* q \rightarrow V_q} = \frac{ieQg^4}{\pi} \frac{s_f}{|p_\perp|^3} \frac{N^2 - 1}{N^2} \left\{ \begin{array}{ll}
(en) I_{T \rightarrow V_L} & \text{for } T\text{-photon } \rightarrow \text{ meson } V_L \\
(ee^*) \delta \cdot I_{T \rightarrow V_T} & \text{for } T\text{-photon } \rightarrow \text{ meson } V_T \\
I_{S \rightarrow V_L} & \text{for } S\text{-photon } \rightarrow \text{ meson } V_L
\end{array} \right\} \]

(24)

with

\[ I_a = \frac{1}{4\pi} \int \frac{F_a(r, n)}{(r - n)^2 (r + n)^2} d^2 r \equiv \int_{-1}^{1} d\xi \varphi_V(\xi) \Phi_a(\xi) \quad (a = T \rightarrow V_L, T \rightarrow V_T, S \rightarrow V_L). \]

(25)

(For \(a = T \rightarrow V_L\) the quantity \((nF_{T \rightarrow V_L})\) is used.)

Just as in refs. [2], [3], we perform first integration over the component of vector \(r\) along \(n\) using residues. The last integration is trivial (but bulky). Then the quantities in eq. (24) get the form

\[ \Phi_{T \rightarrow V_L} = \frac{\xi}{4(1 - \xi^2 - v)} \left[ \frac{(1 + \xi)^2 - v}{(1 + \xi)^2 + v} \ln \frac{(1 + \xi)^2 + v}{2\sqrt{v}} - \frac{(1 - \xi)^2 - v}{(1 - \xi)^2 + v} \ln \frac{(1 - \xi)^2 + v}{2\sqrt{v}} \right] \]

\[ \Phi_{T \rightarrow V_T} = \frac{1}{2(1 - \xi^2 - v)} \left[ \frac{(1 + \xi)}{(1 + \xi)^2 + v} \ln \frac{(1 + \xi)^2 + v}{2\sqrt{v}} + \frac{(1 - \xi)}{(1 - \xi)^2 + v} \ln \frac{(1 - \xi)^2 + v}{2\sqrt{v}} \right] \]

\[ \Phi_{S \rightarrow V_L} = -\sqrt{u}(1 - \xi^2)\Phi_{T \rightarrow V_T}. \]

(26)

We will discuss below the scale of \(Q^2\)-dependence for the cross sections. Let us define this scale \(\Lambda^2\) by the relation

\[ I_T(\Lambda^2) = \frac{1}{2} I_T(Q^2 = 0). \]

(27)

The results differ for the production of mesons consisting of heavy quarks (heavy mesons) and light quarks (light mesons) or photons.

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1 The results in the next three section were presented earlier in preprints [5] – without integration over \(\xi\), and [12] – in the final form.
V. PRODUCTION OF HEAVY MESONS

We begin with a more simple case of mesons consisting of heavy quarks ($J/\Psi$ or $\Upsilon$). It seems more clean since the large quark mass suppresses nonperturbative effects. The results are similar in main features to those obtained in ref. [3] for the mass shell photons. We will speak below about the $J/\Psi$ meson photoproduction for definiteness.

For the wave function of discussed mesons we use the main (non–relativistic) approximation:

$$\phi(\xi) = \delta(\xi).$$

(28)

With this wave function the impact–factor of $\gamma^T \rightarrow V_L$ transition (for production of longitudinally polarized vector meson by transverse photon) vanishes. The deviation from the simple form (28) can be described by the quantity $<\xi^2> = \int \xi^2 \phi(\xi) d\xi \sim 0.1$.

The photoproduction on a quark.

The main results for transverse photon coincide with those for real photons [3] with the natural replacement $\delta^2 \rightarrow \nu$. Finally, in eq. (24)  

$$I_{T \rightarrow \Psi_T} = \frac{1}{2(\nu^2 - 1)} L(\nu); \quad L(\nu) = \ln \left(\frac{1 + \nu}{4\nu}\right); \quad I_{S \rightarrow \Psi_L} = -\sqrt{u} I_{T \rightarrow \Psi_T};$$

$$I_{T \rightarrow \Psi_L} = \frac{<\xi^2>}{(1 + \nu)^2} \left[1 - \frac{\nu}{\nu - 1} L(\nu)\right]; \quad \nu = \frac{(4m^2 + Q^2)}{p_\perp^2}. \quad (30)$$

The helicity conserves in these reactions with high precision. The transverse photon produces mainly transverse $\Psi$. The admixture of longitudinally polarized $\Psi$ is $<\xi^2> \sim 0.01$ [3]. The scalar photon produces longitudinal $\Psi_L$ only. The ratio of amplitude with the production of transverse $J/\Psi$ by $T$-photons to that with the production of longitudinal $J/\Psi$ by $S$-photons is $\sqrt{4m^2/Q^2}$, it is independent on $p_\perp$. At $Q^2 > 4m^2$ the dominant polarization becomes longitudinal.

2 The result for the spin–nonflip amplitude coincides with that in ref. [10].
The largest amplitudes $\gamma^*_T q \rightarrow \Psi_T q$ and $\gamma^*_S q \rightarrow \Psi_L q$ vanish at $p^2_\perp = 4m_c^2 + Q^2$ (or $\nu = 1$). These zeroes shift strongly due to $< \xi^2 >$ corrections. At the higher values of $p_\perp$ these cross sections are small (cf. ref. [3]).

The shape of both main amplitudes is determined by the single function $I_{T \rightarrow \Psi_T}$. One can see that the scale of $Q^2$ dependence $\Lambda^2$ increases from the natural value $4m_c^2/2$ at small $p_\perp$ to $\sim p^2_\perp/10$ at large enough $p_\perp$.

The $Q^2$ dependence for the high energy asymptotic of LLA result in the photoproduction of heavy meson was considered in ref. [10]. Despite the difference in the absolute values, the qualitative picture at small $Q^2$ is similar to that in the two–gluon approximation.

The production of two mesons in $\gamma \gamma$ collision.

We have considered the production of both identical and different mesons by real or virtual photons. In particular, the collision of the virtual photon with the real one is described by two nonzero amplitudes, the first — for the production by $T$-photon and the second — for the production by $S$-photon (these amplitudes are finite at $p_\perp \rightarrow 0$):

$$
M_{\gamma^*_T \gamma \rightarrow \Psi^*_T \Psi_T} = \frac{is}{p^4} e^2 g^4 \pi Q V Q V' f_V f_{V'} \frac{N^2 - 1}{N^2} (e_1 e^*_V) (e_2 e^*_V') \delta \delta' \cdot I_{V'V};
$$

$$
M_{\gamma^*_S \gamma \rightarrow \Psi^*_L \Psi_T} = -\frac{is}{p^4} e^2 g^4 \pi Q V Q V' f_V f_{V'} \frac{N^2 - 1}{N^2} (e_2 e^*_V) \sqrt{u'} \delta \cdot I_{V'V};
$$

$$(31)$$

$$
I_{V'V} = \frac{1}{u'} \left[ \frac{L(\delta^2)}{(\nu' + 1)(\delta - 1)} - \frac{L(\nu')}{(\nu' - 1)(\delta + 1)} \right].
$$

Here $\nu'$ corresponds to the meson produced by off shell photon, and $\delta$ — to the meson produced by on shell photon.

VI. PRODUCTION OF PHOTONS AND LIGHT MESONS ON A QUARK OR A GLUON

The pQCD limit here corresponds to the asymptotic $m/p_\perp \rightarrow 0$. Therefore, we neglect quark mass in this subsection.
The amplitude for the hard Compton effect on a quark with on shell initial photon was obtained in fact in refs. [24, 23] and written in the suitable form in ref. [2] neglecting quark mass. In the region of pQCD validity one can write for unpolarized photons

$$\sigma(\gamma q \rightarrow \gamma q) = \left( \frac{p_\perp}{16.6 \text{GeV}} \right)^2 \sigma(\gamma q \rightarrow \rho q).$$

(32)

For the vector meson production the impact–factor \(J_{\gamma^* V_T}\) contains the factor \(\delta = \frac{2}{p_\perp m}\). Therefore, within the range of pQCD validity (at large enough \(p_\perp\)) transverse photon produces light meson in the states with helicity 0 only for any polarization of initial photon. This fact is in the evident contrast with the well known helicity conservation at small \(p_\perp\) (vector mesons are produced transversely polarized mainly). It is due to the chiral nature of perturbative couplings in the massless limit.

We write in this section for the shortness

$$I_T \equiv I_{T-V_L}; \quad I_S \equiv I_{S-V_L} \equiv -\frac{2\sqrt{u}}{1+u} (I_T + U).$$

(33)

We use the wave functions of mesons consisting of light quarks in the form [29]:

$$\phi_V(\xi) = \frac{3}{4} \left( 1 - \xi^2 \right) \left( 1 - \frac{1}{5} b_V + b_V \xi^2 \right).$$

(34)

Coefficients \(b_\rho = b_\omega = 1.5\), \(b_\phi = 0\) at \(p_\perp \approx 1\) GeV, they tend to 0 slowly with \(p_\perp\) growth.

For the asymptotical wave function \((b_V = 0)\) we obtain:

$$I_T(u) \equiv I_0(u) = \frac{3}{8(1-u)^3} \left[ 2 + 10u - u \left( \frac{1+u}{1-u} \right) \left( \ln^2 \frac{1}{u} + 6 \ln \frac{1}{u} \right) \right];$$

$$U(u) \equiv U_0(u) = \frac{3}{8(1-u)} \left[ 2 - \frac{1+u}{1-u} \ln \frac{1}{u} \right].$$

(35)

For the case \(b_V \neq 0\) the more complicated expressions are obtained:

$$I_T(u) = I_0(u) \left[ 1 - \frac{b_V}{5} + b_V \left( \frac{1+u}{1-u} \right)^2 \right] +$$

$$\frac{b_V}{12(1-u)^4} \left[ -(3-10u)(1-u) + 16u(u^2 + 5u + 1)U_0(u) \right];$$

$$U(u) = U_0(u) + \frac{b_V}{60(1-u)^2} \left[ 5(1-u) + 8(1+8u+u^2)U_0(u) \right].$$

(36)
These expressions are regular at $u = 1$. At $u = 0$ (real photoproduction) $I_T = \frac{3}{4} \left(1 + \frac{7}{45} b_V \right)$.

The dependence on the photon virtuality is concentrated in the factors $I_T$, $I_S$. The shapes of these functions depend weakly on the form of wave function (value of quantity $b_V$). They are plotted in Fig. 3 for $\rho^0$ meson production ($b_V = 1.5$).

The obtained in pQCD cross sections for the light vector meson production on a gluon (the sum $d(\sigma_{\gamma^* g \rightarrow V g} + d\sigma_{\gamma^*_g \rightarrow V g})/dp_{\perp}^2$) are presented in Fig. 4. They are $s$-independent in the used two-gluon approximation.

If the virtuality of photon is less than $p_{\perp}^2$ ($u < 1$), the amplitude for transverse photon dominates over longitudinal one. Fig. 3 shows very sharp peak in $I_T$ near $Q^2 = 0$. It is due to the items $\propto u \ln^2 u$ in eqs. (35), (36). The derivative of the amplitude in $Q^2$ (in $u$) diverges at $Q^2 = 0$, it is infrared unstable in contrast with the amplitude itself, which is infrared stable. The quantity $I_T$ is reduced by half at $u \approx 0.1$. It means, that the scale of $Q^2$ dependence here is

$$\Lambda^2_{\text{pert}} \approx p_{\perp}^2 / 10.$$ (37)

The function $I_S(u)$ changes its sign at small enough $u = u_0$. The quantity $u_0 \approx 0.1$ for the asymptotical form of wave function ($b_V = 0$) and $u_0 \approx 0.02$ for the more wide wave function with $b_V = 1.5$. This behavior is similar in some sense to that for $J/\Psi$ production** at very high values of $p_{\perp}$.

The obtained scale of $Q^2$ dependence is substantially lower than it was expected before calculations. This fact should be considers at the calculation of the production rate in $ep$ collisions.

If the photon virtuality is large, $Q^2 > p_{\perp}^2$ (or $u > 1$), the amplitude with the scalar photon become dominant.

$$M_{\gamma^*_q \rightarrow V_{Lq}} \propto \frac{\ln u}{(Q^2)^{3/2}}; \quad M_{\gamma^*_q \rightarrow V_{Lq}} \propto \frac{p_{\perp}(\ln u)^2}{(Q^2)^2} \left( u = \frac{Q^2}{p_{\perp}^2} \right).$$ (38)

This region of parameters was studied in refs. [10] for the heavy meson photoproduction at the high energy asymptotic of LLA. Here the LLA amplitude contains an additional factor
\( \propto Q/p_\perp \) in comparison with the two–gluon amplitude. The same factor for the light meson photoproduction was found in ref. [13].

**VII. SMALL \( p_\perp \) LIMIT FOR HIGH \( Q^2 (U < 1) \) AND COHERENCE**

In the pQCD limit the amplitudes of photoproduction on a quark or a gluon (29,35,36) diverge at \( p_\perp \to 0 \) (see [3] too). It means that ”soft” nonperturbative region of \( k_\perp \sim \mu \) contributes substantially in this case and pQCD calculations are infrared unstable. Therefore, the details of \( p_\perp \) dependence at \( p_\perp \to 0 \) are out of the range of pQCD validity even at large \( Q^2 \) when we consider the production on a color target.

The reason for this divergence is simple: in the above limit the poles of the both gluon propagators coincide, and we deal with the integral of the form

\[
\int J(k_\perp) d^2k_\perp/k_\perp^4.
\]

In accordance with eq. (7), \( J \propto k_\perp \) at \( k_\perp \to 0 \) and \( J \propto (p - k)_\perp \) at \( (p - k)_\perp \to 0 \). At \( p_\perp \to 0 \) both these zeroes coincide, and \( J \propto k_\perp^2 \). The discussed divergence is only logarithmic, the total cross section is finite.

On the contrary, the \( \gamma^*\gamma \to \Psi\Psi \) amplitude is finite at \( p_\perp \to 0 \) due to additional factor \( J \propto k_\perp^2 \) in the integrand. Therefore, the soft part of integration region gives a negligible contribution here.

The main difference between these amplitudes originates from the fact that in the last case we deal with the collision of two colorless objects; the coherence between quarks results in the additional suppression of soft nonperturbative contributions here (7).

The above comparison shows us that the coherence in the both collided particles should be taken into account to describe phenomena at any \( p_\perp \) within pQCD even in the region of large \( Q^2 \).
VIII. THE RANGE OF VALIDITY OF THE PQCD RESULTS. THE LIGHT VECTOR MESON PRODUCTION AND HARD COMPTON EFFECT

The above results show us that the using of pQCD for the description of experimental data can be inaccurate in some region of parameters. For example, the obtained scale of $Q^2$ dependence $\Lambda^2_{\text{pert}} \approx p^2_{\perp}/10$ \cite{37} is smaller than the natural scale of this dependence near mass shell $\Lambda^2_{\text{soft}} \approx m^2_{\rho}$ even at $p_{\perp} = 2.5$ GeV when our small parameter $\mu^2/p^2_{\perp} < 0.02$.

In the discussion below we assume the impact representation to be valid independent on validity of pQCD for the description of different factors in it. In particular, the proof of impact representation in the lowest nontrivial approximation of pQCD is valid even in the regions near the poles of quark propagators in the impact–factor, where its perturbative form \cite{13,16} becomes incorrect.

The model for amplitude near the bound of pQCD validity region

To study the bound of pQCD validity, we use single scale of QCD nonperturbative effects $\mu$. We will have in mind the value $\mu = 0.2 \div 0.3$ GeV, which is close to the confinement scale, constituent quark mass, mean transverse momentum of quarks in meson, etc. The value $\mu = 180$ MeV is obtained at the analysis of total $\gamma\gamma$ cross section in the model with quark and one-gluon exchange \cite{31}.

We simulate nonperturbative effects by the adding of quantity $\mu^2$ (instead of $m^2$) in the all quark propagator denominators. Besides, we change the quantity $m$ from the quark propagator numerator (in front of item $R$ in eq. (14)) for some new quantity $A \sim \mu$:

$$P(m) \rightarrow P(\mu); \quad mR(m) \rightarrow A \cdot R(\mu) \quad (A \sim \mu).$$ \hspace{1cm} (39)

The regions, where the amplitude is sensitive to $\mu$ value, are beyond the pQCD validity. We denote the bound $p_{\text{pert}}$ of pQCD validity region by the relation

$$d\sigma(p_{\perp} \geq p_{\text{pert}}|\mu) > 0.5 \cdot d\sigma(p_{\perp} \geq p_{\text{pert}}|\mu = 0).$$ \hspace{1cm} (40)
A. Processes with real incident photon

The main part of discussion in this section is devoted to the meson photoproduction.

Contribution of item $R$ provides helicity conservation (production of $V_T$) in the process. The item $P$ in the impact–factor gives longitudinal polarization of produced mesons ($V_L$). The contribution of this item decreases more slow with $p_\perp$ due to extra degree of momentum in the nominator. Therefore, this item describes the amplitude at high enough $p_\perp$.

Let us discuss the limit $\mu \ll p_\perp$ in more detail. The contribution of $R$ diverges in this limit, due to the integration near the poles of quark propagators at $k_\perp = q_i\perp$, it is $\sim \ln(p_\perp^2/\mu^2)$ (i.e. infrared unstable). It dominates at not too large $p_\perp$. Oppositely, the contribution of $P$ is finite in the discussed limit. It is infrared stable, and it defines the amplitude within the range of pQCD validity.

Therefore, it is natural to assume that the contribution $P$ describes the point–like component of a photon in the region where confinement effects are negligible. It dominates at high values of $p_\perp$ and it is responsible for the production of longitudinally polarized mesons. Similarly, the contribution $R$ for transverse photons describes the hadron–like component of a photon. It dominates at not too high values of $p_\perp$ and it gives helicity conservation here. In addition to the boundary $p_{\text{pert}}$ \cite{40} we denote the boundary value $p_{\text{hel}}$ by the condition: At $p_\perp > p_{\text{hel}}$ the mean helicity of produced meson changes from the transversal to the longitudinal one (i.e. the hadron–like component $R$ becomes relatively small).

The bound of pQCD validity, the estimate of $p_{\text{pert}}$ for mesons

We expect that $p_{\text{hel}} < p_{\text{pert}}$. Therefore, to find the bound $p_{\text{pert}}$, one should consider point–like component of a photon (contribution $P$ in the impact–factor) only. We present two estimate here.

First estimate. It is well known that the typical scale of the $Q^2$ dependence for soft processes $\Lambda_{\text{soft}}^2 \approx m_\rho^2$ (here $m_\rho$ is the mass of $\rho$ meson). The known data show us that this
scale increases with the growth of $p_\perp$.

The scale of $Q^2$ dependence for the $\rho$ photoproduction is $\Lambda^2_{\text{pert}} \approx p^2_\perp/10$ (37). The pQCD can be valid for description of the discussed phenomena only if $\Lambda^2_{\text{pert}} > \Lambda^2_{\text{soft}}$, i.e. at $p^2_\perp/10 > m^2_\rho$, that leads to $p_\perp \gtrapprox 3$ GeV. It does not contradict more refined estimate (37).

Second estimate. We calculated numerically the contribution of item $P$ in impact–factor (24)–(26) with some finite value of $\mu$ for different meson wave functions. The influence of the nonperturbative effects is described by the quantity $\Phi(\delta, u) = M(\delta, u)/M(\delta = 0, u)$. Naturally, the ratio $\Phi \to 1$ at $(p_\perp/\mu) \to \infty$. (That is the pQCD limit.) The value $p_{\text{pert}}$ is obtained via eq. (40). At higher values of $p_\perp$ the influence of confinement effects for the pQCD result in the cross section is described by factor $\Phi_2$, which is between 0.5 and 1. In Fig. 5 we present the quantities $\Phi(\delta, u)$ (for real photons).

It is seen that for mass shell photons $p_{\text{pert}} \approx (30 \div 40)\mu$. In this region the coefficient $b_\nu$ in the $\rho$ meson wave function decreases up to $b_\nu \approx 0.7$. Taking this fact into account, we have for $\mu = 0.2$ GeV

$$p_{\text{pert}} \approx \begin{cases} 7.5 \text{ GeV} & \text{for } b_\nu = 0.7 \ (\rho - \text{ meson at } p_\perp \approx 7 \text{ GeV}), \\ 6.2 \text{ GeV} & \text{for } b_\nu = 0 \ (\phi - \text{ meson}). \end{cases} \quad (41)$$

For $\mu = 0.3$ GeV these quantities should be 1.5 times higher.

The obtained values of $p_{\text{pert}}$ (41) for the mass shell photons are very high. It is because the correction to the pQCD result is governed by the parameter $(\mu^2/p^2_\perp) \ln^2(p^2_\perp/\mu^2)$ but not the ”natural” parameter $\mu^2/p^2_\perp$. The effect of ”$\mu$ corrections” in pQCD equations is enhanced near the bounds of kinematical region, at $\xi \rightarrow \pm 1$. Therefore, their influence is higher for the wave function, which is ”shifted” to these bounds (with $b_\nu > 0$). In other words, the bounds for pQCD validity region $p_{\text{pert}}$ are lower for the $\phi$ meson photoproduction ($b_\nu = 0$) in comparison with that for $\rho$ photoproduction ($b_\nu = 1.5$).

The estimate of $p_{\text{pert}}$ for the hard Compton effect

The amplitude of the hard Compton effect (11) for real photons with the necessary accuracy is obtained from that in [24] (with some numerical factors, like [4]). Using the standard
quantity $R, = 3 \sum_{uds} Q^2 = 2$ and the quantity $\epsilon = \mu / p_\perp$, one can write:

$$M_{\gamma q \rightarrow \gamma q} = i \frac{16}{27} \alpha_s R, \frac{2}{7} \left[ A_\parallel (e_1 n) (e_2^* n) + A_\perp ((e_1 e_2^*) - (e_1 n)(e_2^* n)) \right];$$

$$A_\parallel = 11.58 + 6 \epsilon^2 \left[ \frac{8}{3} \ln^3 \epsilon + 2 \ln^2 \epsilon - 32.32 \ln \epsilon - 74.83 \right];$$

$$A_\perp = 5.58 + 6 \epsilon^2 \left[ 6 \ln^2 \epsilon - 10 \ln \epsilon + 6.6 \right].$$

Two independent amplitudes contribute here. The nonperturbative corrections in these amplitudes are of different sign. The largest among them tends faster to its asymptotical value. Naturally, the bound of the region of the pQCD validity for the unpolarized photons is relatively low. Finally, using eq. (40), we obtain:

$$p_{pert} (A_\perp) \approx 3 - 4 \text{ GeV for } \mu = 0.2 - 0.3 \text{ GeV}$$

$$p_{pert} (A_\parallel) \approx 1.3 - 2 \text{ GeV for } \mu = 0.2 - 0.3 \text{ GeV}$$

$$p_{pert} (unpol) \approx 0.8 - 1.2 \text{ GeV for } \mu = 0.2 - 0.3 \text{ GeV}$$

Therefore, despite of smaller value of cross section, the study of pure pQCD behavior in the hard Compton effect can be better than that in the meson photoproduction.

**Estimate of $p_{hel}$**

Let us find the crossover point, in which the longitudinal polarization becomes dominant for the transversal initial photon (the boundary $p_{hel}$). This boundary is less than the boundary $p_{pert}$. Therefore, the calculations near this point depend on the details of the model more strong. To see qualitative features of this crossover, the model (39) is used with the value $A = 1 \text{ GeV}$.

Figs. 6,7 shows the cross sections of the photoproduction by real photons for $\mu = 200 \text{ MeV}$. In these figures the curves $R$ correspond to the production of transverse mesons (helicity conserved contribution, item $R$ (16), hadron–like component of a photon) and the curves $P$ correspond to the production of longitudinal mesons (item $P$ (13), point–like
component of a photon). Fig. 6 shows the curves for ρ meson production ($b_V = 1.5$). Fig. 7 shows the curves for φ meson production (asymptotical wave function, $b_V = 0$).

In both cases the crossover point $p_{hel}$ is $1.5 \div 5$ GeV. Next, the admixture of transversely polarized mesons at $p_\perp > p_{hel}$ for the ρ photoproduction decreases with $p_\perp$ faster than that one for φ mesons. We expect, that this feature conserves for virtual photons. It means, that in the data averaged over some $p_\perp$ interval the fraction of longitudinal φ’s is larger than that for ρ’s. This conclusion is supported by the data [17].

**B. Processes with the off shell photons**

The photon virtuality prevents quark propagators from their poles while $\xi \neq \pm 1$. It is the reason why $p_{pert}$ decreases fast with the photon’s virtuality. Our calculations show that

\[
p^2_{pert} \approx \begin{cases} 
 1.3 \text{ GeV}^2 & \text{for } \rho \\
 1 \text{ GeV}^2 & \text{for } \phi 
\end{cases} \quad \text{at } \mu = 0.2 \text{ GeV}, Q^2 = 1 \text{ GeV}^2; \\
\end{equation}

\[
p^2_{pert} \approx \begin{cases} 
 28 \text{ GeV}^2 & \text{for } \rho \\
 10 \text{ GeV}^2 & \text{for } \phi 
\end{cases} \quad \text{at } \mu = 0.3 \text{ GeV}, Q^2 = 1 \text{ GeV}^2; \\
\end{equation}

\[
p^2_{pert} \approx \begin{cases} 
 3.3 \text{ GeV}^2 & \text{for } \rho \\
 2 \text{ GeV}^2 & \text{for } \phi 
\end{cases} \quad \text{at } \mu = 0.3 \text{ GeV}, Q^2 = 2.25 \text{ GeV}^2; \\
\end{equation}

(45) (46)

It is seen, that the pure pQCD description for the longitudinal meson photoproduction becomes valid earlier for the φ photoproduction as compare with ρ one.

??

**C. The signature of pQCD validity.**

*In the range of pQCD validity the light mesons should be produced in the state with helicity 0 only [2].* It is in strong contrast with the production in "soft" region where the helicity conservation takes place, and real photons produce transversely polarized mesons.
Unfortunately, there is no similar good signature for the hard Compton effect and production of heavy mesons.

Besides, the striking feature of the results obtained is very sharp dependence on the photon virtuality of the amplitude of reactions (1) near the point $Q^2 = 0$ (more precise, on the ratio $u$). The observation of such behavior will be a good test of pQCD.

IX. BRIEF DISCUSSION ABOUT SOME RELATED PAPERS

In the paper [10] the photoproduction of heavy mesons in the process (1) was studied as in the two-gluon approximation as well as in the LLA (using the BFKL equation) in dependence on both $p_{\perp}^2$ and $Q^2$. It was found the lack of validity of the two–gluon approximation when $\rho \geq 0.8$ (see eq. (11) for description and discussion). At $\rho \sim 2$ the LLA result exceeds the Born one by a factor $\sim 10$ in cross section.

In this paper the non–relativistic approximation for the meson wave function (28) was used. The calculations in both this paper and in refs. [13,14] show that many features of results in ref. [10] are connected with this specific form of the wave function and difference in the quark masses.

To describe the production of light mesons it is necessary to consider the nontrivial longitudinal motion of quarks in a light meson according to the standard leading twist approach to the hard exclusive processes, for example, in the form (34) [27,28,30]. This very difference together with the difference in quark masses results in the discussed substantial difference in the produced mesons polarization in the reactions (1). It is the first point, which shows that the experience with the $J/\Psi$ photoproduction is almost useless for the description of the light vector meson photoproduction.

The light vector mesons production in the process (1) was studied in the high energy limit of LLA in ref. [13]. The obtained cross section was found to be less than the that in the two–gluon approximation at $\rho < 3.4$ (cf. eq. (11)). Even at $c_1, c_2 = 1$, $p_{\perp} = 5$ GeV this value of $\rho$ corresponds to $\sqrt{s_{\gamma q}} = 335$ GeV. This energy is unaccesible for the HERA
collider. For the smaller values of $p_\perp$ we come to the lower values of $\sqrt{s_{\gamma q}}$, at which the BFKL result for the amplitude exceeds the Born one, are lower. However, as it is shown above, this region is definitely beyond the pQCD validity. The pure pQCD description based on the "hard Pomeron" concept is invalid here. The hard Compton effect is more favorable to study the pP due to both much lower value of $p_{\text{pert}}$ (43) and lower value of $\rho$, which is necessary to see BFKL effect in comparison with the two–gluon approximation [14].

Other known for us papers, which treat the similar problems for the processes like (11), contain the essential phenomenological components (usually pQCD inspired).

These models are based, in fact, on the impact representation like (11). The description begins with the diffractive region (small $p_\perp$). It is a reasons why authors use the hadron–like component of photon (item $R$ but no point–like one $P$) only with some parameter $\mu$ for the detail description of cross section. These models predict the helicity conservation in reaction $\gamma q \rightarrow \rho^0 q$. They do not predict the change of polarization of produced mesons at high $p_\perp$.

The quasi–elastic process $\gamma^* p \rightarrow pp$ (without proton’s dissociation) was studied in refs. [4,6]. In these papers it was used the QCD inspired phenomenological model, which can be written in the form of impact representation (11) with the replacement of pQCD gluon propagators on the reggeized ones. The $Q^2$ dependence for the forward scattering amplitude in this model differs from that obtained in pQCD [8].

Recently the papers [8], [9], [7] were published, where the problems are studied that are close to those discussed above. In these papers quasi–elastic photoproduction of vector mesons on a proton without proton’s dissociation ($\gamma^* p \rightarrow Vp$) is studied (with $V = \rho$ in [8,7] and $V = J/\Psi$ in [9]).

The first stage in these papers corresponds to the simplest pQCD diagram just as in our paper. The following stages are used some features of processes at $p_\perp \approx 0$. To describe the picture at large $p_\perp$ some phenomenological assumptions were added in papers [9], [7].

The $\rho$ meson photoproduction at $p_\perp \approx 0$ was studied in ref. [8]. The same very region for the $J/\Psi$ photoproduction is the starting point for ref. [9]. Just here some features of LLA provides an opportunity to use unitarity for the construction of cross section in terms
of the LLA proton’s gluon distribution\(^3\). We consider other kinematical region, see eq. (2).

The papers [7] treat the process (1). The crucial point here is the using of hadron–like component of a photon (factor \(R\)). It is the reason why these authors obtain the transversal polarization of \(\rho\) meson for on shell photoproduction even at large enough \(p_\perp\).

**X. CONCLUDING REMARKS**

Let us summarize our predictions (mainly for HERA experiments) related to the photoproduction of light mesons and hard Compton effect. (We remind that the results for the \(J/\Psi\) photoproduction relate weakly to these problems.)

1. For the real photoproduction we expect the change of mean polarization of produced vector mesons at \(p_\perp \sim 1.5 \div 5\) GeV. Above this bound the produced vector mesons should be mainly longitudinally polarized. We expect that for the \(\phi\) photoproduction this bound is lower than that for \(\rho\), and the fraction of transversal \(\phi\) decreases with \(p_\perp\) more fast.

2. The pure pQCD regime is hardly observable for the production of light mesons by real photons, since the corresponding boundary value of transverse momentum is very high, even for \(\mu = 0.2\) GeV (\[11\]). However it seems observable at the study of hard Compton effect.

We believe that this pQCD regime is observable at HERA and at future Photon colliders for both light vector meson and photon production. For the vector meson

\(^3\) This basic construction is broken up at \(p_\perp \neq 0\). To describe the \(J/\Psi\) production in this region, it is used the additional assumption in ref. [8], that the object, which was the proton’s gluon distribution at \(p_\perp = 0\), transforms to the product of this distribution and some proton form factor dependent on \(p_\perp^2\) only.
production this regime can be seen better in the photoproduction by virtual photons (45). The signatures for this regime is: The produced light mesons are polarized longitudinally. Unfortunately this pQCD regime seems to be unobservable at LEP2.

3. One can consider the special region of large enough $p_\perp$ (within the region of pQCD validity) and not too high values of rapidity gap (say, $y < 3$). In accordance with the results of refs. 3, 13, we expect that in this region our two gluon approximation works, i.e. the $y$–dependence is weak and $u$–dependence is given by eqs. (35,36).

The photoproduction of jets in the "direct" configuration and with the rapidity gap provides the opportunity to see the same mechanisms in processes with the larger cross sections. First data on these processes were reported recently 18. The results of corresponding calculations are bulky and needs for detail discussions. One can expect that the point $p_{pert}$ will be lower here than that for the vector meson production (11).

Last, the photoproduction of scalar (or tensor) meson on a gluon is forbidden due to C parity conservation 32. Therefore, the comparative study of the vector and scalar (or tensor) meson production in $ep$ collision can give an additional information about the gluon content of a proton and about the shadowing effects at small $x$.

Acknowledgments. This paper was prepared in the continuous discussions with V.G. Serbo, who checked some results. We are very thankful for his help and criticism. We are grateful to P. Aurhence, A.C. Bawa, W. Buchmuller, V. Chernyak, R. Cudell, A. Efremov, L. Lipatov, K. Melnikov, M. Ryskin, A. Vainshtein and G. Wolf for useful discussions. This work is supported by the grants of Russian Foundation of Fundamental Investigations and INTAS. I.F.G. is thankful to the Soros Educational Program for support.
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FIGURES

\[ s = (p_1 + p_2)^2 \]

\[ p_1' = q_1 + q_2 \]

A. Basic diagram

\[ k \]

\[ p - k \]

\[ p = p_1' - p_1 \]

B. Impact–factor

\[ + (k \leftrightarrow p - k) \]

FIG. 1. Photoproduction of vector meson on a quark (two–gluon exchange).
FIG. 2. Pomeron exchange in the process of vector meson photoproduction.
FIG. 3. Functions $I_T$ and $I_S$ for the process $\gamma^* q \to \rho^0 q$ or $\gamma^* g \to \rho^0 g$. 

$\frac{u = Q^2}{p_{\perp}^2}$
\[ \frac{d\sigma}{dp^2_\perp}, \text{nb} \cdot \text{GeV}^{-2} \]

FIG. 4. Differential cross section of $\gamma^* g \rightarrow \rho^0 g$ process at $Q^2 = 0$, $Q^2 = 2 \text{ GeV}^2$ and $Q^2 = 10 \text{ GeV}^2$. 
FIG. 5. The ratios $\Phi = M(\delta)/M(\delta = 0)$ for mass shell photons ($u = 0$) in dependence on $p_\perp/\mu = 2\delta^{-1}$. 
FIG. 6. The differential cross sections of $\rho^0$ meson photoproduction ($b_V = 1.5$) by real photons for $\mu = 200$ MeV. In these figures curves $R$ correspond to the production of transverse mesons (helicity conserved contribution, item $R$, hadron–like component of photon) and curves $P$ correspond to the production of longitudinal mesons (item $P$, point–like component of photon).
\[ \frac{d\sigma}{dp_{\perp}^2}, \text{nb} \cdot \text{GeV}^{-2} \]

FIG. 7. The same figure as previous one, but for photoproduction of \( \phi \) meson \((b_V = 0)\).
TABLE I. Values of mesons coupling constants.

|      | $\rho^0$ | $\omega$ | $\phi$ | $\Psi$ | $\Psi'$ | $\Upsilon$ | $\Upsilon'$ | $\Upsilon''$ |
|------|----------|----------|--------|--------|---------|------------|------------|-------------|
| $f_V$, GeV | 0.21     | 0.21     | 0.23   | 0.38   | 0.28    | 0.66       | 0.49       | 0.42        |
| $Q_V$   | $1/\sqrt{2}$ | $1/(3\sqrt{2})$ | $1/3$   | $2/3$   | $2/3$   | $1/3$      | $1/3$      | $1/3$       |