The photon structure and exclusive production of vector mesons in $\gamma \gamma$ collisions

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Abstract

The process of exclusive vector meson production $\gamma \gamma \rightarrow J/\psi \rho^0$ is studied for almost real photons. This process may be reduced to photoproduction of $J/\psi$ off the $\rho^0$ meson. We discuss the possibility of extracting the gluon distribution of $\rho^0$ and of the photon from such measurement. Predictions are also given for the reaction $e^+e^- \rightarrow e^+e^- J/\psi \rho^0$ for various $e^+e^-$ cms energies typical for LEP and for the future linear colliders.
The successful operation of LEP2 has given a significant boost for extensive studies of the photon structure — both theoretically and experimentally (see eg. [1, 2]). We may expect further progress in this field after the next generation of high energy linear colliders have started. However, up to now, the existing results for the photon structure have rather limited accuracy. They are based mainly on the inclusive data, i.e. the total $\gamma\gamma^*$ cross section. It should therefore be useful to supplement this classical approach with some other independent methods of measurement of the partonic content of the photon. In fact, the Ryskin process [3] of elastic vector meson photoproduction at HERA may serve as a good example of such alternative way of extracting gluon distribution of the proton [4].

The cross section for the exclusive reaction $\gamma\gamma \rightarrow J/\psi V$ is expected to be dominated by light vector meson $V$ components of the photon. Thus, the exclusive reaction $\gamma\gamma \rightarrow J/\psi V$ should closely resemble the analogous well known one: $\gamma p \rightarrow J/\psi p$. Both of them have the advantage of directly testing the gluon distribution with the enhanced sensitivity to the $x$ dependence at low $x$. Therefore we shall analyze in detail the exclusive vector meson production $\gamma\gamma \rightarrow J/\psi V$ and show that, indeed, it may probe efficiently the gluon distribution of $V = \rho^0$, $\omega$ and $\phi$. Hence it may also constrain the gluon distribution of the photon. This new proposed measurement, when combined with HERA data may also test the universality of the Regge behaviour in exclusive vector meson production off different hadrons. Although such two photon reactions has been already studied, in particular in Refs. [5] and [6], the connection of the amplitude to the gluon distribution has never been exploited before. Finally, in order to estimate the feasibility of this measurement we shall also compute the corresponding $e^+e^-$ cross sections.

In most of the successful models of the photon structure [7, 8, 9] it is assumed that the photon wave function (in the strongly interacting sector) is represented by two significantly different sets of configurations: hadronic-like i.e. virtual light vector mesons $V$ and perturbative ones, corresponding to $q\bar{q}$ or $q\bar{q}g$ systems with transverse momenta in the perturbative domain. For the real photon the vector meson configurations dominate the photon-proton cross section (the Vector Meson Dominance model). The same property holds true for the $\gamma\gamma$ total cross section as well (see e.g. [9]). It is therefore legitimate to assume that in an exclusive process with a light vector meson in the final state the dominance will be even more pronounced. The perturbative configurations, less important for the total cross section, will tend to produce hadronic systems with higher invariant masses, not contributing to the selected exclusive channel. Thus the exclusive process $\gamma\gamma \rightarrow J/\psi V$ occurs predominantly through vector meson component $V$ of one of the incoming photons. It means that the scattering amplitude $\mathcal{M}(\gamma\gamma \rightarrow J/\psi V)$ will be well approximated by the amplitude $\mathcal{M}(\gamma V \rightarrow J/\psi V)$ multiplied by the photon-meson coupling $\sqrt{a g_V}$. 
It was pointed out by Ryskin [3] that the elastic $J/\psi$ photoproduction off the proton at the $\gamma p$ cms energy $W$ may probe the gluon distribution of the proton $xG^p(x, Q^2)$ for $x = M^2_{J/\psi}/W^2$ and $Q^2 = M^2_{J/\psi}/4$. Namely, the obtained differential cross section for $t = 0$

$$\frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt}(W^2, t = 0) = \frac{16\pi^3[\alpha_s(M^2_{J/\psi}/4)]^2\Gamma^{J/\psi}_{ee}}{3\alpha M^3_{J/\psi}} \left[ xG^p(x, M^2_{J/\psi}/4) \right]^2$$

(1)

depends on the square of $xG^p(x, M^2_{J/\psi}/4)$ which allows for the direct measurement of this quantity with enhanced sensitivity. This concept has proven to be extremely succesful, and it strongly stimulated the experimental efforts at HERA [10, 11]. Since the first paper [3] significant theoretical progress in this subject has also been made [12, 13]. A set of important corrections to the leading result (1) was isolated and studied in detail. We shall present them, following the discussion in Refs [4] and [14]. In particular, it was shown that relativistic corrections may be absorbed into the constituent mass of the charmed quark, $m_c = M_{J/\psi}/2$ [4, 15]. Formula (1) takes into account only the dominant imaginary part of the complex amplitude $M(\gamma p \rightarrow J/\psi p)$. The estimate of the smaller real part of $M(\gamma p \rightarrow J/\psi p)$ may be obtained in a standard way from the Regge model. The additional enhancement due to the real part of the matrix element may be described by a multiplicative correction factor:

$$C_{rp} \simeq 1 + \frac{\pi^2\lambda^2}{4}$$

(2)

with $1 + \lambda$ defined as the (local) pomeron intercept:

$$\lambda = \frac{\partial \log[xG(x, Q^2)]}{\partial \log(1/x)}.$$ 

(3)

The QCD NLO corrections to the $\gamma J/\psi$ impact-factor [4] introduce an additional factor of

$$C_{NLO} \simeq 1 + \frac{\alpha_s(M^2_{J/\psi}/4)}{2}. $$

(4)

It has been pointed out that there are non-negligible corrections coming from the fact that the parton distribution entering Eq. (1) should be in fact off-diagonal [16]. The detailed study [17] showed that in order to account for this effect the cross section should be multiplied by a factor

$$C_{off} \simeq 1.2.$$ 

(5)

The value of $C_{off}$ is governed mainly by the degree to which the parton distribution is off-diagonal in the production process and should not be too sensitive to differences in the structure of $\rho^0$ and the proton and to the choice of $x$. It seems that the effects of rescattering of the $c\bar{c}$ pair and of the exchanged gluon transverse momenta partially
cancel each other \[4\]. The overall effect is small hence including these corrections is not neccessary to maintain compatibility between the theoretical and the experimental results \[14\].

For the sake of lowering statistical errors it is favourable to study the total cross section \(\sigma_{\gamma p \rightarrow J/\psi p}(W^2)\). Due to the (approximate) exponential decrease of \(d\sigma/dt\):

\[
\frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt}(W^2, t) \simeq \frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt}(W^2, t = 0) \exp(B_{J/\psi p}t)
\]

with \(B_{J/\psi p}\) equal to 5 GeV\(^{-2}\) and very weakly depending on \(W^2\) \[10\], one may write

\[
\sigma_{\gamma p \rightarrow J/\psi p}(W^2) = \frac{1}{B_{J/\psi p}} \frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt}(W^2, t = 0).
\]

Recent refined studies \[4, 13, 14\] have shown that the theoretical results agree very well with the data from HERA \[10\]. Of course, it is straightforward to generalize formula (1) for the case of production of \(J/\psi\) off \(\rho^0\), \(\omega\) and \(\phi\). There are two different approaches to model the structure of vector mesons. The first one is based on the expected, approximate similarity between spatial wave functions of pions and light vector mesons which implies \(xG^V(x, Q^2) \simeq xG^\pi(x, Q^2)\) \[8\]. Another point of view is presented in Ref. \[7\], in which the differences between vector mesons and pions (e.g. spin, lifetime) are underlined and the parton distributions of \(V = \rho^0, \omega\) and \(\phi\) are fitted to describe the experimental results for the photon structure. We shall include in our analysis both possibilities.

Certainly, there arise subtleties. First, there exist no direct experimental results for \(xG^V(x, Q^2)\) and the existing parametrisations are based on models. So the results we shall obtain will be uncertain. However, this analysis is more aimed to estimate the feasibility of the measurement than to provide a precise answer. Besides, it makes the proposed measurement the first one to probe directly gluonic content of light vector mesons. Second, the value of \(B_{J/\psi \rho}\) for the exclusive production off the light vector mesons has never been measured. Fortunately, it may be constrained by theoretical considerations on the basis of indirect data. With a reasonable accuracy the \(B\) coefficients in the studied processes (\(pp \rightarrow pp, \gamma p \rightarrow Vp, \gamma^*p \rightarrow Vp\) and \(\gamma p \rightarrow J/\psi p\)) may be described as additive combinations of characteristic components \(b_i\) for the hadrons \(h_i\) taking part in the process i.e. \(B_{ij} = b_i + b_j\). In the dipole picture of the diffractive scattering these components may be related to the mean squared sizes of the contributing dipoles (see e.g. \[18\]). For energies \(50 \text{ GeV} < W < 100 \text{ GeV}\) the following values of \(B\) has been reported: for elastic \(pp\) scattering \(B_{pp} \simeq 10 - 12 \text{ GeV}^{-2}\), for \(\rho^0\) photoproduction at HERA \(B_{\rho p} \simeq 11 \text{ GeV}^{-2}\), and it decreases with \(Q^2\) when the photon is virtual \[11\], and finally for the \(J/\psi\) photon- and electroproduction off protons \(B_{J/\psi p} \simeq 5 \text{ GeV}^{-2}\). Taking into account that \(b_{J/\psi} \ll b_p\), we arrive at the conclusion that \(b_p \simeq b_{\rho} \simeq B_{J/\psi p} \simeq 5.5 \text{ GeV}^{-2}\). Due to the experimental
errors for $B$ coefficients (typically $\pm 1$ GeV$^{-2}$) and the crudeness of the estimation of the latter result we adopt $B_{J/\psi\rho} \approx (5.5 \pm 1.0)$ GeV$^{-2}$. Finally, the corrections due to rescattering may differ between the production of the proton and off the light vector mesons. This difference should not be significant for the result because the correction is small anyway, moreover, as suggested by the relation $b_p \simeq b_\rho$, the sizes of the proton and $\rho^0$ are similar. So, for the estimate of the differential $\gamma\gamma \rightarrow J/\psi \rho^0$ cross section we shall use the following formula:

$$
\frac{d\sigma_{\gamma\gamma \rightarrow J/\psi \rho}}{dt}(W^2, t) = C_{\text{eff}}C_{NLO}C_{\eta p}B_{J/\psi}g_\rho^2 \times
$$

$$
\frac{16\pi^3[\alpha_s(M_{J/\psi}^2/4)]^2\Gamma^{J/\psi}_{ee}}{3\alpha M_{J/\psi}^3} \left[ xG^0(x, M_{J/\psi}^2/4) \right]^2 \exp(B_{J/\psi}t),
$$

(8)

where $W$ denotes $\gamma\gamma$ cms energy, $x = M_{J/\psi}^2/W^2$ and $g_\rho^2 = 0.454$.

The real opportunity to study high energy photon-photon collisions is provided so far only in $e^+e^-$ colliders mainly at LEP2\footnote{It might be also possible to test directly such photon-photon processes at future photon colliders.}. There, a large fraction of events may be described in terms of a factorizing $\gamma\gamma$ cross section and known photon fluxes in the colliding leptons $e^+$ and $e^-$. The factorization of the cross section follows directly from kinematics of the type $\gamma\gamma \rightarrow e^+e^-$ cross section we shall consider:

$$
d\sigma_{e^+e^- \rightarrow e^+e^-} = f_{\gamma/e}(z_1, Q_1^2)f_{\gamma/e}(z_2, Q_2^2)\sigma_{\gamma\gamma \rightarrow X}(W^2)dQ_1^2 dQ_2^2 dz_1 dz_2,
$$

(9)

where $W^2 = z_1 z_2 s_{ee}$, $s_{ee}$ is the cms leptonic collision energy squared, and the flux factor for the photon carrying the fraction $z$ of the incoming electron and the virtuality $Q^2$ reads:

$$
f_{\gamma/e}(z, Q^2) = \frac{\alpha}{2\pi} \left[ \frac{1}{Q^2} \frac{1 + (1 - z)^2}{z} - \frac{2zm_e^2}{Q^4} \right],
$$

(10)

where $m_e$ is the electron mass. The lower limit for $Q_1^2$ follows directly from kinematics of the process:

$$
Q_{1\text{min}}^2 = \frac{m_e^2z^2}{1 - z}.
$$

(11)

In the process $\gamma(Q_1^2)\gamma(Q_2^2) \rightarrow J/\psi \rho^0$ (with $J/\psi$ moving in the direction of $\gamma(Q_1^2)$) the cross section $\sigma_{\gamma(Q_1^2)\gamma(Q_2^2) \rightarrow J/\psi \rho}$ depends only weakly on $Q_1^2$ ($Q_2^2$) when $Q_1^2 < M_{J/\psi}^2$ ($Q_2^2 < M_{\rho}^2$). On the other hand, the cross section falls down rapidly for large $Q_1^2$. This follows from the fact, that in the processes of this type the cross section is rather a function of $M_{J/\psi}^2 + Q^2$ than of $Q^2$ alone. So, for untagged measurements we may account for this property of $\sigma_{\gamma(Q_1^2)\gamma(Q_2^2) \rightarrow J/\psi \rho}$ by the standard procedure of taking $\sigma_{\gamma(Q_1^2)\gamma(Q_2^2) \rightarrow J/\psi \rho}$ for $Q_1^2 = Q_2^2 = 0$ and imposing the limits $Q_1^2 < M_{J/\psi}^2$ and $Q_2^2 < M_{\rho}^2$. The dependence of the $e^+e^-$ cross section integrated over $Q_i^2$ on the choice of the upper limits $Q_{i,max}^2$ is only logarithmic, so
there is no need for a more detailed treatment. With this approximation we may integrate over $Q_i^2$ to obtain:

$$d\sigma_{e^+e^-} = f^{(1)}_{\gamma/e}(z_1) f^{(2)}_{\gamma/e}(z_2) \sigma_{\gamma\gamma\to J/\psi\rho}(W^2)\bigg|_{Q_1^2=Q_2^2=0} dz_1 d\zeta_2$$

with

$$f^{(i)}_{\gamma/e}(z) = \frac{\alpha}{2\pi} \left[ \frac{1 + (1 - z)^2}{z} \log \left( \frac{Q_{i,max}^2}{Q_{i,min}^2} \right) - 2z m_e^2 \left( \frac{1}{Q_{i,min}^2} - \frac{1}{Q_{i,max}^2} \right) \right],$$

(13)

where $Q_{1,max}^2 = M_{J/\psi}^2$ and $Q_{2,max}^2 = M_{\rho}^2$.

Let us also introduce a convenient variable to define corresponding differential cross section

$$Y = \log \frac{W^2}{M_{J/\psi}^2},$$

(14)

i.e. $Y$ corresponds to the log($1/x$). It then is useful to define:

$$\frac{d\sigma_{e^+e^-}}{dY}(Y) = \int \frac{d\sigma_{e^+e^-}}{dz_1 d\zeta_2} \delta \left( Y - \log(z_1 z_2 s_{ee}/M_{J/\psi}^2) \right) dz_1 d\zeta_2.$$  

(15)

In fact, in the preceding analysis we assumed that $J/\psi$ follows the direction of a particular photon, and if we intend to describe the process in the inclusive way i.e. irrespectively of the direction of the momentum of the produced mesons, our results should be multiplied by a factor 2. Whenever we use this “direction inclusive” cross section, we shall state it explicitly.

In Fig. 1 we display the set of predicted photon-photon cross sections $\sigma_{\gamma\gamma\to J/\psi\rho}(W^2)$ obtained with different assumptions concerning the gluon distribution of $\rho^0$. Thus we plot the results for the GRS-NLO parametrisation [8] and SaS1D parametrisation [7]. We also include a phenomenological Regge motivated ansatz for $xG^V(x, M_{J/\psi}^2/4)$ by setting for $x < x_0$

$$xG^V(x, M_{J/\psi}^2/4) = x_0G^V(x_0, M_{J/\psi}^2/4) \left( \frac{x}{x_0} \right)^{\lambda_P}$$

(16)

with $x_0 = 0.1$ and $\lambda_P = 0.25$ in accordance with HERA data (see also Ref. [4]). To obtain the value of $x_0G^V(x_0, M_{J/\psi}^2/4)$ the GRS-NLO parametrisation is used. Note, that because of the different $x$-dependencies i.e. the different values of $\lambda$ the correction factors $C_{rp}$ accounting for the real part of the amplitude are different for the three curves. For the rather small $\gamma\gamma$ energy $W = 20$ GeV, our results for the cross section are larger by a factor between 1.5 (Regge motivated) and 4 (SaS1D) than those obtained in [4]. The steepness of the rise with increasing energy $W$ is strongly dependent upon the choice of the gluon parametrisation. The cross sections presented in Fig. 1 might be directly probed at future photon colliders providing constraints on the vector meson structure.
In Fig. 2 we show $d\sigma_{e^+e^-}/dY$ as defined by formula (15) for two $e^+e^-$ cms energies: $\sqrt{s_{ee}} = 200$ (a) and 500 GeV (b) respectively, and for GRS-NLO, Regge-motivated and SaS1D choices of the gluon distribution of the vector meson. The energies are chosen to match LEP2 and future linear collider conditions. The differences in the shape and normalisation of the curves in Fig. 2 are large. Even though the normalisation factors (e.g. the uncertainty of $B_{J/\psi\rho}$) introduce some uncertainty into formula (8), it still remains possible to distinguish between the models.

![Figure 1: Energy dependence of the cross section $\sigma_{\gamma\gamma\to J/\psi\rho}(W)$ for various parametrisations of the vector meson gluonic distribution. Solid line corresponds to the calculations with GRS-NLO parametrisation of the gluon distribution, dashed line represents the results obtained for SaS1D parametrisation of $xG^V(x,Q^2)$, and dotted line shows the cross section for Regge-motivated (Eq. (16)) gluon distribution.](image)

In Tab. 1 the total (“direction inclusive”) $e^+e^-$ cross sections for $J/\psi\rho^0$ production, with a cut $W > W_0 = 10$ GeV (introduced in order to stay in the diffractive regime), are listed for all the three considered models of the gluon distributions and for the energies $\sqrt{s_{ee}} = 90, 200, 500$ and 1000 GeV. In particular, we may read out from the table that at LEP2 with an integrated luminosity of about 700 pb$^{-1}$ per experiment we may expect to have a sizable amount of 1300 to 4900 events. In future colliders, like TESLA [19], the integrated luminosity per year may reach 50 fb$^{-1}$ which would correspond to 0.3 to 1.4 million of events. Certainly, the number of interesting events which can be uniquely identified will be severely cut down when the acceptance is taken into account, mainly
because the $J/\psi$ may be reliably measured only through its leptonic decay products. Another experimental difficulty may arise because, as one may see in the HERA data \cite{10}, the total cross section for the proton dissociative photoproduction of $J/\psi$ is larger than for the elastic process. This should also hold for the production of $\rho^0$. Besides, there may also occur a hard diffraction of one photon accompanied by $\gamma \rightarrow J/\psi$ transition on the other side. Such processes produce background for the exclusive processes that we want to focus on, however, their impact on the feasibility of the measurement depends strongly on particular experimental conditions. For instance, at HERA, the different classes of events (elastic and proton dissociative) are identified with high efficiency. Of course, the given results may be easily generalized to the other neutral vector meson species both within the heavy (e.g. $\psi'$, $\Upsilon$) and light ($\omega$, $\phi$) sectors correspondingly.

It can also be seen that the measurement proposed by us may be useful to distinguish between the models of the gluon distribution of light vector mesons i.e. the non-perturbative component of the photonic gluon distribution. In principle, the region of low $x$ would be probed at LEP2 ($x > 10^{-3}$) and future linear colliders ($x > 10^{-4}$). Both the shape of the differential cross section $d\sigma_{e^+e^-}/dY$ (see Fig. 2) and the value of the total cross section depend significantly on the model. On top of that there is an interesting, model independent question of how the $J/\psi$ photoproduction off $\rho^0$ differs from the photoproduction off proton, in particular, if values of the pomeron intercepts $1 + \lambda_P$ characterizing these processes are the same.

To conclude, we studied in detail the exclusive process $\gamma\gamma \rightarrow J/\psi \rho^0$ using as crucial ingredients the Vector Meson Dominance model and the Ryskin picture of elastic vector meson production off a hadron. Measurement of this process could provide for the first time direct information of the gluon distribution in light vector mesons. It would also constrain parametrisations of the photonic gluon distribution in the low $x$ domain. It

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
$\sqrt{s_{ee}}$ [GeV] & $\sigma(e^+e^- \rightarrow e^+e^-J/\psi \rho^0)$ [pb] & \\
\hline
90 & 0.9 & 1.7 & 0.6 \\
200 & 3.1 & 7.0 & 1.9 \\
500 & 9.8 & 27.2 & 6.0 \\
1000 & 21 & 68 & 13 \\
\hline
\end{tabular}
\caption{The total cross section for the process $e^+e^- \rightarrow e^+e^-J/\psi \rho^0$ for the $\gamma\gamma$ energy $W > 10$ GeV. The values are displayed for four $e^+e^-$ collision energies typical for the existing and future accelerators and for three different parametrisations of the gluon distribution.}
\end{table}
Figure 2: Cross section $d\sigma_{e^+e^-}/dY(Y)$ (Eq. (15)) plotted for three different choices of the gluon distribution and for two $e^+e^-$ collision energies $\sqrt{s_{ee}} = 200$ (a) and 500 GeV (b). Solid line corresponds to the calculations with GRS-NLO parametrisation of the gluon distribution, dashed line represents the results obtained for SaS1D parametrisation of $xG(x,Q^2)$, and dotted line shows the cross section for Regge-motivated (Eq. (16)) gluon distribution.
may be possible to perform a successful experimental analysis already using LEP2 data, and at future linear colliders the number of events would be large enough to perform a thorough study.

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