Exploring GPDs through the photoproduction of a $\gamma\rho$ pair

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We describe the process $\gamma N \rightarrow \gamma\rho N'$ in the generalized Bjorken regime where the $\gamma\rho$ pair has a large invariant mass. In the collinear QCD factorization framework, the amplitude gives access to both chiral-even and chiral-odd quark generalized parton distributions (GPDs), and is insensitive to gluon GPDs. The separation of longitudinally and transversely polarized $\rho$ meson production allows to distinguish chiral-even and chiral-odd contributions. Production rates are estimated in the kinematics of the near-future JLab 12-GeV experiments.

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Photoproduction of a $\gamma \rho$ pair

R. Boussarie

1. Introduction

We report here on our recent work on exclusive photoproduction of a $\gamma \rho$ pair with a large invariant mass \[1\]. In specific kinematics, this process may be described in the framework of collinear QCD factorization, where the short distance part of the amplitude is calculated in a perturbative way. For this first study, this is done at first order in the QCD coupling constant $\alpha_s$ with collinear kinematics and the long distance physics is encapsulated in leading twist hadronic matrix elements, namely the $\rho$ meson distribution amplitude (DA) and the nucleon generalized parton distributions (GPDs).

Exploring various exclusive processes in the generalized Bjorken regime is a mandatory step to check the factorization hypothesis which allows to describe their amplitudes in terms of GPDs with the final goal to explore the 3-dimensional structure of the nucleon, including its spin content \[2\]. Most of the theoretical and experimental effort has been up to now devoted to the analysis of hard lepton production processes where a highly virtual photon probes the hadronic system, but the same experimental facilities produce intense real or quasi-real photon beams. Moreover, intense proton or nuclear high energy beams like those of the LHC produce intense photon beams in the so-called ultra-peripheral kinematics \[3\]. These beams open the way to the study of large invariant mass lepton pair \[4\] and hadron pair \[5\] exclusive production.

2. Kinematics

The process we study here

\[
\gamma(q) + N(p_1) \to \gamma(k) + \rho^0(p_\rho, \varepsilon_\rho) + N'(p_2),
\]  

(2.1)
may be described in the framework of collinear QCD by first considering the factorization procedure of the wide angle Compton scattering on a meson which amounts to write the leading twist amplitude for the process $\gamma + \pi \rightarrow \gamma + \rho$ shown in Fig. in the convolution of two mesonic DAs and a hard scattering subprocess amplitude $\gamma + (q + \bar{q}) \rightarrow \gamma + (q + \bar{q})$ with the meson states replaced by a collinear quark-antiquark pair. We then extract from the proof of factorization of exclusive meson electroproduction amplitude near the forward region the right to replace in Fig. the lower left meson DA by a $N \rightarrow N'$ GPD, and thus get Fig. b. Such a factorization of a partonic amplitude requires to avoid the kinematical regions where a small momentum transfer is exchanged in the upper blob, namely where the invariant mass $M$ and a hard scattering subprocess amplitude requires to avoid the kinematical regions where a small momentum transfer is exchanged as well as hadronic masses, leading to

$$\int_0^1 dz e^{-izp_{\rho} \cdot \phi}(z), \quad \int_0^1 dz e^{-izp_{\rho} \cdot \phi}(z),$$

namely where the invariant mass $M^2_{\rho N} = (p_\rho + p_{N'})^2$ is not large enough.

Introducing two light-cone vectors $p$ and $n$ (with $p \cdot n = \frac{1}{2}$), we write the particle momenta as

$$p_1^\mu = (1 + \xi) p^\mu + \frac{M^2}{s(1 + \xi)} n^\mu, \quad p_2^\mu = (1 - \xi) p^\mu + \frac{M^2 + \Delta^2}{s(1 - \xi)} n^\mu + \Delta^\mu, \quad q^\mu = n^\mu, \quad (2.2)$$

with $M, m_\rho$ the masses of the nucleon and the $\rho$ meson. The squared center-of-mass energy of the $\gamma$-$N$ system is then $S_{\gamma N} = (q + p_1)^2 = (1 + \xi)s + M^2$, while the small squared transferred momentum is $t = (p_2 - p_1)^2 = -\frac{1}{2}(1 - \xi)\Delta^2 - \frac{4\xi M^2}{1 - \xi^2}$. The hard scale $M^2_{\rho N}$ is the invariant squared mass of the $\gamma \rho$ system. In the generalized Bjorken limit, the approximate kinematics allows to neglect $\Delta$ in front of $\bar{p}_1$ as well as hadronic masses, leading to

$$M^2_{\rho N} \approx \frac{\bar{p}_1^2}{\alpha s}, \quad \alpha = 1 - \alpha = \bar{\alpha}, \quad \xi = -\frac{\tau}{2 - \tau}, \quad \tau \approx \frac{M^2_{\rho N}}{S_{\gamma N} - M^2}, \quad -t \approx \bar{\alpha} M^2_{\gamma\rho}, \quad -u' \approx \alpha M^2_{\gamma\rho}. \quad (3.1)$$

It is interesting to note the analogy with the kinematics of timelike Compton scattering. However, the more complex momentum flow of the present process leads to the coexistence of both timelike ($M^2_{\rho N}$) and spacelike ($u'$) large scales, allowing a more complex analytic structure of the amplitude.

3. Ingredients

One of the peculiar features of our process is its sensitivity to both chiral-even and chiral-odd GPDs due to the chiral-even (resp. chiral-odd) character of the leading twist DA of $\rho_L$ (resp. $\rho_T$). Indeed, these twist 2 DAs are defined as

$$\langle 0 | \bar{u}(0) \gamma^\mu u(x) | \rho^0(p_\rho, \epsilon_{p_\rho}) \rangle = \frac{1}{\sqrt{2}} p_\rho^\mu f_{p_\rho} \int_0^1 dz e^{-izp_{p_\rho} \cdot \phi}(z), \quad (3.1)$$

$$\langle 0 | \bar{u}(0) \sigma^{\mu\nu} u(x) | \rho^0(p_\rho, \epsilon_{p_\rho}) \rangle = \frac{i}{\sqrt{2}} (\epsilon_{p_\rho}^\mu p_\rho^\nu - \epsilon_{p_\rho}^\nu p_\rho^\mu) f_{p_\rho} \int_0^1 dz e^{-izp_{p_\rho} \cdot \phi}(z), \quad (3.2)$$

where $\epsilon_{p_\rho}^\mu$ is the $\rho$-meson transverse polarization and with $f_{p_\rho} = 216$ MeV and $f_{p_\rho}^+ = 160$ MeV.
As for the GPDs, they are defined as usual [2]; in particular the transversity GPD of a quark $q$ is defined by:

$$
\langle p(p_2) | \bar{q} \left(-\frac{y}{2}\right) i \sigma^+ | q \left(\frac{y}{2}\right) | p(p_1) \rangle = \int_{-1}^{1} dx \ e^{-\frac{i}{2}x(p_1^+ + p_2^+)\cdot y} \ \bar{u}(p_2) \ [i \sigma^+ H^{q}_{q}(x, \xi, t) + ...] \ u(p_1),
$$

where ... denote the remaining three chiral-odd GPDs which contributions are omitted in the present analysis, in the small $\xi$ limit. We parametrized the GPDs in terms of double distributions without including the quite arbitrary $D$ term.

4. The Scattering Amplitude

The computation of the scattering amplitude of the process is straightforward at leading order in $\alpha_s$, although the number of Feynman diagrams is quite large. After a tensorial decomposition is applied, the integral with respect to the variable $z$ entering the meson DA is trivially performed in the case of a DA expanded in the basis of Gegenbauer polynomials. The integration with respect to the variable $x$ entering the GPDs is then reduced to the numerical evaluation of a few building block integrals. Details can be found in the appendix of Ref. [1].

![Figure 2: Differential cross section $d\sigma/dM_{\gamma\rho}^2$ for a photon and a longitudinally polarized $\rho$ meson production, on a proton (left) or neutron (right) target. The values of $S_{\gamma N}$ vary in the set 8, 10, 12, 14, 16, 18, 20 GeV$^2$. (from 8: left, brown to 20: right, blue), covering the JLab energy range.](image)

5. Cross-sections

The differential cross section as a function of $t, M_{\gamma\rho}^2, -u'$ reads

$$
\frac{d\sigma}{dt du' dM_{\gamma\rho}^2} \bigg|_{-t=-(t)_{\text{min}}} = \frac{\sqrt{M_{\gamma\rho}^2}}{32S_{\gamma N}^2M_{\gamma\rho}^2(2\pi)^3}.
$$

(5.1)
Photoproduction of a γρ pair

R. Boussarie

Figure 3: Differential cross section \(d\sigma/dM_{\gamma\rho}^2\) for a photon and a transversally polarized ρ meson production, on a proton target. The values of \(S_{\gamma N}\) vary in the set 8, 10, 12, 14, 16, 18, 20 GeV\(^2\) (from 8: left, brown to 20: right, blue), covering the JLab energy range.

By lack of space, we refer the interested reader to Ref. [1] for a detailed analysis of this fully differential cross-section. To get an estimate of the total rate of events of interest for our analysis, we restrict here to the \(M_{\gamma\rho}^2\) dependence of the differential cross section integrated over \(u'\) and \(t\),

\[
\frac{d\sigma}{dM_{\gamma\rho}^2} = \int_{-(t)_{\min}}^{-(t)_{\max}} d(-t) \int_{-(u')_{\min}}^{-(u')_{\max}} d(-u') F_H^2(t) \times \frac{d\sigma}{dt\,du'dM_{\gamma\rho}^2} \bigg|_{-t=(t)_{\min}}.
\]

The obtained differential cross sections for the longitudinal and transverse polarization cases, \(d\sigma/dM_{\gamma\rho}^2\) are shown in Fig. 2 and in Fig. 3 for various values of \(S_{\gamma N}\) covering the JLab-12 energy range. These cross sections show a maximum around \(M_{\gamma\rho}^2 \approx 3\) GeV\(^2\), for most energy values. The order of magnitude of the cross sections are large enough for the measurement to seem feasible at JLab. Longitudinal ρ production clearly dominates over the transverse ρ production, at least with our models of the GPDs. To get a better access to the elusive transversity GPDs [9], one may have to measure the off-diagonal spin matrix components \(\rho_{10}\) which is linear in the transversity GPD and measurable through the angular dependence of the ρ meson decay.

Let us note that to confirm the order of magnitude of our present study, the effect of next-to-leading-order corrections, using for example the method of Refs. [10], should be evaluated, as well as the effect of the renormalization/factorization scale fixing (taken here at fixed value) which should be done with care for exclusive processes [11]. This is left for future studies.

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