Study of transversity GPDs from pseudoscalar mesons production at EIC of China

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Abstract
The exclusive η and π⁰ electroproduction is studied in the handbag approach based on the generalized parton distributions (GPDs) factorization. Predictions of π⁰ and η mesons are calculated for future electron-ion collider in China (EIC) energy ranges, using obtained cross sections we extract information on the transversity GPDs contributions to these processes.

Keywords: meson production, general parton distributions, handbag method
(Some figures may appear in colour only in the online journal)

1. Leptoproduction of pseudoscalar mesons
In this paper, we analyze pseudoscalar mesons electroproduction (π⁰, η) on the basis of the handbag approach. Its essential ingredients are the generalized parton distributions (GPDs) that were proposed in [1–3] and provide an extensive information on the hadron structure. GPDs are complicated nonperturbative objects which depend on x -the momentum fraction of proton carried by parton, ξ -skewness and t- momentum transfer. GPDs are connected in the forward limit with parton distribution functions (PDFs), they contain information about hadron form factors and the parton angular momentum [4]. They give information on the 3D structure of the hadrons, see e.g. [5]. More details on GPDs can be found, e.g. in [6–9].

GPDs were proposed to investigate exclusive reactions such as deeply virtual Compton scattering (DVCS) [4, 10, 11], time-like Compton scattering (TCS) [12–14] and deeply virtual meson production (DVMP) [6, 7]. Such processes at large photon virtuality Q² can be factorized into the hard subprocess that can be calculated perturbatively and GPDs [4, 10, 11]. Generally, this factorization was proved in the leading-twist amplitudes with longitudinally polarized photons. This factorization formula is valid up to power corrections of the order 1/Q to the leading twist results which are unknown.

The study of exclusive meson electroproduction is one of the effective ways to access GPDs. An experimental study of π⁰ production was performed by CLAS [15] and COMPASS [16]. For η production, CLAS results are available at [17]. These experimental data can be adopted to constrain the models of GPDs.

On the other hand, electron-ion colliders (EICs) are the next generation collider for the investigation of nucleon structures. Both the USA and China design to build EICs in the future [18–20]. The properties of GPDs is one of the most important aims to investigate for EICs [21].

Theoretical investigation of DVMP in terms of GPDs is based on the handbag approach where, as previously mentioned, the amplitudes are factorized into the hard subprocess and GPDs [2–4, 10] see figure 1. This amplitude has an ingredient, the non-perturbative meson distribution amplitudes, which probe the two-quark component of the meson wave functions. GPDs can be constructed using double distribution (DD) representation [22]. The DD generates ξ-dependence of GPDs by integration of the DD function.

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together with the PDFs, modified by $t$- dependent term. The handbag approach with the DD form of GPDs was successfully applied to the light vector mesons (VM) lepto-production at high photon virtuality $Q^2$ [23] and the pseudoscalar mesons (PM) lepto-production [24].

In this work, we continue our previous study of $\pi^0$ production [25] at the kinematics for EIC in China (EicC) based on the handbag approach. As shown in [24], the leading twist longitudinal cross section $\sigma_L$ is rather small with respect to the predominant contribution determined by transversely polarized photons $\sigma_T$. This result was proved experimentally by the JLab Hall A collaboration [26]. The transversity dominance $\sigma_T \gg \sigma_L$ is confirmed in [25] at all EicC energy ranges for $\pi^0$ production.

This paper is organized as follows. In section 2, we discuss the contributions to the meson production amplitudes from the transversity GPDs $H_T$, $E_T$. More information can be found in [27] and in our previous paper [25]. Using the handbag approach, the transversity GPDs together with the twist-3 meson wave functions [27] contribute to the amplitudes with transversely polarized photons which produce transverse cross sections $\sigma_T$. They give essential contributions to the cross sections that are consistent with the experiment [15, 16].

In section 3, we consider two models for transversity GPDs that give results for the cross sections of the $\pi^0$ and $\eta$ lepto-production that are consistent with experiments at CLAS and COMPASS energies [15–17]. Predictions for $\eta$ cross section at EicC energies are done. In addition to these results that are associated with [25], we analyse what information on the transversity GPDs can be extracted from future EicC experiments on PM lepto-production. We discuss the possibility to perform $u$, $d$ flavor separation for transversity GPDs $H_T$ and $E_T$ using $\pi^0$ and $\eta$ cross sections [28, 29]. Finally, we give some discussion and conclusions in section 4.

2. Handbag approach properties of meson production amplitudes

The process amplitude in the handbag approach is depicted in figure 1. In the handbag approach, the meson photoproduction amplitude is factorized into a hard subprocess amplitude $\mathcal{H}$ which is shown in the upper part of figure 1 and GPDs $F$ which includes information on the hadron structure at sufficiently high photon virtuality $Q^2$. For the leading twist amplitudes, with longitudinally polarized photons, its factorization has been proved [2, 3].

In what follows, we consider the twist-3 contributions from transversity GPDs $H_T$ and $E_T$ as well. Factorization for these twist-3 amplitudes is an assumption now. However, factorization models give results that are consistent with the experiment [27].

In the handbag method, the subprocess amplitude is calculated employing the modified perturbative approach (MPA) [30], where the quark transverse momenta $k_t$ is taken into account. The power $k_t^2/Q^2$ correction is considered in the propagators of the hard subprocess $\mathcal{H}$ together with the nonperturbative $k_t$-dependent meson wave functions [31]. The gluonic corrections are regarded as the form of the Sudakov factor. Resummation of the Sudakov factor can be done in the impact parameter space [30].

The unpolarized $ep \rightarrow e(\pi^0, \eta)p$ cross sections can be decomposed into a number of partial cross sections which are expressed in terms of the $\gamma^* p \rightarrow (\pi^0, \eta)p$ helicity amplitudes. The amplitude $M_{0\ldots,++}$ is close to zero and can be omitted in the calculation. When we consider relation between amplitudes $M_{0\ldots,++} = M_{0\ldots,++}$, the partial cross sections can be written as follows:

\[
\frac{d\sigma_L}{dt} = \frac{1}{\kappa} (|M_{0\ldots,0\ldots}|^2 + |M_{0\ldots,0\ldots}|^2),
\]

\[
\frac{d\sigma_T}{dt} = \frac{1}{2\kappa} (|M_{0\ldots,0\ldots}|^2 + 2|M_{0\ldots,0\ldots}|^2),
\]

\[
\frac{d\sigma_{T,T}}{dt} = -\frac{1}{\sqrt{2}\kappa} \text{Re} [M^{*}_{0\ldots,0\ldots}M_{0\ldots,0\ldots}],
\]

\[
\frac{d\sigma_{T,T}}{dt} = -\frac{1}{\kappa} |M_{0\ldots,0\ldots}|^2.
\]
Here, $\kappa$ is the phase space factor, it reads
\[
\kappa = 16\pi (W^2 - m^2) \sqrt{\lambda(W^2, -Q^2, m^2)}.
\] (2)

$\lambda(x, y, z)$ is expressed as $\lambda(x, y, z) = (x^2 + y^2 + z^2) - 2xy - 2xz - 2yz$. $\sigma_{LT}$ is the interference contributions of the longitudinal and transverse amplitudes while $\sigma_{TT}$ contains transverse amplitudes only.

In (2), $W^2 = (q + p)^2$ is a squared energy in the photon–proton channel, that is connected with the EicC lepton–proton collision energy squared $s = (l + p)^2$ as
\[
W^2 = s_{y} - Q^2 \quad \text{with} \quad y = \frac{(q + p)}{(l + p)}.
\] (3)

Table 1. Regge parameters and normalizations of the GPDs at a scale of 2 GeV for Model-2.

| GPD     | $\alpha(0)$ | $\beta^u$ | $\beta^d$ | $\alpha'$ [GeV$^{-2}$] | $b_l$ [GeV$^{-2}$] | $N^u$ | $N^d$ |
|---------|-------------|-----------|-----------|------------------------|-------------------|-------|-------|
| $E_T$   | -0.1        | 4         | 5         | 0.45                   | 0.67              | 29.23 | 21.61 |
| $H_T$   | -0.1        | -         | -         | 0.45                   | 0.04              | 0.68  | -0.186|

Table 2. Regge parameters and normalizations of the GPDs at a scale of 2 GeV. Model-3.

| GPD     | $\alpha(0)$ | $\beta^u$ | $\beta^d$ | $\alpha'$ [GeV$^{-2}$] | $b_l$ [GeV$^{-2}$] | $N^u$ | $N^d$ |
|---------|-------------|-----------|-----------|------------------------|-------------------|-------|-------|
| $E_T$   | -0.1        | 4         | 5         | 0.45                   | 0.77              | 20.91 | 15.46 |
| $H_T$   | -0.1        | -         | -         | 0.45                   | 0.3               | 1.1   | -0.3  |

Here, $\kappa$ is the phase space factor, it reads
\[
\kappa = 16\pi (W^2 - m^2) \sqrt{\lambda(W^2, -Q^2, m^2)}.
\] (2)

$\lambda(x, y, z)$ is expressed as $\lambda(x, y, z) = (x^2 + y^2 + z^2) - 2xy - 2xz - 2yz$. $\sigma_{LT}$ is the interference contributions of the longitudinal and transverse amplitudes while $\sigma_{TT}$ contains transverse amplitudes only.

In (2), $W^2 = (q + p)^2$ is a squared energy in the photon–proton channel, that is connected with the EicC lepton–proton collision energy squared $s = (l + p)^2$ as
\[
W^2 = s_{y} - Q^2 \quad \text{with} \quad y = \frac{(q + p)}{(l + p)}.
\] (3)

where $y$ is an inelasticity variable that is usually used in lepton–proton reactions, (see e.g. [18, 19]). The typical $W$-energy interval for EicC is 6 GeV < $W$ < 16 GeV.

The leading twist amplitudes $M_{0,-0^+}$ and $M_{0,+0^+}$ are listed in our previous paper [25]. The transversity amplitudes
that are essential in our study can be written in terms of convolutions as

\[ M_{0-++} = \frac{e_0}{Q} \sqrt{1 - \xi^2} \langle H_T \rangle, \]
\[ M_{0++} = -\frac{e_0}{Q} \frac{t'}{4m} \langle E_T \rangle, \]

where \( e_0 \) is a positron charge. The other variables are defined as

\[ \xi = \frac{x_B}{2 - x_B} \left( 1 + \frac{m_P^2}{Q^2} \right), \]
\[ t' = t - t_0, \]
\[ t_0 = -\frac{4m^2 \xi^2}{1 - \xi^2}. \]

(4)

(5)

\( x_B \) is the Bjorken variable which is given as \( x_B = Q^2/(W^2 + Q^2 - m^2) \), \( m \) is the proton mass and \( m_P \) is the pseudoscalar meson mass.

The GPDs \( F(x, \xi, t) \) are calculated as the integration of the double distributions function [22]

\[ F(x, \xi, t) = \int_{-1}^{1} d\rho \int_{-1 + |\rho|}^{1 - |\rho|} d\gamma (\rho + \xi \gamma - x) \times f(\rho, t) v(\rho, \gamma, t). \]

(6)

For the valence quark double distributions read as

\[ v(\rho, \gamma, t) = \frac{3}{4} \left[ (1 - |\rho|^2 - \gamma^2)^2 \right] \]

The \( t \)-dependence in PDFs \( f \) is expressed as the Regge form

\[ f(\rho, t) = N e^{\alpha(0) \ln \rho} \rho^{-\alpha(t)(1 - \rho)^{\beta}}, \]

and \( \alpha(t) = \alpha(0) + \alpha' t \) is the corresponding Regge trajectory factor.

It was found that for PM lepton production the contributions of the transversity GPDs \( H_T \) and \( E_T = 2H_T + E_T \) are essential [27]. We use the following form for \( h_T \) based on the model [32]

\[ h_T(\rho, 0) = N \sqrt{\rho(1 - \rho)} [f(\rho, 0) + \Delta f(\rho, 0)]. \]

(9)

It generates \( H_T \) with the help of equation (6). In equation (9), \( f \) and \( \Delta f \) are valence and polarized quark distributions, respectively. The parameters in equation (8) for these PDFs are fitted from the known information about CTEQ6 PDF [33] e.g. or from the nucleon form factor analysis [34]. Some knowledge on GPDs \( E_T \) can only now be obtained from the lattice QCD [35]. We parameterized \( E_T \) as equation (8). The evolution of transversity GPDs was analyzed in [36]. We show that if we consider the evolution of GPDs via \( Q^2 \) evolution of \( h_T \) PDF in equation (9), the evolution of \( H_T \)

Figure 5. Cross sections of \( \eta \) production at EicC energy. Upper part of the figure presents \( \sigma = \sigma_T + \epsilon \sigma_L \) and down part- \( \sigma_{TT} \) as in figure 4.

Figure 6. Cross section of \( \eta \) production at EicC energy. The labels are the same as in figure 5.
GPDs, found in [36] is reproduced quite well. The evolution of $E_T \bar{G}$ is rather weak [36] and we do not consider $Q^2$ evolution in GPDs. Generally, in this work, the explicit form of GPDs evolution is not so important because we work at very limited $Q^2$ intervals. 

GPDs $H_T$ and $E_T$ determine the amplitudes $M_{0-}^{++}$ and $M_{0+}^{++}$ respectively, see equation (4). With the handbag approach the transversity GPDs are accompanied by a twist-3 PM wave functions in the hard amplitude $\mathcal{H}$ [27] which is the same for both the $M_{0+}^{++}$ amplitudes in equation (4). This property is demonstrated in figure 1, where the parton helicities of the subprocess amplitude $\mathcal{H}$ are presented. For corresponding transversity convolutions we have forms:

$$
\langle H_T \rangle = \int_{-1}^{1} dx H_{0-}^{++}(x,\ldots) H_T;
$$

$$
\langle E_T \rangle = \int_{-1}^{1} dx H_{0+}^{++}(x,\ldots) E_T.
$$

There is a parameter $\mu_P$ in twist-3 meson wave function that is large and enhanced by the chiral condensate. In our calculation, we use $\mu_P = 2$ GeV at scale of 2 GeV. 

More details of leading twist polarized GPDs $H$ and $E$ which contribute to the leading twist amplitudes with longitudinally polarized virtual photons can be found in papers [24, 27]. These amplitudes contribute to longitudinal cross section $\sigma_L$ which is rather small with respect to transversity contribution $\sigma_T$ for $\pi^0$ and $\eta$ production.

For additional information about transversity GPDs parameterization see [27] and [25]. The $\pi^0$ estimations at EicC are presented in our previous paper [25]. A study of $\eta$ meson lepton production can be performed within the handbag approach too, for details see [27].

3. Model results for $\pi^0$ and $\eta$ lepton production and convolution extraction from the data

We consider the transversity effects described in equation (10) and take into account the leading twist contribution in equation (1). The amplitudes are transferred from the program produced by PARTONS collaboration codes [37] which was changed into Fortran employing results of GK model for GPDs [27].

In our previous paper [25], two models for transversity GPDs were analyzed. Model-1 was applied in [27] and described fine low energy CLAS data [15], but gave results about two times larger with respect to COMPASS data [16]. This was the reason to change GPDs parameters, especially for $E_T$ contribution that is important in $\sigma_T$ and $\sigma_{TT}$ cross sections. Some changes were done for $H_T$ as well. The parameters for new models labeled as Model-2 are exhibited in table 1 [38].
Results of this model are shown at COMPASS energies in figure 2 by dashed lines. It can be seen that there is some discrepancy between Model-2 results and COMPASS data [16] at large $-t > 0.3 \text{ GeV}^2$. That was the reason to test in addition to the new Model-3 results for $\pi^0$ and $\eta$ leptoproduction. The parameters for the new Model-3 are listed in table 2 [38]. Note that in this model parameters are close to model I in [25], only parameters of $E_T$ were changed. It can be seen from the $N$ parameters that Model-2 has larger $E_T$ and smaller $H_T$ values with respect to Model-3. In Model-3, we have smaller $E_T$ and larger $H_T$. Both models describe well $\pi^0$ production at COMPASS. Model-3 gives better results for large $-t > 0.3 \text{ GeV}^2$, see figure 2.

Model-2 and 3 results for $\pi^0$ production at CLAS energy are exhibited in figure 3. It can be seen that both models are in accordance with unseparated cross sections $\sigma = \sigma_T + c \sigma_L$, where $\sigma_T$ predominated. At the same time, Model-3 gives closer results for $\sigma_{T_T}$ that is smaller with respect to Model-2. This confirms the previously mentioned smaller values of $E_T$ in the Model-3. $\sigma_{T_L}$ cross sections are shown as well.

Calculation of the amplitudes of $\eta$ production is based on the singlet-octet decomposition of the $\eta$-state [39] where the amplitude is presented in the form

$$M_\eta = \cos \theta_8 M_8^{(8)} - \sin \theta_8 M_8^{(1)}.$$  

In the case if we omit the strange sea contribution which is small and can be neglected, the GPDs contribution to these amplitudes has a form

$$F^{(8)} = \frac{1}{\sqrt{6}} (e^u F^u + e^d F^d); \quad F^{(1)} = \sqrt{2} F^{(8)}. \quad (12)$$

We use the values of mixing angles and decay coupling constant from [39]

$$\theta_8 = -21.2^\circ, \quad \theta_1 = -9.2^\circ; \quad f_8 = 1.26 f_\pi, \quad f_1 = 1.17 f_\pi. \quad (13)$$

This gives us the possibility to calculate the $\eta$ production amplitude in a similar way as was used for the $\pi^0$ case [27].

The flavor factors for $\pi^0$ and $\eta$ production appear in combinations

$$F^{\pi^0} = \frac{1}{3\sqrt{2}} (2F^u + F^d); \quad F^{\eta} = \frac{1}{3\sqrt{6}} (2F^u - F^d). \quad (14)$$

Here, the explicit values $e_u = 2/3$, $e_d = -1/3$ of quark charges are used.

From table 1 and 2, it can be seen that $E_T$ has the same signs for $u$ and $d$ quarks but $H_T$ has the different signs, respectively. This means that for $\pi^0$ case $E_T$ contributions for $u, d$ quarks are added but $H_T$ are subtracted. For $\eta$ production, we have opposite cases: $H_T$ contributions are added but $E_T$ compensated.
Thus we have $E_T$ enhancement for the $\pi^0$ case. For $\eta$ production, $H_T$ is increased. Therefore, $\pi^0$ process is more sensitive to $E_T$ effects but for $\eta$ production $H_T$ influences are more visible.

Model results for $\eta$ production at CLAS energy [17] are depicted in figure 4. It can be seen that Model-3 with a larger $H_T$ contribution describes experimental data better at small momentum transfers. Model-2 with smaller $H_T$ produces an essential dip in the cross section that is not observed experimentally. Cross sections $\sigma_{TT}$ and $\sigma_{LT}$ are described properly for both models.

Model-2 predictions at EicC energies for $\pi^0$ production are presented at [25]. For Model-3 at these energies, we have results similar to those shown in figure 2. The $\pi^0$ cross sections for Model-3 don’t have deep near $|t'|=0$ GeV$^2$ as we have for Model-2. Model-2 and 3 results are similar for $|t'| \sim 0.2$ GeV$^2$ and cross section is a bit smaller for Model-3 with respect to Model-2 at $|t'| > 0.3$ GeV$^2$.

Our results for EicC energies $W=7$–$16$ GeV for $\eta$ production are exhibited in figures 5 and 6. It can be concluded that Model-3 results are higher for the cross section $\sigma$ with respect to Model-2 and for $\sigma_{TT}$ result is opposite- Model-2 gives higher results. This is caused by larger $H_T$ contribution in Model-3 and larger $E_T$ effects in Model-2 that is important in $\sigma_{TT}$. These model results can be checked experimentally by EicC and determine what Model-2 or 3 is more adequate to experiment.

Now we shall discuss how we can get information about transversity convolutions $E_T$ and $H_T$ from experimental data. From equation (1), we can obtain

$$|M_{0++}| = \sqrt{-\kappa \frac{d\sigma_{TT}}{dt}},$$

$$|M_{0--}| = \sqrt{2\kappa \left( \frac{d\sigma_{TT}}{dt} + \frac{d\sigma_{LT}}{dt} \right)},$$

we can determine the absolute values of the amplitudes. Employing the normalization factor from equation (4) we can determine $H_T$ and $E_T$ convolutions. This procedure was adopted to extract transversity convolutions from CLAS experimental data in [28, 29].

At present, we do not have experimental data from China EicC. To analyse what information on the transversity GPDs can be extracted from future EicC experiments on PM lepton-production, we shall instead use realistic experimental data, our model calculations for the cross sections $\sigma_{TT}$ and $\sigma_{LT}$. Our results for $H_T$ and $E_T$ convolutions for $\pi^0$ and $\eta$ production are depicted in figure 7. They are close to results found in [28, 29] at CLAS energies. As expected we find that $H_T$ convolution is larger for Model-3, and for Model-2 we get a larger $E_T$. Using these results, we can extract convolutions for

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**Figure 9.** Extracted from the cross section transversity convolution functions for $\pi^0$ (upper part) and $\eta$ (lower part) production at EicC ($W=12$ GeV).
\[
F^u = \frac{3}{4}(\sqrt{2} F^{\pi^0} + \sqrt{6} F^\eta),
\]

\[
F^d = \frac{3}{2}(\sqrt{2} F^{\pi^0} - \sqrt{6} F^\eta),
\]

(16)

which is a consequence of equation (14). Here, \( F \) is the corresponding transversity of \( H_T \) or \( E_T \) convolution functions. Such analyses were performed at CLAS energies in \([29]\).

We will not do this here, because we have model results for flavor convolutions, but the extraction of transversity convolution functions from future experimental data can be important in results for later experiments.

Our predictions for \( H_T \) or \( E_T \) convolution functions that were extracted from the cross sections at the energies \( W = 8, 12 \) GeV which are typical at EicC energy ranges are exhibited in figures 8 and 9. Experimental analyses of these quantities can give information on the preferable models for transversity GPDs.

In figure 10, we present our model predictions for energy dependencies of transversity convolution functions at fixed \( Q^2 \) and momentum transfer. Such analyses will be important to give constraints on the \( W \)-dependence of \( H_T \) or \( E_T \) GPDs from future experimental data.

Note that the transversity dominance \( \sigma_T \gg \sigma_L \) that was tested for \( \pi^0 \) production at high energies is valid for \( \eta \) production at the energies \( W = 2 \sim 15 \) GeV. This means that in experimental analyses of transversity convolutions, unseparated cross section \( \sigma = \sigma_T + \sigma_L \) can be applied instead \( \sigma_T \) for both processes of \( \pi^0 \) and \( \eta \) production.

4. Conclusion

In this paper, we investigate the exclusive electroproduction of pseudoscalar \( \pi^0 \) and \( \eta \) meson at China EicC energies. The process amplitudes are calculated in the model where amplitudes are factorized into subprocess amplitudes and GPDs. For the transversity twist-3 effects, the subprocess amplitude \( \mathcal{H}_{00++} \) is the same in equation (10) for both contributions that contain \( H_T \) and \( E_T \) GPDs.

We consider two GPDs parameterization Model-2 and Model-3. Both models describe properly \( \pi^0 \) and \( \eta \) production at CLAS energies. It seems that Model-3 gives better results for \( \pi^0 \) production at COMPASS for large momentum transfer and gives better descriptions of \( \eta \) production at CLAS at momentum transfer \( |t| < 0.5 \) GeV

We perform predictions for unseparated \( \sigma \) and \( \sigma_{TT} \) cross sections for EicC kinematics for \( \eta \) production with Model-2 and Model-3. We observe that transversity dominance \( \sigma_T \gg \sigma_L \), found at low CLAS energies \([27]\) and confirmed at
EicC energies in [25] for the $\pi^0$ process is valid at all these energies for $\eta$ production too.

Adopting a combination of the cross sections, we extract GPDs $H_T$ and $E_T$ convolutions determined in equation (4) for the cases of $\pi^0$ and $\eta$ mesons. These results for EicC energies are quite different that give possibilities to determine a preferable model at future experiments. In addition, we analyze energy dependencies of transversity convolutions at fixed $t'$ and $Q^2$ that can give information about energy parameters of GPDs $H_T$ and $E_T$ from the data.

Note that the reactions $\pi^0$ and $\eta$ production considered have different flavor contributions to the amplitudes. This provides a possibility to perform $u$ and $d$ flavor separation for transversity GPDs [29].

Our results can be useful in future experiments at China EicC on the pseudoscalar mesons production and give more important knowledge on transversity influences at these energy ranges.

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References

[1] Müller D, Robaschik D, Geyer B, Dittes F M and Hořejší J 1994 Wave functions, evolution equations and evolution kernels from light ray operators of QCD Fortsch. Phys. 42 101–41

[2] Ji X D 1997 Gauge-invariant decomposition of nucleon spin Phys. Rev. Lett. 78 610–3

[3] Radyushkin A V 1996 Asymmetric gluon distributions and hard diffractive electroproduction Phys. Lett. B 385 333–42

[4] Ji X D 1997 Deeply virtual compton scattering Phys. Rev. D 55 7114–25

[5] Constantinou M et al 2021 Parton distributions and lattice-QCD calculations: toward 3D structure Prog. Part. Nucl. Phys. 121 103908

[6] Goeke K, Polyakov M V and Vanderhaeghen M 2001 Hard exclusive reactions and the structure of hadrons Prog. Part. Nucl. Phys. 47 401–515

[7] Vanderhaeghen M, Guichon P A M and Guidal M 1999 Deeply virtual electroproduction of photons and mesons on the nucleon: Leading order amplitudes and power corrections Phys. Rev. D 60 094017

[8] Diehl M 2003 Generalized parton distributions Phys. Rept. 388 41–277

[9] Belitsky A V and Radyushkin A V 2005 Unraveling hadron structure with generalized parton distributions Phys. Rept. 418 1–387

[10] Radyushkin A V 1997 Nonforward parton distributions Phys. Rev. D 56 5524–57

[11] Collins J J C, Frankfurt L and Strikman M 1997 Factorization for hard exclusive electroproduction of mesons in QCD Phys. Rev. D 56 2962–3006

[12] Berger E R, Diehl M and Pire B 2002 Time—like Compton scattering: exclusive photoproduction of lepton pairs Eur. Phys. J. C 23 675–89

[13] Pire B, Szymanowski L and Wagner J 2009 Can one measure timelike Compton scattering at LHC? Phys. Rev. D 79 014010

[14] Mueller D, Pire B, Szymanowski L and Wagner J 2012 On timelike and spacelike hard exclusive reactions Phys. Rev. D 86 031502

[15] Bedlinskiy I et al (CLAS) 2014 Exclusive $\pi^0$ electroproduction at $W > 2$ GeV with CLAS Phys. Rev. C 90 025205

[16] Alexeev M G et al (COMPASS) 2020 Measurement of the cross section for hard exclusive $\pi^0$ muoproduction on the proton Phys. Lett. B 805 135454

[17] Bedlinskiy I et al (CLAS Collab) 2017 Phys. Rev. C 95 035202

[18] Accardi A et al 2016 Electron ion collider: the next QCD frontier: understanding the glue that binds us all Eur. Phys. J. A 52 268

[19] Abdul Khalek R et al 2022 Nucl. Phys. A 1026 12447

[20] Anderle D P et al 2021 Electron-ion collider in China Front. Phys. (Beijing) 16 64701

[21] Chen X, Guo F K, Roberts C D and Wang R 2020 Selected science opportunities for the EicC Few Body Syst. 61 43

[22] Chávez J M M et al 2022 Accessing the pion 3D structure at US and China electron-ion colliders Phys. Rev. Lett. 128 202501

[23] Musatov I V and Radyushkin A V 2000 Evolution and models for skewed parton distributions Phys. Rev. D 61 074027

[24] Goloskokov S V and Kroll P 2005 Vector meson electroproduction at small Bjorken-x and generalized parton distributions Eur. Phys. J. C 42 281–301

[25] Goloskokov S V and Kroll P 2007 The longitudinal cross-section of vector meson electroproduction Eur. Phys. J. C 50 829–42

Goloskokov S V and Kroll P 2009 The target asymmetry in hard vector-meson electroproduction and parton angular momenta Eur. Phys. J. C 59 809–19

[26] Goloskokov S V and Kroll P 2010 An Attempt to understand exclusive $\pi^+$ electroproduction Eur. Phys. J. C 65 137–51

[27] Goloskokov S V, Xie Y P and Chen X 2022 Exclusive $\pi^0$ production at EIC of China within handbag approach” Chin. Phys. C 46 123101

[28] Defurne M et al (Jefferson Lab Hall A) 2016 Rosenbluth separation of the $\pi^0$ electroproduction cross section Phys. Rev. Lett. 117 262001

[29] Goloskokov S V and Kroll P 2011 Transversity in hard exclusive electroproduction of pseudoscalar mesons Eur. Phys. J. A 47 112

[30] Kroll P 2016 Hard exclusive pion leptoproduction Few Body Syst. 57 1041–50

[31] Kubarovsky V 2016 Deeply virtual pseudoscalar meson production at Jefferson lab and transversity GPDs Int. J. Mod. Phys. Conf. Ser. 40 166005

Kubarovsky V 2019 Status of the experimental studies on DVMP and transversity GPDs PoS SPIN2018 07

[32] Botts J and Sterman G F 1989 Hard Elastic Scattering in QCD: leading Behavior Nucl. Phys. B 325 62–100

[33] Jakob R and Kroll P 1993 The Pion form-factor: Sudakov suppressions and intrinsic transverse momentum Phys. Lett. B 315 463–70 [erratum: Phys. Lett. B 319, 545 (1993)] [arXiv:hep-ph/9306259 [hep-ph]]

Bolz J, Kroll P and Korner J G 1994 1 = 0 to 1 = transition form-factors Z. Phys. A 350 145–59

[34] Anselmino M et al 2009 Update on transversity and Collins functions from SIDIS and e+ e− data Nucl. Phys. B Proc. Suppl. 191 98–107

[35] Pumplin J et al 2002 New generation of parton distributions with uncertainties from global QCD analysis J. High Energy Phys. JHEP07(2002)012
[34] Diehl M, Feldmann T, Jakob R and Kroll P 2005 Generalized parton distributions from nucleon form-factor data Eur. Phys. J. C 39 1–39

[35] Göckeler M et al (QCDSF and UKQCD) 2007 Transverse spin structure of the nucleon from lattice QCD simulations Phys. Rev. Lett. 98 222001

[36] Kroll P 2019 Hard exclusive processes involving kaons Eur. Phys. J. A 55 76

[37] Berthou B et al 2018 PARTONS: PARtomic tomography of nucleon software: a computing framework for the phenomenology of generalized parton distributions Eur. Phys. J. C 78 478

[38] Kroll P 2019 private communication

[39] Feldmann T, Kroll P and Stech B 1998 Mixing and decay constants of pseudoscalar mesons Phys. Rev. D 58 114006