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# Deeply Virtual Pseudoscalar Meson Production at Jefferson Lab and Transversity GPDs

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The cross section of the exclusive $\pi^0$ and $\eta$ electroproduction reaction $ep \to e'p'\pi^0/\eta$ was measured at Jefferson Lab with a 5.75-GeV electron beam and the CLAS detector. Differential cross sections $d^4\sigma/dtdQ^2dx_Bd\phi_\pi$ and structure functions $\sigma_T + \epsilon\sigma_L, \sigma_{TT}$ and $\sigma_{LT}$ as functions of $t$ were obtained over a wide range of $Q^2$ and $x_B$. The data are compared with the GPD based theoretical models. Analyses find that a large dominance of transverse processes is necessary to explain the experimental results. Generalized form factors of the transversity GPDs $\langle H_T\rangle^{\pi,\eta}$ and $\langle \bar{E}_T\rangle^{\pi,\eta}$ were directly extracted from the experimental observables for the first time. It was found that GPD $\bar{E}_T$ dominates in the pseudoscalar meson production. The combined $\pi^0$ and $\eta$ data opens the way for the flavor decomposition of the transversity GPDs. The first ever evaluation of this decomposition was demonstrated.

*Keywords*: pseudoscalar; meson; electroproduction; Generalized Parton Distributions; Transversity

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## 1. Introduction

Understanding nucleon structure in terms of the fundamental degrees of freedom of Quantum Chromodynamics (QCD) is one of the main goals in the theory of strong interactions. In recent years it became clear that exclusive reactions may provide information encoded in so-called Generalized Parton Distributions [1,2] (GPDs). For each quark flavor $q$ there are eight GPDs. Four correspond to parton helicity-conserving (chiral-even) processes, denoted by $H^q$, $\tilde{H}^q$, $E^q$ and $\tilde{E}^q$, and four correspond to parton helicity-flip (chiral-odd) processes [3,4], $H^q_T$, $\tilde{H}^q_T$, $E^q_T$ and $\tilde{E}^q_T$. At a given $Q^2$ the GPDs depend on three kinematic variables: $x$, $\xi$ and $t$. In a symmetric frame, $x$ is the average longitudinal momentum fraction of the struck parton before and after the hard interaction and $\xi$ (skewness) is half of the longitudinal momentum fraction transferred to the struck parton. The skewness can be expressed in terms of the Bjorken variable $x_B$ as $\xi \simeq x_B/(2-x_B)$. Here $x_B = Q^2/(2p \cdot q)$ and $t = (p-p')^2$, where $p$ and $p'$ are the initial and final four-momenta of the nucleon.

When the theoretical calculations for longitudinal virtual photons were compared with the JLab $\pi^0$ data[5,6] they were found to underestimate the measured cross sections by more than an order of magnitude in their accessible kinematic regions. The failure to describe the experimental results with quark helicity-conserving operators stimulated a consideration of the role of the chiral-odd quark helicity-flip processes. Pseudoscalar meson electroproduction, and in particular $\pi^0$ production in the reaction $ep \to e'p'\pi^0$, was identified [7,8,9] as especially sensitive to the quark helicity-flip subprocesses. During the past few years, two parallel theoretical approaches - [7,10] (GL) and [8,9] (GK) have been developed utilizing the chiral-odd GPDs in the calculation of pseudoscalar meson electroproduction. The GL and GK approaches, though employing different models of GPDs, lead to *transverse* photon amplitudes that are much larger than the longitudinal amplitudes.

## 2. Definition of Structure Functions

The unpolarized reduced meson cross section is described by 4 structure functions $\sigma_T$, $\sigma_L$, $\sigma_{TT}$ and $\sigma_{LT}$

$$2\pi \frac{d^2\sigma(\gamma^* p \to p\pi^0)}{dt d\phi_\pi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dt} \cos \phi.$$

References [9,10] obtain the following relations for unpolarized structure functions:

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'} \frac{1}{Q^4} \left\{ \left(1-\xi^2\right) \left|\langle \tilde{H} \rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle \tilde{H} \rangle^* \langle \tilde{E} \rangle\right] - \frac{t'}{4m^2} \xi^2 \left|\langle \tilde{E} \rangle\right|^2 \right\}, \tag{1}$$

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'Q^4} \left[ \left(1-\xi^2\right) \left|\langle H_T \rangle\right|^2 - \frac{t'}{8m^2} \left|\langle \bar{E}_T \rangle\right|^2 \right], \tag{2}$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'Q^4} \xi \sqrt{1-\xi^2} \frac{\sqrt{-t'}}{2m} \mathrm{Re}\left[\langle H_T \rangle^* \langle \tilde{E} \rangle\right], \tag{3}$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'Q^4} \frac{t'}{16m^2} \left|\langle \bar{E}_T \rangle\right|^2, \tag{4}$$

Here $m$ is the mass of the proton, $t' = t - t_{min}$, where $|t_{min}|$ is the minimum value of $|t|$ corresponding to $\theta_\pi = 0$, $k'(Q^2, x_B)$ is a phase space factor and $\bar{E}_T = 2\widetilde{H}_T + E_T$. The brackets $\langle H_T \rangle$ and $\langle \bar{E}_T \rangle$ denote the convolution of the elementary process $\gamma^* q \to q\pi^0$ with the GPDs $H_T$ and $\bar{E}_T$. We call them generalized form factors.

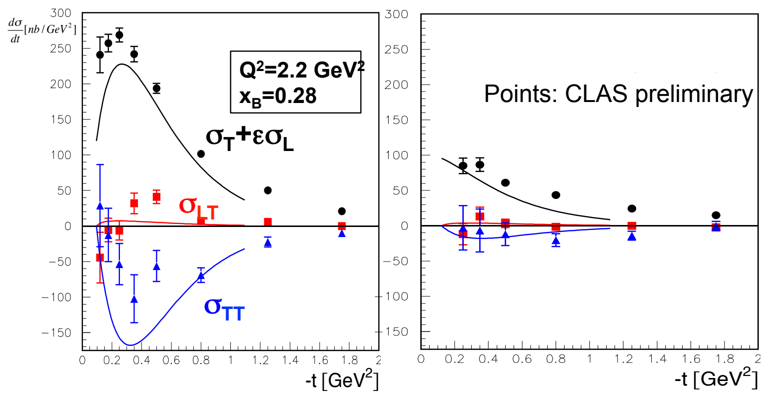


Fig. 1. Color online. Structure functions $\sigma_T + \epsilon\sigma_L$ (black), $\sigma_{TT}$ (blue) and $\sigma_{LT}$ (red) as a function of -$t$ for $\pi^0$ (left) and $\eta$(right) exclusive electroproduction for kinematic point ($Q^2$ = 2.2 GeV$^2$,$x_B$=0.28). Data points: CLAS, preliminary. Curves: theoretical predictions produced with the GK handbag model.

## 3. Experimental data

Cross section of the reaction $ep \to ep\pi^0$ measured by CLAS spectrometer in 1800 kinematic points in bins of $Q^2$, $x_B$, $t$ and $\phi$ were published in [5,6]. Structure functions $\sigma_U = \sigma_T + \epsilon\sigma_L$, $\sigma_{LT}$ and $\sigma_{TT}$ have been obtained. These functions were compared with the predictions of the GPD models [9,10]. CLAS confirmed that the measured unseparated cross sections are much larger than expected from leading-twist handbag calculations which are dominated by longitudinal photons. The same conclusion can be made in an almost model-independent way by noting that the structure functions $\sigma_U$ and $|\sigma_{TT}|$ are comparable to each other while $|\sigma_{LT}|$ is quite small (see Fig.1).

The comparison of the $\pi^0$ and preliminary $\eta$ structure functions is shown in Fig. 1. $\sigma_U$ drops by a factor of 2.5 for $\eta$ in comparison with $\pi^0$ and $\sigma_{TT}$ drops by a factor of 10. The GK GPD model [9] (curves) follows the experimental data. The inclusion of $\eta$ data into consideration strengthens the statement about the transversity GPD dominance in the pseudoscalar electroproduction process.

## 4. Generalized Form Factors

Generalized form factors $|\langle H_T\rangle|^2$ and $\left|\langle \bar{E}_T\rangle\right|^2$ may be directly extracted from the experimental data (see Eqs. 2 and 4 ) in the framework of GPD models

$$\begin{aligned} \left|\langle \bar{E}_T\rangle^{\pi,\eta}\right|^2 &= \frac{k'Q^4}{4\pi\alpha}\frac{16m^2}{t'}\frac{d\sigma_{TT}^{\pi,\eta}}{dt} \\ |\langle H_T\rangle^{\pi,\eta}|^2 &= \frac{2k'Q^4}{4\pi\alpha}\frac{1}{1-\xi^2}\left[\frac{d\sigma_T^{\pi,\eta}}{dt} + \frac{d\sigma_{TT}^{\pi,\eta}}{dt}\right]. \end{aligned} \quad (5)$$

Fig. 2 presents the modules of the generalized form factors $|\langle H_T\rangle^\pi|$, $\left|\langle \bar{E}_T\rangle^\pi\right|$, $|\langle H_T\rangle^\eta|$ and $\left|\langle \bar{E}_T\rangle^\eta\right|$ for 4 different kinematics. Note the dominance of the $\left|\langle \bar{E}_T\rangle\right|$ over $|\langle H_T\rangle|$ for both $\pi^0$ and $\eta$ for all kinematics.

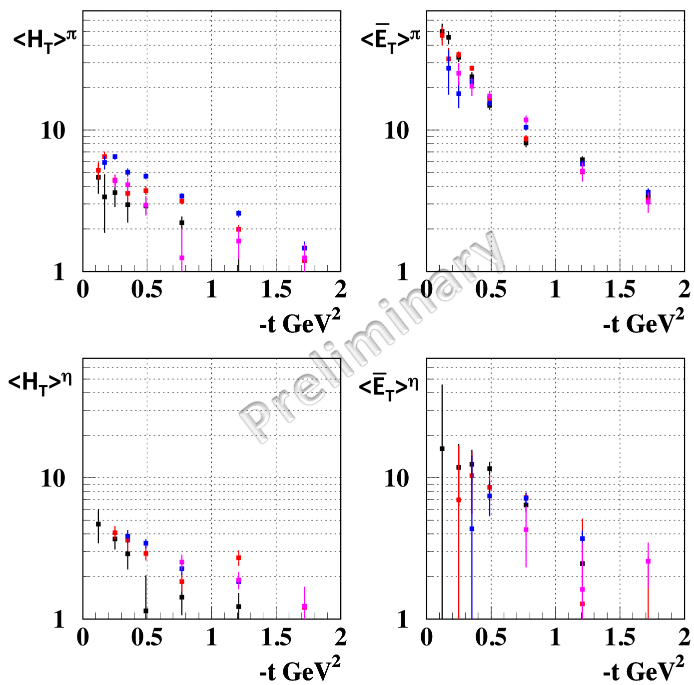


Fig. 2. Color online. Data points: CLAS, preliminary. Top left: $|\langle H_T\rangle^\pi|$, top right: $\left|\langle \bar{E}_T\rangle^\pi\right|$, bottom left: $|\langle H_T\rangle^\eta|$, bottom right: $\left|\langle \bar{E}_T\rangle^\eta\right|$ as a function of $-t$ for different values of ($Q^2$ [$GeV^2$], $x_B$)=(1.2, 0.15) black, (1.8, 0.22) red, (2.2, 0.27) blue, (2.7, 0.34) magenta.

## 5. Flavor Decomposition

In electroproduction the GPDs $F_i$ appears in the following combinations

$$\begin{aligned} F_i^\pi &= \frac{1}{\sqrt{2}}[e_u F_i^u - e_d F_i^d] \\ F_i^\eta &= \frac{1}{\sqrt{6}}[e_u F_i^u + e_d F_i^d - 2e_s F_i^s] \end{aligned} \tag{6}$$

The $q$ and $\bar{q}$ GPDs contribute in the quark combinations $F_i^q - F_i^{\bar{q}}$. Hence there is no contribution from the strange quarks if we assume that $F_i^s \simeq F_i^{\bar{s}}$. For flavor decomposition we have to take into account the decay constants $f_\pi$ and $f_\eta$, the chiral condensate constants $\mu_{\pi^0}$ =2.57 GeV, $\mu_1$ =0.958 GeV and $\mu_8$=2.32 GeV, and contribution from singlet and octet $\eta$ states.[9]

$$F_i^{\eta} = F_i^{\pi}\left(\cos\theta_8 - \sqrt{2}\frac{\mu_1}{\mu_8}\frac{f_1}{f_8}\sin\theta_1\right)\frac{f_8}{f_{\pi^0}}\frac{\mu_8}{\mu_{\pi^0}} = \frac{F_i^8}{k_\eta}, \tag{7}$$

where mixing angles are: $\theta_8 = -21.2^o$ and $\theta_1 = -9.2^o$. The octet and singlet wave functions are very similar and the decay constants are close as well $f_8 = 1.26 f_\pi$ and $f_1 = 1.17 f_\pi$. The overall factor for $\eta$ meson is $k_\eta = 0.863$. Using $e_u = \frac{2}{3}$ and $e_d = -\frac{1}{3}$ we will end up with equations

$$\begin{aligned} F_i^{\pi} &= \frac{1}{3\sqrt{2}}[2F_i^u + F_i^d] \\ k_\eta F_i^{\eta} &= \frac{1}{3\sqrt{6}}[2F_i^u - F_i^d]. \end{aligned} \tag{8}$$

Experimentally we have access only to the $|\langle F_i^{\pi}\rangle|^2$ and $|\langle F_i^{\eta}\rangle|^2$ (see Eq. 5). The final equation for the $\langle H_T\rangle$ convolution reads

$$\begin{cases} \frac{1}{18}\left|2\langle H_T\rangle^u + \langle H_T\rangle^d\right|^2 = |\langle H_T\rangle^{\pi}|^2 \\ \frac{1}{54}\left|2\langle H_T\rangle^u - \langle H_T\rangle^d\right|^2 = k_\eta^2\,|\langle H_T\rangle^{\eta}|^2 \end{cases} \tag{9}$$

and simular equations for $\langle \bar{E}_T\rangle$. The solution of these equations will lead to the

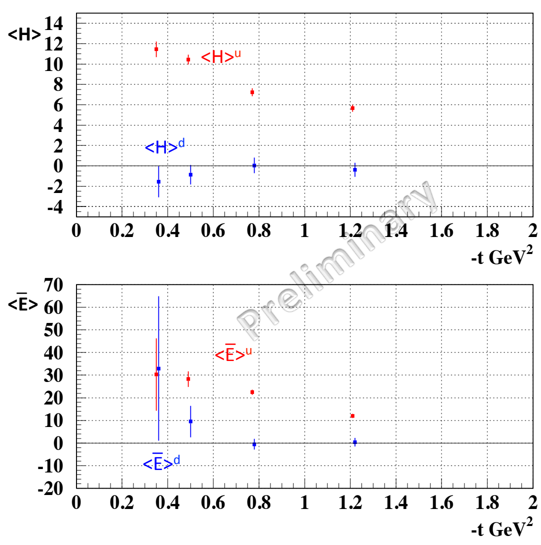


Fig. 3. Preliminary. Top: Extracted $\langle H_T\rangle^u$ (red) and $\langle H_T\rangle^d$ (blue); Bottom: $\langle \bar{E}_T\rangle^u$ (red) and $\langle \bar{E}_T\rangle^d$ (blue), as a function of -$t$ for $Q^2 = 2.2\ GeV^2$ and $x_B$=0.27.

flavor decomposition of the transversity GPDs $\langle H_T\rangle^u$ and $\langle H_T\rangle^d$ as well as $\langle \bar{E}_T\rangle^u$ and $\langle \bar{E}_T\rangle^d$. However the convolution integrals have real and imaginary parts. So it is impossible to solve these equations unambiguously with only two equations in hands. Like a guidance we can estimate the form factors if we suppose that relative phase $\Delta\phi$ between $\langle H_T\rangle^u$ and $\langle H_T\rangle^d$ equals 0 or 180 degrees. Ignoring an overall phase, the form factors are then real and we arbitrarily choose the solution with $\langle H_T\rangle^u$ and $\langle \bar{E}_T\rangle^u$ positive. Fig. 3 presents $\langle H_T\rangle^u$, $\langle H_T\rangle^d$, $\langle \bar{E}_T\rangle^u$ and $\langle \bar{E}_T\rangle^d$ for one kinematic point ($Q^2 = 2.2\ GeV^2, x_B = 0.27$) calculated in this assumption. Note the different signs of $\langle H_T\rangle^u$ and $\langle H_T\rangle^d$ convolutions and the same sign of $\langle \bar{E}_T\rangle^u$ and $\langle \bar{E}_T\rangle^d$.

## 6. Conclusion

Differential cross sections of exclusive $\pi^0$ and $\eta$ electroproduction have been obtained in the few-GeV region at more than 1800 kinematic points in bins of $Q^2, x_B$, $t$ and $\phi_\pi$. Virtual photon structure functions $\sigma_U$, $\sigma_{TT}$ and $d\sigma_{LT}$ have been obtained. It is found that $\sigma_U$ and $\sigma_{TT}$ are comparable in magnitude with each other, while $\sigma_{LT}$ is very much smaller than either. Generalized form factors of the transversity GPDs $\langle H_T\rangle^{\pi,\eta}$ and $\langle \bar{E}_T\rangle^{\pi,\eta}$ were directly extracted from the experimental observables for the first time. It was found that GPD $\bar{E}_T$ dominates in the pseudoscalar meson production. The combined $\pi^0$ and $\eta$ data opens the way for the flavor decomposition of the transversity GPDs. Within some simplifying assumptions, the first ever evaluation of this decomposition was demonstrated.

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