Deeply Virtual Meson Production at Jefferson Lab

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Outline

• Physics motivation
• CLAS data on pseudoscalar meson electroproduction
• Transversity GPD and structure functions
• Flavor decomposition of the Transversity GPDs
• Conclusion
Description of hadron structure in terms of GPDs

D. Müllér, X. Ji, A. Radyushkin

**Nucleon form factors**
transverse charge & current densities
Nobel prize 1961 - R. Hofstadter

**Structure functions**
quark longitudinal momentum (polarized and unpolarized) distributions
Nobel prize 1990 – J. Friedman, H. Kendall, R. Taylor

**GPDs**
correlated quark momentum distributions (polarized and unpolarized) in transverse space
Generalized Parton Distributions

• GPDs are the functions of three kinematic variables: $x$, $\xi$ and $t$
• There are 4 chiral even GPDs where partons do not flip helicity $H$, $\tilde{H}$, $E$, $\tilde{E}$
• 4 chiral odd GPDs flip the parton helicity $H_T$, $\tilde{H}_T$, $E_T$, $\tilde{E}_T$
• The chiral-odd GPDs are difficult to access since subprocesses with quark helicity-flip are suppressed
Chiral-odd GPDs

• Very little known about the chiral-odd GPDs
• Anomalous tensor magnetic moment
  \[ \kappa_T = \int_{-1}^{+1} dx \, \bar{E}_T(x, \xi, t = 0) \]
• (Compare with anomalous magnetic moment)
  \[ \kappa = \int_{-1}^{+1} dx \, E(x, \xi, t = 0) = F_2(t = 0) \]
• Transversity distribution
  \[ H_T^q(x, 0, 0) = h_1^q(x) \]

The transversity describes the distribution of transversely polarized quarks in a transversely polarized nucleon.
Structure functions and GPDs

\[
\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E) \frac{1}{2\pi} (\sigma_T + \epsilon\sigma_L + \epsilon \cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi_\pi \sigma_{LT})
\]

Leading twist \(\sigma_L\)

\[
\sigma_L = \frac{4\pi\alpha_e}{\kappa Q^2} [(1 - \xi^2) |\langle \tilde{H} \rangle|^2 - 2\xi^2 \Re(\langle \tilde{H} \rangle \langle \tilde{E} \rangle) - \frac{t}{4m^2 \xi^2} |\langle \tilde{E} \rangle|^2]
\]

\(\sigma_L\) suppressed by a factor coming from:

\[
\tilde{H} = \frac{1}{3\sqrt{2}} [2\tilde{H}^u + \tilde{H}^d]
\]

\(\tilde{H}^u\) and \(\tilde{H}^d\) have opposite signes

\[
\langle \tilde{H} \rangle = \sum_\lambda \int_{-1}^{1} dx M(x, \xi, Q^2, \lambda) \tilde{H}(x, \xi, t)
\]

\[
\langle \tilde{E} \rangle = \sum_\lambda \int_{-1}^{1} dx M(x, \xi, Q^2, \lambda) \tilde{E}(x, \xi, t)
\]

The brackets \(\langle F \rangle\) denote the convolution of the elementary process with the GPD \(F\) (generalized form factors)

S. Goloskokov and P. Kroll
S. Liuti and G. Goldstein
**Structure functions and GPDs**

\[
\frac{d^4 \sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E) \frac{1}{2\pi} (\sigma_T + \epsilon \sigma_L + \epsilon \cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi_\pi \sigma_{LT})
\]

\[
\sigma_T = \frac{4\pi \alpha_e \mu_\pi^2}{2\kappa} \frac{Q^4}{\xi^2} \left[(1 - \xi^2) \left| \langle H_T \rangle \right|^2 - \frac{t'}{8m^2} \left| \langle E_T \rangle \right|^2 \right]
\]

\[
\sigma_{TT} = \frac{4\pi \alpha_e \mu_\pi^2}{2\kappa} \frac{t'}{Q^4} \frac{\left| \langle E_T \rangle \right|^2}{8m^2}
\]

**Transversity GPD model**

S. Goloskokov and P. Kroll
S. Liuti and G. Goldstein

- \( \sigma_L \ll \sigma_T \)
- t-dependence at \( t = t_{\text{min}} \) is determined by the interplay between \( H_T \) and \( \bar{E}_T = 2H_T + E_T \)
Transverse Densities for u and d Quarks in the Nucleon

Strong distortions for unpolarized quarks in transversely polarized nucleon

Described by $E$

Described by $\bar{E}_T = 2\bar{H}_T + E_T$

Gockeler et al, hep-lat/0612032
CEBAF Large Acceptance Spectrometer CLAS

CLAS Lead Tungstate Electromagnetic Calorimeter

424 crystals, 18 RL, Pointing geometry, APD readout
4 Dimensional Grid

Rectangular bins are used.

- $Q^2$: 7 bins (1. - 4.5 GeV$^2$)
- $x_B$: 7 bins (0.1 - 0.58)
- $t$: 8 bins (0.09 - 2.0 GeV)
- $\phi$: 20 bins (0 - 360°)
- $\pi^0$ data: ~2000 points
- $\eta$ data: ~1000 points

$ep \rightarrow ep\pi^0$
Structure Functions

\[ \sigma_U = \sigma_T + \varepsilon \sigma_L \quad \sigma_{TT} \quad \sigma_{LT} \]

\[
\frac{d\sigma}{dt\phi} (Q^2, x, t, \phi) = \frac{1}{2\pi} \left( \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} \right) + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi + \sqrt{2\varepsilon (\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos \phi
\]

\[ \phi \text{ distribution} \]
\[ \frac{d\sigma}{dt}(\gamma^* p \rightarrow ep\pi^0) \propto e^{bt} \]

\begin{align*}
&d\sigma \quad (\gamma^* p \rightarrow ep\pi^0) \propto e^{bt} \\
&\frac{d\sigma}{dt} = d\sigma_{U}/dt
\end{align*}
The slope parameter is decreasing with increasing $x_B$. The $Q^2$ dependence is weak. Looking to this picture we can say that the perp width of the partons with $x \to 1$ goes to zero.
Structure Functions

$$(\sigma_T + \epsilon \sigma_L) \quad \sigma_{TT} \quad \sigma_{LT}$$

$\gamma^* p \rightarrow p\pi^0$

Curves: Goloskokov, Kroll
Transversity GPD model

Data: I.Bedlinskiy et al. (CLAS)
CLAS data and GPD theory predictions

- **Transversity** GPDs $H_T$ and $E_T = 2\tilde{H}_T + E_T$ dominate in CLAS kinematics.
- The model was optimized for low $x_B$ and high $Q^2$. The corrections $t/Q^2$ were omitted.
- The model successfully describes CLAS data even at low $Q^2$.
- Pseudoscalar meson production provides unique possibility to access the transversity GPDs.

Comparison $\pi^0/\eta$

preliminary

- $\sigma_{u}=\sigma_{T}+\varepsilon\sigma_{L}$ drops by a factor of 2.5 for $\eta$
- $\sigma_{TT}$ drops by a factor of 10
- The GK GPD model (curves) follows the experimental data
- The statement about the transversity GPD dominance in the pseudoscalar electroproduction becomes more solid with the inclusion of $\eta$ data
• The dependence on $x_B$ and $Q^2$ is very weak.
• Chiral odd GPD models predict this ratio to be ~1/3 at CLAS kinematics
• Chiral even GPD models predict this ratio to be around 1 (at low $-t$).
The dependence on the $x_B$ and $Q^2$ is very weak.

Chiral even GPD models predict this ratio to be around 1 (at low $-t$).

Chiral odd GPD models predict this ratio to be around $1/3$ at CLAS kinematics.

Theoretical prediction $R=1$ for the Chiral-even GPD models ($\sigma_L >> \sigma_T$)
Structure functions and GPDs

\[ \frac{d\sigma_T}{dt} = \frac{4\pi\alpha \mu_P^2}{2k'} Q^8 \left[ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8m^2} |\langle \bar{E}_T \rangle|^2 \right] \]
\[ \frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha \mu_P^2}{k'} Q^8 \frac{t'}{16m^2} |\langle \bar{E}_T \rangle|^2 \]

Goloskokov, Kroll
Transversity GPD model

\[ |\langle \bar{E}_T \rangle|^2 = \frac{k'}{4\pi\alpha \mu_P^2} \frac{Q^8}{t'} \frac{16m^2}{d\sigma_{TT}/dt} \]
\[ |\langle H_T \rangle|^2 = \frac{2k'}{4\pi\alpha \mu_P^2} \frac{Q^8}{1 - \xi^2} \left[ \frac{d\sigma_{TT}}{dt} + \frac{d\sigma_{TT}}{dt} \right] \]

- We did not separate \( \sigma_T \) and \( \sigma_L \)
- However, in the approximation of the transversity GPDs dominance, that is supported by CLAS data, \( \sigma_L \ll \sigma_T \) we have direct access to the generalized form factors for \( \pi \) and \( \eta \) production.

\[ \langle H_T \rangle = \sum_\chi \int_{-1}^1 dx M(x, \xi, Q^2, \lambda) H_T(x, \xi, t) \]
\[ \langle \bar{E}_T \rangle = \sum_\chi \int_{-1}^1 dx M(x, \xi, Q^2, \lambda) \bar{E}_T(x, \xi, t) \]

The brackets \( <F> \) denote the convolution of the elementary process with the GPD \( F \) (generalized form factors)

\[ \bar{E}_T = 2\bar{\bar{H}}_T + \bar{E}_T \]
Generalized Form factors

- $|\langle H_T \rangle|$ vs. $-t$ GeV$^2$
- $|\langle \bar{E}_T \rangle|$ vs. $-t$ GeV$^2$

<table>
<thead>
<tr>
<th>$Q^2$ GeV$^2$</th>
<th>$x_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>0.15</td>
</tr>
<tr>
<td>1.8</td>
<td>0.22</td>
</tr>
<tr>
<td>2.2</td>
<td>0.27</td>
</tr>
<tr>
<td>2.7</td>
<td>0.34</td>
</tr>
</tbody>
</table>

- $\bar{E}_T > H_T$ for $\pi^0$ and $\eta$
- $t$-dependence is steeper for $\bar{E}_T$ than for $H_T$
- Estimation of the systematic uncertainties connected with the used approximation is in progress
Generalized Form Factors

\[ Q^2 = 2.2 \text{ GeV}^2, \quad x_B = 0.27 \]

- \( \bar{E}_T > H_T \)
- t-dependence is steeper for \( \bar{E}_T \) than for \( H_T \)

- \( |\langle E_T, H_T \rangle| \sim \exp(bt) \)
- \( b(E_T) = 1.27 \text{ GeV}^{-2} \)
- \( b(H_T) = 0.98 \text{ GeV}^{-2} \)
GPD Flavor Decomposition

\[ H_T^{\pi} = \frac{1}{3\sqrt{2}} [2H_T^u + H_T^d] \]
\[ H_T^\eta = \frac{1}{\sqrt{6}} [2H_T^u - H_T^d] \]

- GPDs appear in different flavor combinations for \( \pi^0 \) and \( \eta \)
- The combined \( \pi^0 \) and \( \eta \) data permit the flavor (u and d) decomposition for GPDs \( H_T \) and \( E_T \)
- The u/d decomposition was done under **simple assumption** that the relative phase between u and d is 0 or 180 degrees.

\[ H_T^u = \frac{3}{2\sqrt{2}} [H_T^{\pi} + \sqrt{3}H_T^\eta] \]
\[ H_T^d = \frac{3}{\sqrt{2}} [H_T^{\pi} - \sqrt{3}H_T^\eta] \]

Similar expressions for \( E_T \)
Flavor Decomposition of the Transversity GPDs

$Q^2 = 1.8 \text{ GeV}^2, \; x_B = 0.22$

- $<H_T>^u$ and $<H_T>^d$ have different signs for $u$ and $d$-quarks in accordance with the transversity function $h_1$ (Anselmino et al.)
- $|<E_T>|^d$ and $|<E_T>|^u$ seem to have the same signs
- Decisions shown with positive values of $u$-quark's GPDs only
Summary

- The discovery of Generalized Parton Distributions has opened up a new and exciting avenue of hadron physics that needs exploration in dedicated experiments.

- CLAS $\pi^0$ and $\eta$ data supports the dominance of the transversity GPDs $H_T$ and $E_T$ in the processes of the pseudoscalar meson electroproduction.

- The generalized form factors $<H_T>$ and $<E_T>$ are directly connected to the structure functions $\sigma_T$ and $\sigma_{TT}$ within handbag approach.

- The combined $\pi^0$ and $\eta$ data will provide the way for the flavor decomposition of transversity GPD.
END
\( ep \rightarrow ep\pi^0 \) : spin asymmetries

**Beam Spin Asymmetries**

R. De Masi et al. (CLAS collaboration) PRC77: 042201 (2008)

\[
A_{LU}^{\sin \phi} \sigma_0 \sim \text{Im} \left[ \langle H_T \rangle^* \langle \tilde{E} \rangle \right]
\]

\[
A_{UL}^{\sin \phi} \sigma_0 \sim \text{Im} \left[ \langle E_T \rangle^* \langle \tilde{H} \rangle + \xi \langle H_T \rangle^* \langle \tilde{E} \rangle \right]
\]

\[
A_{LL}^{\text{const}} \sigma_0 \sim |\langle H_T \rangle|^2
\]

\[
A_{LL}^{\cos \phi} \sigma_0 \sim \text{Re} \left[ \langle E_T \rangle^* \langle \tilde{H} \rangle + \xi \langle H_T \rangle^* \langle \tilde{E} \rangle \right]
\]

**Target and Double Spin Asymmetries**

\( \langle Q^2 \rangle = 1.94 \text{ GeV}^2; \langle x_B \rangle = 0.25 \)

\( \langle Q^2 \rangle = 2.83 \text{ GeV}^2; \langle x_B \rangle = 0.40 \)

Dominated by transverse virtual photons contribution

↓

Unique sensitivity for constraining the chiral-odd GPDs