Generalized Parton Distributions in Hall A at Jefferson Lab

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Outline

1. Introduction

2. Nucleon 3D-imaging & Generalized Parton Distributions (GPDs)

3. Deeply Virtual Compton Scattering (DVCS): $ep \rightarrow ep\gamma$
   - Results on both proton and neutron (preliminary)

4. Exclusive $\pi^0$ electroproduction (DVMP): $eN \rightarrow eN\pi^0$
   - Also: proton + neutron $\Rightarrow$ flavor separation

5. First (preliminary) results at 12 GeV and future plans

6. Summary
Deeply Virtual Compton Scattering (DVCS): $\gamma^* p \rightarrow \gamma p$

**Handbag diagram**

Bjorken limit:

$$Q^2 = -q^2 \rightarrow \infty \quad \nu \rightarrow \infty$$

$$x_B = \frac{Q^2}{2M \nu} \quad \text{fixed}$$
DVCS experimentally: interference with Bethe-Heitler

At leading order in $1/Q$ (leading twist):

\begin{align*}
\sigma^5 \rightarrow \sigma - \sigma^5 \leftarrow \sigma &= \Im \left( T^{BH} \cdot T^{DVCS} \right) \\
\sigma^5 \rightarrow \sigma + \sigma^5 \leftarrow \sigma &= |BH|^2 + \Re \left( T^{BH} \cdot T^{DVCS} \right) + |DVCS|^2
\end{align*}

\[ T^{DVCS} = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} + \cdots = \]

\[ \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi H(x = \xi, \xi, t) + \cdots \]

Access in helicity-independent cross section

Access in helicity-dependent cross-section
8 GPDs related to the different combination of quark/nucleon helicities

4 chiral-even GPDs: conserve the helicity of the quark

Access through DVCS (and DVMP)
8 GPDs related to the different combination of quark/nucleon helicities

\[ H_T \quad E_T \quad \tilde{H}_T \quad \tilde{E}_T \]

4 chiral-odd GPDs: flip helicity of the quark

"transversity GPDs"

Experimental access more complicated ($\pi^0$ electroproduction?)
Accessing different GDPs

Polarized beam, unpolarized target (BSA)
\[ d\sigma_{LU} = \sin \phi \cdot \mathcal{I}m\{F_1 \mathcal{H} + x_B (F_1 + F_2) \mathcal{H} - kF_2 \mathcal{E}\} \, d\phi \]

Unpolarized beam, longitudinal target (ITSA)
\[ d\sigma_{UL} = \sin \phi \cdot \mathcal{I}m\{F_1 \mathcal{H} + x_B (F_1 + F_2) (\mathcal{H} + x_B/2\mathcal{E}) - x_B kF_2 \mathcal{E} \ldots \} \, d\phi \]

Polarized beam, longitudinal target (BITSA)
\[ d\sigma_{LL} = (A + B \cos \phi) \cdot \mathcal{R}e\{F_1 \mathcal{H} + x_B (F_1 + F_2) (\mathcal{H} + x_B/2\mathcal{E}) \ldots \} \, d\phi \]

Unpolarized beam, transverse target (tTSA)
\[ d\sigma_{UT} = \cos \phi \cdot \mathcal{I}m\{k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots \} \, d\phi \]
Kinematic coverage

Kinematic complementarity between different facilities:
Experimental setup

- 100-channel scintillator array
- High Resolution Spectrometer
- 132-block PbF$_2$ electromagnetic calorimeter
Recent results on DVCS

DVCS cross sections: azimuthal analysis

\[ Q^2 = 2.36 \text{ GeV}^2, \quad x_B = 0.37, \quad -t = 0.32 \text{ GeV}^2 \]

\[ d^4 \sigma = \mathcal{T}_{\text{BH}}^2 + \mathcal{T}_{\text{BH}} \Re(\mathcal{T}_{\text{DVCS}}) + \mathcal{T}_{\text{DVCS}}^2 \]

\[ \Re(\mathcal{T}_{\text{DVCS}}) \sim c^T_0 + c^T_1 \cos \phi + c^T_2 \cos 2\phi \]

\[ \mathcal{T}_{\text{DVCS}}^2 \sim c^\text{DVCS}_0 + c^\text{DVCS}_1 \cos \phi \]

\[ \Delta^4 \sigma = \frac{d^4 \sigma^- - d^4 \sigma^+}{2} = \Im(\mathcal{T}_{\text{DVCS}}) \]

\[ \Im(\mathcal{T}_{\text{DVCS}}) \sim s^T_1 \sin \phi + s^T_2 \sin 2\phi \]

Recents results on DVCS

DVCS cross sections: $Q^2$–dependance

No $Q^2$-dependance within limited range $\Rightarrow$ leading twist dominance
Recents results on DVCS

DVCS cross sections: kinematical power corrections

KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries

Kumericki and Mueller (2010)
DVCS cross sections: kinematical power corrections

- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries
  Kumericki and Mueller (2010)

- Target-mass corrections (TMC): $\sim \mathcal{O}(M^2/Q^2)$ and $\sim \mathcal{O}(t/Q^2)$
  Braun, Manashov, Mueller and Pirnay (2014)

Kin2
$x_B = 0.34 - 0.38$
$Q^2 = 1.8 - 2.0 \text{ GeV}^2$

- Bethe-Heitler
- KM10a
- KM10a + TMC*

Braun et al.,
Phys. Rev. D89, 074022
Rosenbluth-like separation of the DVCS cross section

\[\sigma(ep \rightarrow ep\gamma) = |BH|^2 + \mathcal{I}(BH \cdot DVCS) + |DVCS|^2\]

- Known to \(\sim 1\%\)
- Linear combination of GPDs
- Bilinear combination of GPDs

\[\mathcal{I} \propto \frac{1}{y^3} = \left(\frac{k}{\nu}\right)^3,\]
\[|\mathcal{T}^{DVCS}|^2 \propto \frac{1}{y^2} = \left(\frac{k}{\nu}\right)^2\]

BKM-2010 – at leading twist \(\rightarrow 7\) independent GPD terms:

\(\{\text{Re, Im } [C^I, C^{I,V}, C^{I,A}] (\mathcal{F})\}\), and \(C^{DVCS}(\mathcal{F}, \mathcal{F}^*)\).

\(\varphi\)-dependence provides 5 independent observables:

\(\sim 1, \sim \cos \varphi, \sim \sin \varphi, \sim \cos(2\varphi), \sim \sin(2\varphi)\)

The measurement of the cross section at two or more beam energies for exactly the same \(Q^2, x_B, t\) kinematics, provides the additional information in order to extract all leading twist observables independently.
DVCS process: leading twist ambiguity

- DVCS defines a preferred axis: light-cone axis
- At finite $Q^2$ and non-zero $t$, there is an ambiguity:
  2. Braun et al. (“BMP”, 2014): light-cone axis in plane $(q,q')$

  - easier to account for kin. corrections $\sim \mathcal{O}(M^2/Q^2)$, $\sim \mathcal{O}(t/Q^2)$

\[
\begin{align*}
\mathcal{F}_{++} & = F_{++} + \frac{X}{2} [F_{++} + F_{--}] - \chi_0 F_{0+} \\
\mathcal{F}_{--} & = F_{--} + \frac{X}{2} [F_{++} + F_{--}] - \chi_0 F_{0+} \\
\mathcal{F}_{0+} & = -(1 + \chi) F_{0+} + \chi_0 [F_{++} + F_{--}] \\
\end{align*}
\]

\[
\left\{ \begin{array}{c}
\frac{F_{--}}{F_{0+}} = 0 \\
\frac{F_{++}}{F_{0+}} = 0 \\
\end{array} \right\}
\left\{ \begin{array}{c}
\mathcal{F}_{++} = (1 + \frac{X}{2}) F_{++} \\
\mathcal{F}_{--} = \frac{X}{2} F_{++} \\
\mathcal{F}_{0+} = \chi_0 F_{++} \\
\end{array} \right\}
\]

(eg. $\chi_0 = 0.25$, $\chi = 0.06$ for $Q^2 = 2$ GeV$^2$, $x_B = 0.36$, $t = -0.24$ GeV$^2$)
E07-007: DVCS beam-energy dependence

- Cross section measured at 2 beam energies and constant $Q^2$, $x_B$, $t$

\[ E = 4.5 \text{ GeV} \quad \quad \quad \quad \quad \quad E = 5.6 \text{ GeV} \]

- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

**Light-cone axis in the $(q,q')$ plane (Braun et al.):** $H_{++}, \tilde{H}_{++}, E_{++}, \tilde{E}_{++}$
Beyond Leading Order (LO) and Leading Twist (LT)

**Two fit-scenarios:**

**Light-cone axis in the \((q,q')\) plane (Braun et al.)**

**LO/LT + HT**

\[ H_{++}, \tilde{H}_{++}, H_{0+}, \tilde{H}_{0+} \]

**LO/LT + NLO**

\[ H_{++}, \tilde{H}_{++}, H_{-+}, \tilde{H}_{-+} \]
E07-007: DVCS beam-energy dependence

- Cross section measured at 2 beam energies and constant $Q^2$, $x_B$, $t$

- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

- Including either NLO or higher-twist effects (dark solid line) satisfactorily reproduce the angular dependence
DVCS$^2$ and $\mathcal{I}$ (DVCS·BH) separation

DVCS$^2$ and $\mathcal{I}$ (DVCS·BH) separated in NLO and higher-twist scenarios

- DVCS$^2$ & $\mathcal{I}$ significantly different in each scenario
- Sizeable DVCS$^2$ contribution in the higher-twist scenario in the helicity-dependent cross section

Nature Commun. 8, 1408 (2017)
DVCS on the neutron: experiment E03-106 at JLab

LD$_2$ target (\(F_2^n(t) \gg F_1^n(t)\))

\[
\sigma^\rightarrow - \sigma^\leftarrow = \Gamma(A \sin \varphi + \ldots)
\]

\[
A = F_1(t) \mathcal{H} + \frac{x_B}{2 - x_B} [F_1(t) + F_2(t)] \tilde{\mathcal{H}} - \frac{t}{4M^2} \cdot F_2(t) \cdot \mathcal{E}
\]

Main contribution for neutron
E08-025: DVCS off the neutron at different beam energies

- LD$_2$ as a target
- Quasi-free $p$ evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LD2/LD2 → minimize uncertainties

\[ D(e, e\gamma)X - p(e, e\gamma)p = n(e, e\gamma)n + d(e, e\gamma)d \]

The average momentum transfer to the target is much larger than the $np$ relative momentum, justifying this impulse approximation.
$\pi^0$ electroproduction ($ep \rightarrow ep\pi^0$)

At leading twist:

$$\frac{d\sigma_{L}}{dt} = \frac{1}{2} \Gamma \sum_{h_N, h'_N} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6}$$

$$\sigma_T \propto \frac{1}{Q^8}$$

$$\mathcal{M}^L \propto \left[ \int_{0}^{1} dz \frac{\phi_\pi(z)}{z} \right] \int_{-1}^{1} dx \left[ \frac{1}{x - \xi} + \frac{1}{x + \xi} \right] \times \left\{ \Gamma_1 \tilde{H}_{\pi^0} + \Gamma_2 \tilde{E}_{\pi^0} \right\}$$

Different quark weights: flavor separation of GPDs

$$|\pi^0\rangle = \frac{1}{\sqrt{2}} \{ |u\bar{u}\rangle - |d\bar{d}\rangle \}$$

$$\tilde{H}_{\pi^0} = \frac{1}{\sqrt{2}} \left\{ \frac{2}{3} \tilde{H}^u + \frac{1}{3} \tilde{H}^d \right\}$$

$$|p\rangle = |uud\rangle$$

$$H_{DVCS} = \frac{4}{9} H^u + \frac{1}{9} H^d$$

C. Muñoz Camacho (IPNO, CNRS/IN2P3)  
GPD at JLab/Hall A  
September 25, 2018 21 / 34
Exclusive $\pi^0$ electroproduction cross-sections – Hall A

- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$  
  (similar to $\sigma_T( e p \rightarrow e p \pi^+) $ measured in Hall C)
- GPDs predict $\sigma_L \sim Q^{-6}$
- $\sigma_T$ likely to dominate at these $Q^2$, but L/T separation necessary ($\rightarrow$ new experiment...)

### Rosenbluth separation

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

### Kinematics

<table>
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<tr>
<th>Setting</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
<th>$E_{beam}$ (GeV)</th>
<th>$\epsilon$</th>
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<td>5.55</td>
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</tbody>
</table>

$t_{\text{min}} - t = 0.025$ GeV$^2$
π^0 electroproduction and transversity GPDs

Modified handbag approach:

Divergencies regularized by $k_\perp$ of $q, \bar{q}$ + Sudakov suppression factor:

model of $\sigma_T$ using transversity GPDs of the nucleon + twist-3 $\pi$ DA
$\pi^0$ separated response functions

\begin{align*}
\text{Goloskokov, Kroll (2011)} \\
\text{Goldstein, Hernandez, Liuti (2011)} \\
\text{Vanderhaeghen, Guichon, Guidal (1999)}
\end{align*}
**E08-025: DVCS and $\pi^0$ off quasi-free neutrons**

- LD$_2$ as a target
- Quasi-free $p$ evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LD2/LD2 $\rightarrow$ minimize uncertainties

$$D(e, e \pi^0)X - p(e, e \pi^0)p = n(e, e \pi^0)n + d(e, e \pi^0)d$$

The average momentum transfer to the target is much larger than the $np$ relative momentum, justifying this **impulse approximation**
**\( \pi^0 \) electroproduction cross section off the neutron**

- Cross section off coherent \( d \) found negligible within uncertainties.
- Very low \( E_{\text{beam}} \) dependence of the \( n \) cross section \( \rightarrow \) dominance of \( \sigma_T \).
Separated $\pi^0$ cross section off the neutron

In the modified factorization approach (KG):

- $d\sigma_T \propto \left[ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2 \right]$
- $d\sigma_{TT} \propto \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2$


C. Muñoz Camacho (IPNO, CNRS/IN2P3) GPD at JLab/Hall A September 25, 2018 28 / 34
E12-06-114: JLab Hall A at 11 GeV

JLab12 with 3, 4, 5 pass beam

(6.6, 8.8, 11.0 GeV beam energy)

DVCS measurements in Hall A/JLab

1 year of operations in JLab/Hall A

88 days
250k events/setting
Preliminary results

\( Q^2 = 4.4 \text{ GeV}^2 \)

\( x_B = 0.36 \)

F. Georges, SPIN 2018
E12-13-010: DVCS in Hall C

- HMS ($p < 7.3 GeV$): scattered electron
- PbWO$_4$ calorimeter: $\gamma/\pi^0$ detection
- Sweeping magnet
E12-13-010: beam energy separation in Hall C

Resonance region
\[ W < 2 \text{ GeV} \]
Inaccessible with \( E_b < 11 \text{ GeV} \)

Approved by the PAC, possible running in \( \gtrsim 2021 \)
Projections

- PbF$_2$ → PbWO$_4$
- Improved $E$ resolution wrt Hall A

NPS cantelevered off SHMS platform

\( \sigma_{\text{PbF}_2} = 0.229 \)
\( \sigma_{\text{PbWO}_4} = 0.127 \)

NPS angle range: 5.5 – 30 degrees
Summary

- Recent high precision DVCS cross sections from Hall A at JLab

- Need of higher twist and/or NLO contributions to fully describe the data (e.g., in global GPD fits)

- First separation of DVCS\(^2\) and BH-DVCS interference in the \(eN \rightarrow e\gamma N\) cross section, off the proton and neutron

- L/T separation of \(\pi^0\) electroproduction cross section off neutron: dominance of \(\sigma_T\) measured

- Flavor separation of transversity GPD convolutions within the modified factorization approach

- Approved program of experiments in Hall A and C to continue these high precision DVCS measurements at 12 GeV
Back-up