DVCS at HERMES

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Exclusive Reactions, JLab, USA, May 2007

- **The GPD $H$ via:**
  - Beam-Spin Asymmetry (BSA)
  - Beam-Charge Asymmetry (BCA)

- **The GPD $E$ via transverse Target-Spin Asymmetry (TTSA)**

- DVCS on Nuclei
**Parameterization of the Nucleon Structure**

- **Form Factors** $\rightarrow$ **Transverse position** $\leftarrow$ **Elastic scattering**

- **PDFs** $\rightarrow$ **Longitudinal momentum distribution** $\leftarrow$ **DIS**

- **GPDs** $\rightarrow$ **Access to transverse position and longitudinal momentum distr. at the same time, 3-D picture** $\leftarrow$ **Exclusive reactions**

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Generalized Parton Distributions (GPDs)

Simplest/cleanest hard exclusive process:
Deeply-virtual electroproduction of real photons: \( e p \rightarrow e' p' \gamma \)
Deeply-virtual Compton Scattering (DVCS):

- Longitudinal momentum fractions:
  \( x \in [-1, 1] \) (not accessible)
  \( \xi \approx x_B/(2 - x_B) \)
- \( t = (q - q')^2 \) (\( \gamma^* \rightarrow \gamma \) Momentum transfer)
- \( Q^2 = -q^2 \)

⇒ Measurements as function of \( x_B, t, Q^2 \)

DVCS: Access to all four GPDs \( H, \tilde{H}, E, \tilde{E} \)
Mesons: Access to \( H, E \) (VM) and \( \tilde{H}, \tilde{E} \) (PS)
**Overview GPDs**

**PDFs:** GPDs in the limit $t \to 0$

\[
H^q(x, 0, 0) = q(x), \\
\tilde{H}^q(x, 0, 0) = \Delta q(x), \ldots
\]

**FFs:** First moments of GPDs

\[
\int_{-1}^{1} dx H(x, \xi, t) = F_1(t), \ldots
\]

**Only known (quantitative) access to (total)**

**Orbital angular momentum:**

\[
J_{q,g} = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} dx \ x \ [H^{q,g}(x, \xi, t) + E^{q,g}(x, \xi, t)]
\]

(X. Ji, 97)

**Original (HERMES) Motivation:**

**Nucleon (Long.) Spin Structure:**

\[
1/2 = \frac{1}{2} (\Delta u + \Delta d + \Delta s) + \frac{?}{L_q} + \frac{?}{J_g}
\]

\[\sim 30\% \]

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How To Access GPDs via DVCS?

DVCS Final state \( e + p \rightarrow e' + p' + \gamma \) is indistinguishable from the Bethe-Heitler Process (BH) \( \rightarrow \) Amplitudes add coherently

\[ d\sigma \propto |\tau_{DVCS} + \tau_{BH}|^2 = |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau_{DVCS}^* \tau_{BH} + \tau_{BH}^* \tau_{DVCS}) \]

Fixed-Target, Collider

Collider

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DVCS MEASUREMENTS

\[
d\sigma \propto |\tau_{BH}|^2 + \underbrace{(\tau^*_{DVCS} \tau_{BH} + \tau^*_{BH} \tau_{DVCS})}_{I} + |\tau_{DVCS}|^2
\]

|\tau_{BH}|^2 calculable in QED with the knowledge of the form factors

\[
I \propto \pm \left( c^I_0 + \sum_{n=1}^{3} c^I_n \cos(n\phi) + \lambda \sum_{n=1}^{3} s^I_n \sin(n\phi) \right)
\]

DVCS cross section (H1, Zeus): Measurement integrated over \( \phi \) → \( I = 0 \) (at Twist–2), subtract |\tau_{BH}|^2

Azimuthal asymmetries (HERMES, JLab): DVCS amplitudes directly accessible via \( I \Rightarrow \text{Magnitude} + \text{Phase}!!! \)

(GPDs enter in linear combinations)
Azimuthal Asymmetries

\[ I \propto \pm (c_0^I + \sum_n [c_n^I \cos(n\phi) + \lambda s_n^I \sin(n\phi)]) \]

**Beam–Spin Asymmetry (BSA) and Beam–Charge Asymmetry (BCA)**

**ON UNPOLARIZED TARGET:**

**BSA:**
\[ d\sigma(e^+p) - d\sigma(e^+\bar{p}) \sim s_{1,\text{unp}}^{I} \sin(\phi) \sim \sin(\phi) \times \text{Im} \, M_{\text{unp}}^{1,1} \]

**BCA:**
\[ d\sigma(e^+p) - d\sigma(e^-p) \sim c_{1,\text{unp}}^{I} \cos(\phi) \sim \cos(\phi) \times \text{Re} \, M_{\text{unp}}^{1,1} \]

(Higher Twist/Order \(\rightarrow\) \(\cos 2\phi, \cos 3\phi, \sin 2\phi\))

**Longitudinal Target–Spin Asymmetry (LTSA)**

**LTSA:**
\[ d\sigma(e^+\bar{p}) - d\sigma(e^+\bar{p}) \sim s_{1,\text{LP}}^{I} \sin(\phi) \sim \sin(\phi) \times \text{Im} \, M_{\text{LP}}^{1,1} \]

(Higher Twist/Order \(\rightarrow\) \(\sin 2\phi, \sin 3\phi\))
From Amplitudes to GPDs

\[ M^{1,1}_{unp} = F_1(t) H_1(\xi, t) + \frac{x_B}{2-x_B} (F_1(t) + F_2(t)) \tilde{H}_1(\xi, t) - \frac{t}{4M^2} F_2(t) E_1(\xi, t) \]

\[ \langle x_B \rangle, \langle -t \rangle \approx 0.1 \Rightarrow \text{Compton Form-Factor} \ H_1 \]

\[ \text{Im} \ H_1 \sim -\pi \sum_q e_q^2 (H^q(\xi, \xi, t) - H^q(-\xi, \xi, t)) \]

\[ \text{Re} \ H_1 \sim \sum_q e_q^2 \left[ P \int_{-1}^{1} H^q(x, \xi, t) \left( \frac{1}{x - \xi} + \frac{1}{x + \xi} \right) dx \right] \]

BSA: \text{Im} \ M^{1,1}_{unp} \text{ mainly accesses the GPD } H^q(x, \xi, t) \text{ at } x = \xi \Rightarrow \text{measures } H^q(\xi, \xi, t) \]

BCA: \text{Re} \ M^{1,1}_{unp} \text{ contains full } x\text{-dependence of the GPD } H^q(x, \xi, t),

\text{x is not accessible } \Rightarrow \text{GPD Model } \rightarrow \text{Observables } \leftarrow \text{Measurement}
HERMES Event Selection

HERA Beam: 27.6 GeV, $e^+$ AND $e^-$, $\langle P \rangle \approx 35 - 55\%$
POL. + UNPOL. Gas Targets: H/D/Ne/Kr/..

Events with exactly one DIS-positron/DIS-electron and exactly one photon in the calorimeter

Data shown taken before installation of recoil detector ⇒

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Exclusivity for DVCS via Missing Mass

\[ M^2_x \equiv (q + p - p_\gamma)^2 \Rightarrow MC \] for background and cuts (→ resolution)!

- **Elastic BH** \((e p \to e' p' \gamma)\)
- **Associated BH** (mainly \(e p \to e' \Delta^+ \gamma\))
- **Semi-Inclusive** (mainly \(e p \to e' \pi^0 X\))
- **Exclusive** \(\pi^0 (e p \to e' \pi^0)\) NOT SHOWN (SMALL)

Not simulated: DVCS process (DVCS c.s. “unknown”, DVCS \(<\!< BH\)) + Radiative corrections to BH (→ excl. peak overestimated, BG underestimated)

⇒ “Exclusive” bin \((-1.5 < M_x < 1.7 \text{ GeV})\)
⇒ Overall background contribution \(\approx 15\%\)
**Beam–Spin Asymmetry (BSA)**

\[ A_{LU}(\phi) = \frac{1}{<|P_b|>} \frac{\vec{N}(\phi) - \vec{N}(\phi)}{\vec{N}(\phi) + \vec{N}(\phi)} \]

\[ e^+ p \rightarrow e^+ \gamma X \quad (M_x < 1.7 \text{ GeV}) \]

**HERMES PREL. 2000** (refined)

- **P1** = -0.04 ± 0.02 (stat)
- **P2** = -0.18 ± 0.03 (stat)
- **P3** = 0.00 ± 0.03 (stat)

\[ \langle -t \rangle = 0.18 \text{ GeV}^2, \langle x_B \rangle = 0.12, \langle Q^2 \rangle = 2.5 \text{ GeV}^2 \]

**A\text{LU}** in exclusive bin: **Expected sin(\phi) dependence \Rightarrow Im M^{1,1}_{unp}**

\[ \sin(\phi) - \text{Moment in non–exclusive region: small and slightly positive (\( \rightarrow \pi^0 \))} \]

(Results from 1996/97 \( \rightarrow \) PRL 87, 182001 (2001))

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Kinematic dependences of Beam–Spin Asymmetry (BSA)

Kinematic dependence of combined 96/97 (published, PRL) and 2000 (preliminary, hep-ex/0212019) data, reanalyzed with common cuts

\[ A_{LU}(\phi) = \frac{1}{\langle |P_b| \rangle} \frac{\overline{N}(\phi) - \overline{N}(\phi)}{\overline{N}(\phi) + \overline{N}(\phi)} \]

\[ A_{LU}^{\sin \phi} \leq 0.2 \]

\[ A_{LU}^{\sin 2\phi} \text{ consistent with zero} \]

\[ \Rightarrow \text{Weak kinematic dependence (kinematics correlated!)} \]

Compare to calculations at average \( x, Q^2, t \) per bin →

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**Kinematic dependences of Beam–Spin Asymmetry (BSA)**

- **Model calculations using VGG code** give too large asymmetries compared to **Preliminary HERMES (blue)** and **published CLAS (green, PRL)** data.
- **Similar magnitude** seen in other model calculations.

Flat kinematic dependence well described by models.

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The models (Guzey/Teckentrup, PRD 74, 2006) are in agreement with “all” other DVCS data so far:
→ Cross section at H1/ZEUS
→ BCA at HERMES (→ later…)
→ Published average BSA values from HERMES+CLAS (PRL, 2001)

The size and kinematic dependence of the asymmetry is reproduced (except maybe at small $Q^2$).

More data with improved systematics to come, but BSA less sensitive to models when compared to BCA.
BCA: Beam–Charge Asymmetry \((hep-ex/0605108, PRD 2007)\)

\[ A_C(\phi) = \frac{N^+(\phi)-N^-(\phi)}{N^+(\phi)+N^-(\phi)} \propto I \propto \pm (c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi)) \]

\[ \Rightarrow \text{Calculate "symmetrized" BCA } (\phi \rightarrow |\phi|) \text{ to get rid of all } \sin(\phi) - \text{dependences due to polarized beam.} \]

\[ A_C \text{ in exclusive bin: Expected } \cos(\phi) \text{ dependence } \Rightarrow \Re M_{\text{unp}}^{1,1} \]

\[ \cos(\phi) \text{-Moments zero at higher missing mass} \]

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Beam-Charge Asymmetry versus $-t$ (PRD 2007)

VGG
⇒ Regge+D-Term disfavored

TINY $e^- p$ sample (only ≈ 700 events) ⇒ Now ≈ 20 times more on disk!
⇒ $t$–dependence of BCA has high sensitivity to GPD models!
Utilize both charges for BSA: A closer look . . .

\[ d\sigma |\tau_{DVCS}|^2 \propto |\tau_{BH}|^2 + \left( \tau_{DVCS}^* \tau_{BH} + \tau_{BH}^* \tau_{DVCS} \right) \]

**Fourier Expansion (unpolarized p target):**

\[ |\tau_{BH}|^2 \propto c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi) \]

\[ |\tau_{DVCS}|^2 \propto c_0^{DVCS} + \sum_{n=1}^{2} c_n^{DVCS} \cos(n\phi) + \lambda s_1^{DVCS} \sin(\phi) \]

\[ I \propto \pm \left( c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi) \right) \]

**The approximation:**

\[ A_{LU}^{e- / e^+} (\phi) = \frac{1}{<|P_b|>} \frac{\hat{N}(\phi) - \overline{\hat{N}}(\phi)}{\hat{N}(\phi) + \overline{\hat{N}}(\phi)} \approx \frac{\pm s_1^I \sin \phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS} \cos \phi \pm c_0^I \pm c_1^I \cos \phi} \]

The approximation is too simple . . .
Using both beam charges for the BSA:

\[ A_{LU}^{e-} = \frac{1}{|P_b|} \frac{\overrightarrow{N}(\phi) - \overline{N}(\phi)}{\overrightarrow{N}(\phi) + \overline{N}(\phi)} \approx \pm s_1^I \sin \phi + s_1^{DVCS} \sin \phi \]

\[ A_{LU}^{e+} = \frac{1}{|P_b|} \frac{\overrightarrow{N}(\phi) - \overline{N}(\phi)}{\overrightarrow{N}(\phi) + \overline{N}(\phi)} \approx \frac{-s_1^I \sin \phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS} \cos \phi} \]

\[ \sin \phi \text{ amplitude of the “usual” BSA is not only sensitive to the interference term, but gets contributions from the DVCS term} \]

The “usual” BSA is complicated, it depends on the beam-charge and on the size of the BCA

⇒ Disentangle contributions from the interference term and the DVCS term by measuring two new asymmetries:

The “Interference” BSA:

\[ A_{LU}^I(\phi) = \frac{1}{|P_b|} \frac{\overrightarrow{N}^+(\phi) + \overrightarrow{N}^-(\phi) - \overrightarrow{N}^+(\phi) - \overrightarrow{N}^-(\phi)}{\overrightarrow{N}^+(\phi) + \overrightarrow{N}^-(\phi) + \overrightarrow{N}^+(\phi) + \overrightarrow{N}^-(\phi)} \approx \frac{-s_1^I \sin \phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS} \cos \phi} \]

The “DVCS” BSA:

\[ A_{LU}^{DVCS}(\phi) = \frac{1}{|P_b|} \frac{\overrightarrow{N}^+(\phi) - \overrightarrow{N}^-(\phi) - \overrightarrow{N}^+(\phi) + \overrightarrow{N}^-(\phi)}{\overrightarrow{N}^+(\phi) + \overrightarrow{N}^-(\phi) + \overrightarrow{N}^+(\phi) + \overrightarrow{N}^-(\phi)} \approx \frac{s_1^{DVCS} \sin \phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS} \cos \phi} \]

⇒ New asymmetries can disentangle (both charges needed) the contributions from interference and DVCS\(^2\) term

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Recoil Detector and unpol. Targets (2006/2007)
- Ensures exclusivity of events
  - Semi-inclusive background $5\% \Rightarrow \ll 1\%$
  - Associated background $10\% \Rightarrow \approx 1\%$

$\Rightarrow$ Essential at larger $-t$ values

$\Rightarrow$ Talk by R. Perez-Benito

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**What about the GDP $E$?**

**Remember:**

$$J_q = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} dx \, x \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right]$$

**GPD $E$ (on p target) is always kinematically suppressed, except in:**

$A_{UT}$: unpolarized beam, transversely pol. target

$$A_{UT}(\phi, \phi_s) = \frac{1}{|P_T|} \cdot \frac{d\sigma^\uparrow(\phi, \phi_s) - d\sigma^\downarrow(\phi, \phi'_s)}{d\sigma^\uparrow(\phi, \phi_s) + d\sigma^\downarrow(\phi, \phi'_s)}$$

$$\propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \cdot \sin(\phi - \phi_S) \cos \phi + \text{Im}[F_2 \tilde{\mathcal{H}} - F_1 \xi \tilde{\mathcal{E}}] \cdot \cos(\phi - \phi_S) \sin \phi$$

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DVCS TTSA compared to the Model Calculations!

Data taking with transverse Hydrogen target finished
≈ 10 million on tape, half the data (2002-2004) analyzed

\[ A_{UT} \sin(\phi - \phi_s) \cos \phi \]

LARGELY INDEPENDENT on all model parameters but \( J_u \)

(F.E., Nowak, Vinnikov, Ye, EPJ C46 (2006), hep-ph/0506264)

⇒ First model dependent extraction of \( J_u \) possible!

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First model dependent constraint on total quark angular momentum $J_u, J_d$. 

$e^+ p \rightarrow e^+ \gamma X$ ($M_X<1.7$ GeV)

$A_{UT}^{\sin (\phi-\theta)} \cos \phi = -0.149 \pm 0.058$ (stat) $\pm 0.033$ (syst)

$<-t> = 0.12$ GeV$^2$, $<x> = 0.095$, $<Q^2> = 2.5$ GeV$^2$

GPD Model: LO/Regge/D-term=0


Code: VGG [Vanderhaeghen et al., priv. comm.]
• **On the other hand, the models** (Guzey/Teckentrup, PRD 74, 2006) **suggest a small value** for $J_u$ **under the assumption** that $J_d = 0$.

• **The way to go:** Constrain models for GPD $H$ **by BSA/BCA** (first). Some model parameters might be the same for the GPD $E$ . . .

  ⇒ Compare the remaining models to the TTSA and learn about the GPD $E$ ($J_u$, $J_d$)
Investigate the internal structure of Nuclei

DVCS on Neon (hep-ex/0212019) triggered first calculations for DVCS on Nuclei

⇒ Possibility (?) to explore nuclear structure in terms of quarks and gluons, EMC effect, (anti-)shadowing, color transparency, …

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**Contributions from different processes from MC**

- **Coherent Bethe-Heitler contribution**
- **Incoherent Bethe-Heitler contribution**
- **Semi-inclusive $\pi^0$ resonances**

- **DVCS not simulated**

**Task:** Find upper (lower) $-t'$ cut for each target in order to compare the BSA for the coherent (incoherent) production at similar average values of $-t'$, $x_B$, and $Q^2$

- **Coherent:** $\langle -t' \rangle = 0.018 \text{ GeV}^2$
- **Incoherent:** $\langle -t' \rangle = 0.2 \text{ GeV}^2$
### Average Kinematic Values for Coherent Production

<table>
<thead>
<tr>
<th>Target</th>
<th>$\langle -t' \rangle = 0.018$</th>
<th>%Coherent</th>
<th>$\langle Q^2 \rangle$</th>
<th>$\langle x_B \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>$-t' &lt; 0.030$</td>
<td>0</td>
<td>1.68</td>
<td>0.068</td>
</tr>
<tr>
<td>Deuterium</td>
<td>$-t' &lt; 0.030$</td>
<td>56%</td>
<td>1.70</td>
<td>0.066</td>
</tr>
<tr>
<td>Helium-4</td>
<td>$-t' &lt; 0.030$</td>
<td>68%</td>
<td>1.74</td>
<td>0.066</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$-t' &lt; 0.043$</td>
<td>82%</td>
<td>1.77</td>
<td>0.064</td>
</tr>
<tr>
<td>Neon</td>
<td>$-t' &lt; 0.050$</td>
<td>82%</td>
<td>1.73</td>
<td>0.064</td>
</tr>
<tr>
<td>Krypton</td>
<td>$-t' &lt; 0.081$</td>
<td>82%</td>
<td>1.63</td>
<td>0.060</td>
</tr>
<tr>
<td>Xenon</td>
<td>$-t' &lt; 0.085$</td>
<td>82%</td>
<td>1.60</td>
<td>0.059</td>
</tr>
</tbody>
</table>

- $\langle Q^2 \rangle$ and $\langle x_B \rangle$ very similar.

- Fraction of coherent production is $\simeq 82\%$ for all but light targets.

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A-DEPENDENCE OF THE BSA


- $A_{LU}^{\sin 2\phi}$ is consistent with zero for all targets

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**RATIO** $A_{LU}^A / A_{LU}^P$

\begin{align*}
\text{HERMES PRELIMINARY} \\
\text{Coherent enriched} \\
\text{Fit to a constant : } 1.75 \pm 0.39 \\
\langle -t' \rangle = 0.018 \text{ GeV}^2
\end{align*}

\begin{align*}
\text{Incoherent enriched} \\
\langle -t' \rangle = 0.2 \text{ GeV}^2
\end{align*}

- **COHERENT ENRICHED**: MEAN RATIO DEVIATES FROM UNITY BY $2\sigma$.
  - CALCULATION OF $R=1-1.1$ FOR $^4He$ (Liuti, Taneja, Phys.Rev.C 2005) CONSISTENT WITH MEASUREMENT (LARGE STAT. ERROR, CALCULATIONS FOR HEAVIER TARGETS UNDERWAY)

- **INCOHERENT ENRICHED**: CONSISTENT WITH UNITY AS NAIVELY EXPECTED
**Ratio** \( A_{LU}^A / A_{LU}^p \)

**Consistent with two predictions by Guzev/Siddikov, one disfavored (J.Phys.G, 2006)**

**Consistent with predictions by Guzev/Strikman (Phys.Rev.C, 2003)**

⇒ **Promising, more data needed** ...
HERA/HERMES: End of data taking 7/2/2007:
Goal: “map out” GPD $H^u$ via DVCS Beam-Spin and Beam-Charge Asymmetries

Contributions form the Interference term and the DVCS$^2$ term can be disentangled by new asymmetries involving both beam charges

First model dependent constraint on the total angular momentum of u-quarks ($J_u$) and d-quarks ($J_d$) in the nucleon.

DVCS on Nuclei looks promising

Final remark: Orbital angular momentum sum rule needs $t \rightarrow 0$
Hermes measurements on GPD E at “small” $t$ will not be precise
JLab@12 will yield precision measurements at “large” $t \Rightarrow$ EIC

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The GPD $\tilde{H}$, Long. Target–Spin Asymmetry (LTSA)

$$A_{UL}(\phi) = \frac{1}{<|P_T|>} \frac{\bar{N}(\phi) - \tilde{N}(\phi)}{\bar{N}(\phi) + \tilde{N}(\phi)} \propto \sin \phi \times Im\tilde{H}_1$$

\[ A = s_0 + s_1 \sin \phi + s_2 \sin 2\phi \]

\[ \chi^2/\text{ndf}: 8.5/7 \]
\[ s_0: -0.009 \pm 0.024 \text{ (stat.)} \]
\[ s_1: -0.071 \pm 0.034 \text{ (stat.)} \]
\[ s_2: -0.113 \pm 0.034 \text{ (stat.)} \]

\[ <t> = 0.12 \text{ GeV}^2, <x_B> = 0.10, <Q^2> = 2.5 \text{ GeV}^2 \]

$A_{UL}(\vec{p})$ in exclusive bin:
**Expected $\sin(\phi)$ dep. $\Rightarrow$ GPD $\tilde{H}$, Unexpected $\sin(2\phi)$ dependence**

$A_{UL}(\vec{d})$ in exclusive bin:
$\Rightarrow$ Consistent with zero

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**The GPD $\tilde{H}$, Long. Target–Spin Asymmetry (LTSA)**

- **No effect seen from 40% coherent contribution in first bin**

- **Difference at higher $-t$**
  $\Rightarrow$ **Different asymmetry on the neutron when comp. to proton**

- $A_{UL}^{\sin 2\phi} \Rightarrow$ Difference due to missing QGq twist-3 in the models?

- $A_{UL}^{\sin 2\phi} \Rightarrow$ Difference due to large $\sin 2\phi$ (while $\sin \phi$ is small) in $\pi^0$ background (CLAS, hep-ex/0605012)?

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