Transverse Target
Asymmetry in Exclusive
Charged Pion Production
at 11 GeV

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Over the last decade, tremendous progress has been made on the theory of generalized parton distributions (GPD).

**PDFs**: Squared hadronic wavefunctions = probability of finding a parton with specified longitudinal momentum fraction and polarization in fast moving hadron.

**GPDs**: interference between wavefns of parton with momentum fraction $x+\xi$ and parton with momentum fraction $x-\xi$.

- In addition to $x$ and $\xi$, GPDs depend also on $t=-(p-p')^2$.
  - $t$ is independent of $x$, $\xi$ since $p$, $p'$ may differ in either their longitudinal or transverse components.
- GPDs interrelate the longitudinal and transverse momentum structure of partons within a fast moving hadron.

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A special kinematic regime is probed in deep exclusive meson production, where initial hadron emits a $q\bar{q}$ or $gg$ pair. This has no counterpart in usual PDFs. Since GPDs correlate different parton configurations in the hadron at the quantum mechanical level, GPDs determined in this regime carry information about $q\bar{q}$ and $gg$-components in the hadron wavefunction.
GPDs require Hard Exclusive Reactions

- In order to access the physics contained in GPDs, one is restricted to the hard scattering regime.

- Factorization property of hard reactions:
  - Hard probe creates a small size $q\bar{q}$ and gluon configuration,
    - interactions can be described by pQCD.
  - Non-perturbative part describes how hadron reacts to this configuration, or how the probe is transformed into hadrons (parameterized by GPDs).

- Hard exclusive meson electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD 56 (1997) 2982].

- Factorization applies when the $\gamma^*$ is longitudinally polarized.
  - corresponds to small size configuration compared to transversely polarized $\gamma^*$.
Leading Twist GPD Parameterization

- GPDs are universal quantities and reflect nucleon structure independently of the probing reaction.
  - At leading twist-2, four quark chirality conserving GPDs for each quark, gluon type.
  - Because quark helicity is conserved in the hard scattering regime, the produced meson acts as a helicity filter.

Leading order QCD predicts:
- Vector meson production sensitive to unpolarized GPDs, $H$ and $E$.
- Pseudoscalar mesons sensitive to polarized GPDs, $\tilde{H}$ and $\tilde{E}$. 
First moments of GPDs are related to nucleon elastic form factors through model-independent sum rules:

\[ \sum_q e_q \int_{-1}^{+1} dx \, H^q(x, \xi, t) = F_1(t) \]

Dirac and Pauli elastic nucleon form factors. 
\( t \) -dependence fairly well known.

\[ \sum_q e_q \int_{-1}^{+1} dx \, E^q(x, \xi, t) = F_2(t) \]

Isovector axial form factor. 
\( t \) –dep. poorly known.

\[ \sum_q e_q \int_{-1}^{+1} dx \, \tilde{H}^q(x, \xi, t) = G_A(t) \]

Pseudoscalar form factor. 
Very poorly known.
Spin-flip GPD $\tilde{E}$

- $G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of $\beta$-decay.
- Because of PCAC, $G_P(t)$ alone receives contributions from $J^{PG}=0^-$ states.
  - These are the quantum numbers of the pion, so $\tilde{E}$ contains an important pion pole contribution.

![Pion pole contribution to $G_P(t)$](image1)

For this reason, a pion pole-dominated ansatz is typically assumed:

$$\tilde{E}^{u,d}(x, \xi, t) = F_\pi(t) \frac{\Theta(\xi > |x|)}{2\xi} \phi_\pi \left( \frac{x + \xi}{2\xi} \right)$$

where $F_\pi$ is the pion FF and $\phi_\pi$ the pion PDF.

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How to determine $\tilde{E}$

- GPD $\tilde{E}$ not related to an already known parton distribution.
- Experimental information on $\tilde{E}$ can provide new nucleon structure info unlikely to be available from any other source.
- The most sensitive observable to probe $\tilde{E}$ is the transverse single-spin asymmetry in exclusive $\pi$ production:

$$A_{\perp} = \frac{\int_{0}^{\pi} d\beta \frac{d\sigma_{L}^{\pi}}{d\beta} - \int_{0}^{2\pi} d\beta \frac{d\sigma_{T}^{\pi}}{d\beta}}{\int_{0}^{2\pi} d\beta \frac{d\sigma_{L}^{\pi}}{d\beta}}$$

$d\sigma_{\pi}^{L}$ = exclusive $\pi$ cross section for longitudinal $\gamma^*$
$\beta$ = angle between transversely polarized target vector and the reaction plane.
Single Spin Asymmetry in Exclusive $\pi$ Production

- Frankfurt et al. [PRD 60(1999)014010] have shown the $A_L^\perp$ asymmetry vanishes if $\tilde{E}$ is zero.
  - If $\tilde{E} \neq 0$, the asymmetry will display a $\sin\beta$ dependence.

- $A_L^\perp$ is also expected to display precocious factorization at moderate $Q^2 \sim 2-4$ GeV$^2$.

  - Precocious factorization of the $\pi$ production amplitude into three blocks is likely:
    1. overlap integral between $\gamma, \pi$ wave functions.
    2. the hard interaction.
    3. the GPD.

  - Higher order corrections, which may be significant at low $Q^2$, likely cancel in the asymmetry ratio.
Cancellation of Higher Twist Corrections in $A_L^\perp$

- Belitsky and Müller GPD based calc. reinforces this expectation:
  - Even at $Q^2=10$ GeV$^2$, NLO effects can be large, but cancel in the asymmetry, $A_L^\perp$ (PL B513(2001)349).
  - At $Q^2=4$ GeV$^2$, higher twist effects even larger in $\sigma_L$, but still cancel in asymmetry (CIPANP 2003).

This relatively low value of $Q^2$ for the expected onset of precocious scaling is important, because it is experimentally accessible at JLab 12 GeV.

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L/T Separations Essential

- In hard meson electroproduction, factorization can only be applied to longitudinal photons.

- Unlike other ongoing or proposed experiments, where dominance of longitudinal contribution is simply assumed, JLab’s unique contribution to this field is in:
  - ability to take measurements at multiple beam energies.
  - unambiguous isolation of $A_L^\perp$ using Rosenbluth separation.

- A JLab $A_L^\perp$ measurement could thus establish the applicability of the GPD formalism, and precocious scaling expectations, for other $A^\perp$ experiments.
Require Target Polarization Parallel to $\hat{q} \times \hat{p}_\pi$

- Target polarization components ($P_x$, $P_y$) are defined relative to reaction plane.
- $\beta =$ azimuthal angle between (transverse) target polarization and reaction plane
- $P_x = P_\perp \cos \beta$ and $P_y = P_\perp \sin \beta$
- $P_y \parallel \hat{q} \times \hat{p}_\pi$ uniquely defined only in non-parallel kinematics.

Unpolarized Cross section

$$\frac{d\sigma}{d\Omega} = \sigma_T + \epsilon \sigma_L + \sqrt{\frac{1}{2} \epsilon (\epsilon + 1) \sigma_{LT} \cos \phi + \epsilon \sigma_{TT} \cos 2\phi}$$

$$A_\perp = \frac{1}{P_\perp \pi} \frac{2}{\epsilon} 2\sigma_L^y$$

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SHMS+HMS Kinematic Considerations

SHMS and HMS have their largest acceptances in vertical direction.

- **Scattered e\(^-\) detected at some vertical angle in the HMS.**
  - Forces scattering plane and q-vector to be non-horizontal.

- **π\(^-\)** is detected in SHMS.
  - Either above or below q-vector, depending if scattered e\(^-\) is detected above or below horizontal plane.

- **Target polarization is horizontal, parallel to \(\hat{q} \times \hat{p}_\pi\).**
  - Nearly transverse to \(\vec{q}\) for all angles between the scattering and reaction planes.
High Luminosity Essential

- Physics case for a measurement of $A_L^\perp$ is compelling.
- High luminosity required:
  - $\sigma_L$ is largest in parallel kinematics, where $A_L^\perp=0$.
  - $\sigma_L$ is small where $A_L^\perp$ is maximal.

- We have performed numerous studies, but the measurement has not been feasible to date because of the lack of a polarized target that can handle the required high luminosity.

- Recent advancements in polarized $^3$He target technology may allow the measurement to proceed via the $n(e,e'\pi^-)p$ reaction.
XeMed/UNH Target Loop Concept

- Compress polarized $^3$He and deliver to 40cm long titanium target cell
- Commercial compressors achieve >3500 psi (238 bar)
- Requires compression ratio ~16, immersion in magnetic field, rubidium-free gas leaving polarizer, entrance and exit, <3% polarization loss

Requirements:
- 14 atm
- 200 atm
- Requires two ports, entrance and exit

Recirculating at 1.0 scfm

1 cm x 40 cm titanium target cell
Getter purifier? RGA?
<table>
<thead>
<tr>
<th>Property</th>
<th>Hall A</th>
<th>UNH</th>
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</thead>
<tbody>
<tr>
<td>Polarization (%)</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>Beam Current (µA)</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>Cell type</td>
<td>Glass/sealed</td>
<td>Ti/continuous flow</td>
</tr>
<tr>
<td>“Spin UP” time (h)</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Beam Relaxation (h⁻¹)</td>
<td>41</td>
<td>0.1</td>
</tr>
<tr>
<td>Laser Power (W)</td>
<td>150</td>
<td>1500-2500</td>
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<tr>
<td>Thickness (cm⁻²)</td>
<td>1.07E+22</td>
<td>1E+24</td>
</tr>
<tr>
<td><strong>FOM (P²L )</strong></td>
<td>0.22E+36</td>
<td>0.55E+38</td>
</tr>
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</table>
**SHMS+HMS Kinematics**

- **n(e,e’π-)p Kinematics at Q^2=4.0 GeV^2, W=2.8 GeV**

<table>
<thead>
<tr>
<th></th>
<th>(E_{e'}) (GeV)</th>
<th>(\theta_{e'}) (deg)</th>
<th>(p_\pi) (GeV/c)</th>
<th>(\theta_\pi) (deg)</th>
<th>(\Theta_{\pi q}) (deg)</th>
<th>(-t) (GeV^2)</th>
<th>(x)</th>
<th>(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High (\varepsilon=0.745) Setting, (E_{beam}=11.00) GeV</strong></td>
<td>5.160</td>
<td>15.25</td>
<td>5.744</td>
<td>-12.70</td>
<td>0</td>
<td>0.175</td>
<td>0.365</td>
<td>0.984</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.666</td>
<td>±3</td>
<td>0.322</td>
<td>0.365</td>
<td>0.970</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>5.531</td>
<td>±5</td>
<td>0.576</td>
<td>0.365</td>
<td>0.947</td>
<td></td>
</tr>
<tr>
<td><strong>Low (\varepsilon=0.200) Setting, (E_{beam}=6.60) GeV</strong></td>
<td>0.860</td>
<td>49.23</td>
<td>5.744</td>
<td>-6.06</td>
<td>0</td>
<td>0.175</td>
<td>0.365</td>
<td>0.984</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

- Near peak of Figure of Merit in Belitsky’s calculation

- **Scattered electron in HMS, \(\pi^-\) in SHMS.**
- **\(\Theta_{\pi q}\) is \(\pi^-\) lab angle wrt \(\vec{q}\), mostly above or below scattering plane.**
- **For \(Q^2=4\) GeV^2, \(x=0.365\) \(\rightarrow\) \(-t_{max} \approx 1-(M^2x^2/Q^2)=0.97\) GeV^2.**

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Simulated SHMS+HMS Acceptance

\[ n(e,e'\pi \, p) \]

low \( \varepsilon \)  high \( \varepsilon \)  \( \Delta \varepsilon = 0.55 \)

Q\(^2\)-W acceptance at high and low \( \varepsilon \).

Azimuthal angle of (transversely) polarized target wrt hadron reaction plane.

SHMS+HMS acceptance covers 0.1\( \leq \psi \leq 0.7 \) GeV\(^2\) at nearly fixed \( x_{\text{BJ}} \).

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Reliable L/T Separations require shorter $^3\text{He}$ cells

- For reliable L/T separations, an 8cm $^3\text{He}$ cell seems optimal.
- The UNH target is designed for nominal 40cm cells, but Bill Hersman does not believe shorter cells will cause any problem.
- In fact, by cooling the entrance and exit lines of the cell with LN$_2$ he believes he can reduce the wall thickness by $\sim$X3 or increase the pressure while keeping the wall thickness same.
- These issues need closer investigation to better understand target cell backgrounds for UNH target.

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Estimated Rates and Uncertainties

- Simulated error bars after 18 days:
  - 12 days @ low $\varepsilon$, 5k evts in largest $-t$ bin.
  - 6 days @ high $\varepsilon$, 30k evts in largest $-t$ bin.
- Luminosity = $1.2 \times 10^{37}/cm^2/s$ (8cm tgt).
- $P_{\text{targ}} = 65\% \rightarrow P_n = 55.3\%$.
  - No target dilution since exclusive $\pi^-$ can be only from neutron.
- 2% random systematic uncertainties
  - slightly larger than assumed for Fpi-12.
- $\sigma_L/\sigma_T$ values similar to pionCT $^1H$ data.

<table>
<thead>
<tr>
<th>$Q^2=4.0$, $W=2.8$, $x=0.365$</th>
<th>$-t$ (GeV$^2$)</th>
<th>$R=\sigma_L/\sigma_T$</th>
<th>$A_L^\perp$</th>
<th>$\delta A_L^\perp$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2</td>
<td>1.0</td>
<td>0.2</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>1.0</td>
<td>0.5</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1.5</td>
<td>0.6</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Solid: asymptotic pion distribution amp.
Dashed: CZ pion dist. amp.

$t = -0.5$ GeV$^2$
$t = -0.3$ GeV$^2$
$t = -0.1$ GeV$^2$

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Summary

PAC24 Comments on our 2003 6 GeV LOI:

- The experiment is extremely challenging since it requires first the isolation of a Fourier component in the polarized target cross section and then, by Rosenbluth techniques, the separation of the cross section for longitudinally polarized photons.

- The measurement may allow for an extraction of further information on GPDs and is complementary to DVCS. Deep virtual electroproduction of pions is sensitive only to the GPDs \( \tilde{H} \) and \( \tilde{E} \); \( H \) and \( E \) do contribute.

- Moreover, since the asymmetry requires proton helicity flip, the experiment may allow the extraction of \( \tilde{E} \), one of the two GPDs not constrained by knowledge of ordinary parton distributions. The measurement is therefore very important.

- The lack of a transversely polarized cryotarget that can handle the required high luminosity has precluded our development of this experiment since 2003.

- A transversely polarized \(^3\)He target based on the UNH design offers the best hope of measuring this observable.