PR12-12-005: The Longitudinal Photon, Transverse Nucleon, Single-Spin Asymmetry in Exclusive Pion Production

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GPDs in Deep Exclusive Meson Production

PDFs: probability of finding a parton with longitudinal momentum fraction \( x \) and specified polarization in fast moving hadron.

GPDs: interference between partons with \( x+\xi \) and \( x-\xi \), interrelating longitudinal and transverse momentum structure of partons within fast moving hadron.

A special kinematic regime is probed in Deep Exclusive Meson Production, where the initial hadron emits \( q\bar{q} \) or \( gg \) pair.

- No counterpart in usual PDFs.
- GPDs determined in this regime carry information about \( q\bar{q} \) and \( gg \)-components in the hadron wavefunction.
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.
- more favorable to produce a small size configuration than transversely polarized $\gamma^*$.
Leading Twist GPD Parameterization

**Leading order QCD predicts:**

- Vector meson production sensitive to unpolarized GPDs, $H$ and $E$.
- Pseudoscalar mesons sensitive to polarized GPDs, $\tilde{H}$ and $\tilde{E}$.

Dirac and Pauli elastic form factors. $t$-dependence fairly well known.

Isovector axial form factor. $t$-dep. poorly known.

Pseudoscalar form factor. Very poorly known.

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

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

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

$$
\sum_q e_q \int_{-1}^{+1} dx \, \tilde{E}^q(x, \xi, t) = G_P(t)
$$

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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.

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

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

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

$$A_\perp = \frac{\int_0^\pi d\beta \frac{d\sigma^L}{d\beta} - \int_0^{2\pi} d\beta \frac{d\sigma^L}{d\beta}}{\int_0^{2\pi} d\beta \frac{d\sigma^L}{d\beta}}$$

$d\sigma^L = \text{exclusive } \pi \text{ cross section for longitudinal } \gamma^*$

$\beta = \text{angle between transversely polarized target vector and the reaction plane.}$
Single Spin Asymmetry in Exclusive $\pi$ Production

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

- They also argue that 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 $Q^2$ for $\sigma_L$, likely cancel in $A_L^{\perp}$.

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

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Cancellation of Higher Twist Corrections in $A_L^\perp$

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

● The study of $A_L^\perp$ is also important for the reliable extraction of $F_\pi$ from $p(e,e'\pi^+)n$ data at high $Q^2$ [Frankfurt, Polyakov, Strikman, Vanderhaeghen PRL 84(2000)2589].
   - Non-pion pole contributions need to be accounted for in some manner in order to reliably extract $F_\pi$ from $\sigma_L$ data at low $-t$.
   - “A-rated” 12 GeV Pion Form Factor experiment restricted to $Q^2=6$ GeV$^2$ by need to keep non-pole contributions to an acceptable level ($-t_{\text{min}}<0.2$ GeV$^2$).

● $A_L^\perp$ is an interference between pseudoscalar and pseudovector contributions.
   - Help constrain the non-pole contribution to $p(e,e'\pi^+)n$.
   - Assist the more reliable extraction of the pion form factor.
   - Possibly extend the kinematic region for $F_\pi$ measurements.
Measurement of $A_L^\perp$

\[ A_L^\perp = \frac{1}{P_\perp} \frac{2}{\pi} \frac{\sigma_L^y}{\sigma_L} \]

- At very high $Q^2$, $\sigma_T$ suppressed by $1/Q^2$ compared to $\sigma_L$.
- At JLab energies, can’t ignore contributions from transverse photons.
  - Require two Rosenbluth separations and ratio of longitudinal cross sections:
    \[
    \sigma_A = \sigma_T^\perp + \varepsilon \sigma_L^\perp \\
    \sigma_U = \sigma_T + \varepsilon \sigma_L
    \]
    where $\sigma(\varepsilon) = \sigma_U + \sigma_A \sin \beta + \ldots$

To cleanly extract $A_L^\perp$, we need:
- Target polarized transverse to $\gamma^*$ direction.
- Large acceptance in $\pi$ azimuthal angle (i.e. $\varphi$, $\beta$).
- Measurements at multiple beam energies and electron scattering angles.
  - $\varepsilon$ dependence (L/T separation)
    (advantage of focusing spectrometers in Hall C)
  - Need $\Delta \varepsilon$ as large as possible.
HERMES Transverse Spin Asymmetry

- Exclusive $\pi^+$ production by scattering 27.6 GeV positrons or electrons from transverse polarized $^1\text{H}$ without L/T separation. [PLB 682(2010)345].
- Analyzed in terms of 6 Fourier amplitudes for $\varphi_\pi, \varphi_s$.
- $\langle x_B \rangle = 0.13$, $\langle Q^2 \rangle = 2.38$ GeV$^2$, $\langle -t \rangle = 0.46$ GeV$^2$.

- Goloskokov and Kroll indicate the HERMES results have significant contributions from transverse photons, as well as from L and T interferences [Eur Phys.J. C65(2010)137].
- Because no factorization theorems exist for exclusive $\pi$ production by transverse photons, these data cannot be simply interpreted in terms of GPDs.

- Without L/T separation, at JLab the asymmetry dilution is also expected to be substantial [-0.13 vs. -0.32].

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$A_L \perp$ a Key GPD Measurement in Meson Sector

- In Deep Exclusive Meson Electroproduction, factorization can only be applied to longitudinal photons.
- 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.

$A_L \perp$ is the ratio of two purely longitudinal quantities. If the predicted precocious scaling is shown to not occur, then it may never be possible to experimentally determine GPDs via Deep Exclusive Meson Production.
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.

- **New polarized $^3$He target technology developed by Bill Hersman’s group at UNH could allow the measurement to proceed via the $n(e,e'\pi^-)p$ reaction.**
  - Expected to achieve $L = 5 \times 10^{37}$ cm$^{-2}$s$^{-1}$ needed for feasible measurement.
  - **Not intended to replace target for upcoming $A_1^n d_2^n$ measurements, but should be seen as the development of a next generation $^3$He target.**
**UNH/Xemed Target Loop Concept**

- Compress polarized $^3$He and deliver to aluminum target cell
- Non-ferrous diaphragm compressor achieves 3000 psi (~200 bar)
- Returns through a pressure-reducing orifice

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**External polarizer**

**Non-ferrous diaphragm compressor**

**Nuclear physics target**

- 20 Bar
- 200 Bar

Expansion through an orifice

Recirculates at 25 SLPM

9 cm aluminum target cell
Cooled with LN$_2$ to 77K
Thickness of 0.5 g/cm$^2$

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Working Large-Scale $^3$He Polarizer Prototype

- 8.5L aluminosilicate glass cell.
- Pressure-vessel enclosure.
- Operation up to 20 atm.
- Hybrid pumping with K:Rb.
- Spectrally narrowed 2.5kW laser.

Assembled, Operating $^3$He Polarizer

- Spin-up curve measured by laser-polarization-inversion.
- Spin-up rate ~15%/hr.

April 23, 2012

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Working Non-ferrous Diaphragm Compressor

- Titanium diaphragm head.
- Phosphor-bronze diaphragm.
- PEEK valves.
- Prototype designed for 1000 psi output pressure.
- Flow of 22 SLPM achieved ($^4$He).
- Incorporated into flow test facility for tests of $^3$He depolarization.

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High Luminosity Polarized $^3$He Target Status

Many of the hardest technological hurdles have been demonstrated through working prototypes.

1. Large-scale $^3$He polarizer can operate at temperatures, pressures and laser-beam intensities that replace spins (much) faster than they will be destroyed by the beam at $L=5 \times 10^{37}$ cm$^{-2}$s$^{-1}$.

2. Capability to develop and produce industrial-quality compressor pumps from non-ferrous materials.

Next phase of development:

1. Need to demonstrate high polarization (inadvertent contamination has limited asymptotic polarization <50%).

2. Need to make a cell with inlet and exit ports.

3. Need to measure $^3$He depolarization in a loop that includes pump and orifice.
Reliable L/T Separations require short target cells

- Shorter target cell needed so full cell is within coincidence acceptance at high, low $\varepsilon$.
  - 9.5cm target is fully within acceptance, but will use 9.0cm to provide extra safety margin.

- To achieve $L=5 \times 10^{37} \text{cm}^{-1}\text{s}^{-1}$ require 200atm $^3\text{He}$ gas at 130K.
  - Cool entrance and exit lines of cell with LN$_2$.
  - Initial design assumes 500µm Al walls. Final design will depend on JLab technical reviews, etc.

- Target wall contributions will be subtracted via dedicated Al dummy target runs.

$Q^2=4.0 \text{ GeV}^2$, $W=2.6 \text{ GeV}$.
Acceptance matching "diamond cut" applied.

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**SHMS+HMS Kinematics**

Near peak of Figure of Merit in Belitsky’s calculation

![Graph showing Q^2 vs. Bjorken x with NLO and LO curves.]

### n(e,e'\pi^-)p Kinematics

<table>
<thead>
<tr>
<th>E_{beam}</th>
<th>E_{e'}</th>
<th>\theta_{e'}</th>
<th>\epsilon</th>
<th>\theta_q</th>
<th>p_\pi</th>
<th>\Theta_{\pi q}</th>
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<tbody>
<tr>
<td><strong>MAIN Q^2=4.0 W=2.6 x=0.40 -t_{min}=0.22</strong></td>
<td></td>
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<td>6.60</td>
<td>1.34</td>
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<td><strong>SCALING Q^2=3.0 W=2.3 x=0.40 -t_{min}=0.22</strong></td>
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<tr>
<td>6.60</td>
<td>2.66</td>
<td>23.9</td>
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<td>10.92</td>
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<td><strong>NON POLE Q^2=4.0 W=2.25 x=0.50 -t_{min}=0.39</strong></td>
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<td>0.87</td>
<td>-19.4</td>
<td>4.03</td>
<td>0, ±2.5</td>
</tr>
</tbody>
</table>

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Simulated SHMS+HMS Acceptance

$^3\text{He}(e,e'\pi)p(p)p_{\text{SP}}$

$Q^2=4.0 \quad W=2.6 \quad \text{low } \varepsilon \text{ high } \varepsilon \quad \Delta \varepsilon = 0.46$

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

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

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TAC question re. effect of $\beta$ acceptance on $A_L$ extraction

Simple MC exercise:
- Generate data with 10% asymmetry:
  - $Q^2=4.0$, $W=2.6$ at $\varepsilon=0.79$, 0.33.
  - Two different target polarization orientations.
  - Diamond cuts to equalize high, low $\varepsilon$ acceptances.
- For each target polarization setting, perform L/T separation separately for each $\beta$ bin.

$$A_L^y = \frac{\sigma_{L\uparrow} - \sigma_{L\downarrow}}{\sigma_{L\uparrow} + \sigma_{L\downarrow}}$$

shows clear $\beta$-dependence, consistent with the injected asymmetry.

Actual experimental analysis will be considerably more sophisticated, involving multiple SHMS settings to equalize the azimuthal acceptance for each $t$-bin.
Similarly to $F_{\pi-2}$, we propose to use the over-constrained $p(e,e'p)$ reaction and inelastic $e^+{^{12}}C$ in the DIS region to calibrate spectrometer acceptances, momenta, offsets, etc.

- $F_{\pi-2}$ beam energy and spectrometer momenta determined to <0.1%.
- Spectrometer angles <0.5 mr.
- $F_{\pi-2}$ agreement with published $p+e$ elastics cross sections <2%.

Some partial cancellation of uncorrelated uncertainties will occur when forming ratio of two longitudinal cross sections ($A_L^\perp$).

<table>
<thead>
<tr>
<th>Magnetic Spectrometer Calibrations</th>
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</thead>
<tbody>
<tr>
<td><strong>Projected Systematic Uncertainty</strong></td>
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<tr>
<td>Source</td>
</tr>
<tr>
<td>Spectrometer Acceptance</td>
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<tr>
<td>Target Thickness</td>
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<tr>
<td>Beam Charge</td>
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<tr>
<td>HMS+SHMS Tracking</td>
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<td>Coincidence Blocking</td>
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<tr>
<td>Kinematic Offsets</td>
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<tr>
<td><strong>TOTAL</strong></td>
</tr>
</tbody>
</table>

Uncorrelated uncertainties in $\sigma_{UNS}$ are amplified by $1/\Delta\epsilon$ in L-T separation.

Scale uncertainty propagates directly into separated cross section.

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**Projected $A_L \perp$ Uncertainties**

- **Q$^2$-scaling**
  - $Q^2 = 3.0 \text{ (GeV/c)}^2$
  - $W = 2.3 \text{ GeV}$
  - $t = -0.1, -0.3, -0.5 \text{ GeV}^2$

  - **Non-pole**

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

- **Example t-binning only.** Finer binning will depend on actual experimental factors.
- Errors include statistical and uncorrelated systematic uncertainties (including partial cancellation of uncorrelated systematic errors when forming the ratio).
- Assumes $\sigma_L/\sigma_T = 1$ and $^3\text{He}$ target polarization of 65%.

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Projected $A_L^\perp$ uncertainties vs. $-t$

- Curve is very approximate:
  - Goloskokov & Kroll calculation for the unseparated asymmetry at $Q^2=4.0$ GeV$^2$, scaled by the ratio of their calculations for HERMES kinematics.

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Beam Time Request

<table>
<thead>
<tr>
<th></th>
<th>(Q^2) (GeV(^2))</th>
<th>(W) (GeV)</th>
<th>(\varepsilon)</th>
<th>3He Hours</th>
<th>Dummy Target</th>
<th>Overhead</th>
<th>Total Hours</th>
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<tbody>
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<td></td>
<td><strong>1738</strong></td>
</tr>
</tbody>
</table>

Grand Total: 1738 hours (72.4 days)

- Hours are for all \(\Theta \pi q\) settings at a given \(\varepsilon\).
- Dummy includes both aluminum for target cell wall subtraction, and nitrogen mock target cell as part of calibrations.
- Where possible, thicker dummy target walls are used to reduce required beam time.