Final HERMES Results on Single-Spin Asymmetries in Lepto-Production of Oppositely Charged Pion Pairs from the Transversely Polarized Hydrogen Target

Xiaorui Lu
(on behalf of HERMES Collaboration)

Tokyo Institute of Technology

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DIS2008, UCL, UK
Quark Structure of Nucleon

• quark number density: 
  measures spin averaged distribution
  \( f_1^q \) well known!!!

• quark helicity distribution: 
  measures helicity difference
  \( g_1^q \) known!
  precise inclusive measurement: HERMES PRD75(2007)
  flavor-separated measurement: HERMES PRD71(2005)

• transversity distribution: 
  measures helicity flip
  \( h_1^q \) first glimpses!
  first measurement: HERMES PRL94 (2005)

• completes leading-twist picture of nucleon structure
• no gluon transversity \( \Rightarrow \) weaker \( Q^2 \) evolution than \( f_1 \) and \( g_1 \)
• related to relativistic effects inside the nucleon
Measurement of Transversity Distribution

- Chirality of the transversity distribution
  chiral-odd quark Distribution Function (DF)

  \[ \sim \text{Im}(A_{+-,-+}) \]

  need another chiral-odd object

  cannot be determined in inclusive DIS

- Semi-Inclusive DIS (SIDIS) Cross Section

  \[
  \sigma^{ep\rightarrow ehX} = \sum_q h_1^q \otimes \sigma^{eq\rightarrow eq} \otimes FF^{q\rightarrow h}
  \]

  ↓

  chiral-odd DF

  chiral-odd FF

  Semi-Inclusive DIS: coupled to a chiral-odd Fragmentation Function (FF)
Two-Pion SIDIS Production

semi-inclusive DIS on a transversely polarized hydrogen target

\[ e + p^\uparrow \rightarrow e'^+ + \pi^+ + \pi^- + X \]

The target-spin asymmetry:

\[ A_{U\perp} \equiv \frac{1}{|S_{\perp}|} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \sim \frac{\sigma_{UT}}{\sigma_{UU}} \]

\[ \sigma_{UU} \sim f_1 D_1 \]

\[ \sigma_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin \theta \]

The asymmetry is related to **transversity**

It appears with an unknown **Dihadron FF** sensitive to quark transverse quark polarization

Simpler probe of transversity than one-hadron SIDIS:

universal factorization and known \( Q^2 \) evolution
Dihadron Fragmentation Function

Dihadron FF $H_1^\perp$: transfer of the transverse spin of the fragmenting quark to the orientation of the hadron pair

Dihadron FFs can be expanded in terms of Legendre functions of $\cos \theta$:

$$D_1(\cos \theta) \simeq D_1 + D_1^{sp} \cos \theta + D_1^{pp} \frac{1}{4}(3 \cos^2 \theta - 1)$$

$$H_1^\perp (\cos \theta) \simeq H_1^{\perp,sp} + H_1^{\perp,pp} \cos \theta$$

$sp$: interference between $s$- and $p$-wave components of the hadron pair

The transverse target-spin asymmetry becomes

$$A_{U \perp} \sim \sin(\phi_{R \perp} + \phi_S) h_1 \frac{H_1^{\perp,sp} \sin \theta + \frac{1}{2} H_1^{\perp,pp} \sin(2\theta)}{f_1(D_1 + \cos \theta D_1^{sp} + \frac{1}{4}(3 \cos^2 \theta - 1) D_1^{pp})}$$
Theoretical Predictions

Sign Change $\sim \rho^0(770)$

No Sign Change $\sim \rho^0(770)$ but Maximal Asymmetry

Dominance of real (Jaffe) vs. imaginary (Radici) part of $\rho^0$ decay amplitude.
Reconstruction: $\Delta p/p < 2\%$, $\Delta \theta < 0.6$ mrad

Positron/Hadron separation efficiency: > 99%

Hadron Identification: dual radiator RICH Detector:

$\pi$, K and p identification at 2 – 15 GeV/c

Atomic hydrogen target with transversely polarization ~75%

- atomic pure gas target $\Rightarrow$ no dilution
- flipping time ~90s $\Rightarrow$ small systematic errors
Extracting Asymmetry Amplitude

Two-dimensional fit binned to \((\phi_{R\perp} + \phi_S)\) and \(\theta' \equiv |\theta - \pi/2| - \pi/2| :\)

\[
A_{U\perp}(\phi_{R\perp} + \phi_S, \theta') = \sin(\phi_{R\perp} + \phi_S) \frac{a \sin \theta'}{1 + b \frac{1}{4}(3 \cos^2 \theta' - 1)}
\]

where \(a \equiv A_{U\perp} \sin(\phi_{R\perp} + \phi_S) \sin \theta' \sim \frac{h_1 H_{q,sp}}{f_1 D_1}\)

varying \(b\) within positivity limits:

\[
-\frac{3D_1^p(z, M_{\pi\pi})}{2D_1(z, M_{\pi\pi})} \leq b \leq \frac{3D_1^p(z, M_{\pi\pi})}{D_1(z, M_{\pi\pi})}
\]

• limits estimated by PYTHIA6 Monte Carlo
• take the center value in the range of \(a\) as asymmetry amplitude, the standard deviation as systematic uncertainty (doing a \(b\)-scan).
Monte Carlo Simulation

Tuned to HERMES single-hadron multiplicities

- MC describes two-hadron spectrum well
- $\rho^0$ and $\omega$ resonances contribute strongly to the spectrum
- $H_{1^{q,sp}}$ is predicted to be maximal near $\rho^0(770)$ by theory
Estimate of Acceptance Effects

- Introduce target-spin dependence to the MC
- Combine models for Dihadron FF (Bacchetta & Radici [PRD74:114007, 2006]), \( h_1 (\text{Schweitzer et al. [PRD64:034013, 2001];}) \) and \( f_1 (\text{Gluck et al. [EPJC5:461, 1998]}) \)
- Compare the asymmetry amplitudes in \( 4\pi \) and HERMES acceptance.

\[ \begin{align*}
A_{U,U} (\theta, \phi) \sin^2 \theta \\
\langle \hat{z} \rangle \; (\text{GeV}) \\
\langle \hat{z} \rangle \\
M_{\pi\pi} \; [\text{GeV}] \\
x \\
z
\end{align*} \]

\( \text{Fractional acceptance effect taken as systematic uncertainty} \)
Extracted Asymmetry Amplitudes

- Average amplitude positive:
  \[ A_{U \perp}^{\sin(\phi_R + \phi_S) \sin \theta} = 0.018 \pm 0.005_{\text{stat}} \pm 0.002_{\text{b-scan}} + 0.004_{\text{acc}} \]
- 8.1% scale systematic uncertainty contribution from target polarization
- The asymmetric error band combines \textit{b-scan} effect and acceptance effect
Discussion of the Results

- Non-zero asymmetry amplitudes
- World first evidence of the Dihadron FF $H_1^{\perp}$
- Positive amplitudes in the whole range of the invariant mass
  - rule out the sign change predicted by Jaffe
  - shape consistent with later model by Radici & Bacchetta
- Big contribution from $s-p$ wave interference around $\rho^0(770)$
- Asymmetry results sensitive to transversity
Summary

- Semi-Inclusive two-hadron production from a transversely polarized hydrogen measured at HERMES; Full data analyzed
- First evidence for a spin-dependent Dihadron FF
- Transversity can thus be accessed in two-pion SIDIS
- No evidence of a sign change of the asymmetry amplitudes around $\rho^0(770)$: Jaffe’s model not favored
- An analogous mechanism can be studied in pp collisions at RHIC and SIDIS at COMPASS
- Dihadron FF can be extracted from $e^+e^-$ data at BELLE, which can be combined with SIDIS and pp collisions data to extract transversity
Backup Slides
Semi-Inclusive DIS Cross Section

One-Hadron Production

\[ \sigma_{UT} \sim \sin(\phi + \phi_S) \sum_q e_q^2 \mathcal{I} \left[ \frac{k_T \hat{P}_h c}{M_h} h_q H_1^\perp \right] \]

- Convolution integral over intrinsic quark transverse momenta
- To extract \( h_1 H_1^\perp \), need to de-convolve transverse momentum integral
- Competition with Sivers Effect
  ➔ Well distinguished via Fourier component

Two-Hadron Production

\[ \sigma_{UT} \sim \sin(\phi_{R \perp} + \phi_S) \sum_q e_q^2 h_1^q H_1^\perp \]

- Only relative momentum of two-hadron survives the integral over \( \vec{H}_{h_1} \)
- Directly proportional to \( h_1 H_1^\perp \)
- Independent measurement of transversity from one-hadron case

But:
- Lower statistics
- More kinematic dependence (\( d^9 \sigma \))
- No 2-hadron FF measured so far (can be measured by BELLE)
The fully differential asymmetry depends on 9 kinematic variables:

\[ x, y, z, \phi_{R\perp}, \phi_S, \text{ and } \theta, M_{\pi\pi}, \text{ and } P_{h\perp} \quad (d^2P_{h\perp} = |P_{h\perp}|d|P_{h\perp}|d\phi_h). \]

Measured number of events convoluted with the experimental acceptance:

\[
N^{\uparrow(\downarrow)}(\phi_{R\perp}, \phi_S, \theta, M_{\pi\pi}) \propto \int dx \, dy \, dz \, d^2P_{h\perp} \, \epsilon(x, y, z, P_{h\perp}, \phi_{R\perp}, \phi_S, \theta, M_{\pi\pi})
\times \sigma_{U^{\uparrow(\downarrow)}}(x, y, z, P_{h\perp}, \phi_{R\perp}, \phi_S, \theta, M_{\pi\pi}),
\]

To study the acceptance effect, the single target-spin asymmetry was introduced to the HERMES-tuned PYTHIA6 Monte Carlo simulation based on the theoretical model:

\[
A_{UT}(x, y, z, M_{\pi\pi}, |P_{h\perp}|, \phi_{R\perp}, \phi_S, \phi_h, \theta)
= -\sin(\phi_{R\perp} + \phi_S) \frac{B(y)}{A(y)} \sqrt{1 - 4 \left( \frac{M_\pi}{M_{\pi\pi}} \right)^2 \sum_q e^2_q h_1^q(x) H_{1,q}^{\perp,sp}(M_{\pi\pi}, z)} \sum_q e^2_q f_1^q(x) D_{1,q}(M_{\pi\pi}, z)
\]

- \(H_{1,q}^{\perp,sp}(z, M_{\pi\pi})\) and \(D_{1,q}(z, M_{\pi\pi})\) from A. Bacchetta and M. Radici (hep-ph/0608037)
- \(h_1^q(x)\) at \(Q^2 = 2.5 GeV^2\) from P. Schweitzer et al. (hep-ph/0101300)
- \(f_1^q(x)\) at \(Q^2 = 2.5 GeV^2\) from GRV (M. Glueck, E. Reya, A. Vogt (hep-ph/9806404))
Theoretical and Extracted Amplitudes

Overestimated asymmetry from theory!