Transversity at HERMES

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Outline

- Motivation and Background
- Single hadron production
- Two hadron production
- Other distribution functions
  - Sivers function
  - Pretzelocity
  - Boer-Mulders function
- Conclusion
Motivation and Background
Motivation and Background

Transverse Momentum Dependent Functions

- SIDIS cross section can be written
  \[ \sigma^{ep \rightarrow ehX} = \sum_q DF \otimes \sigma^{eq \rightarrow eq} \otimes FF \]
- Access integrals of DFs and FFs through azimuthal asymmetries in \( \phi_h, \phi_S, \phi_{R\perp} \)

Distribution Functions (DF)

<table>
<thead>
<tr>
<th>nucleon</th>
<th>quark</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>f_1</td>
<td>∙</td>
<td></td>
<td>h_\perp</td>
</tr>
<tr>
<td>L</td>
<td>g_1</td>
<td></td>
<td>∙</td>
<td>h_{\perp\perp}</td>
</tr>
<tr>
<td>T</td>
<td>f_{1T}</td>
<td>∙</td>
<td></td>
<td>h_1</td>
</tr>
<tr>
<td></td>
<td>g_{1T}</td>
<td></td>
<td>∙</td>
<td>h_{1T}</td>
</tr>
</tbody>
</table>

Fragmentation Functions (FF)

<table>
<thead>
<tr>
<th>quark</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_1</td>
<td>G_\perp</td>
<td>H_\perp</td>
<td></td>
</tr>
</tbody>
</table>

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**Motivation and Background**

**The Hermes Experiment**

**Beam** Long. pol. $e^{\pm}$ at 27.6 GeV

**Target** Trans. pol. H ($\approx 75\%$)
Log. pol. H ($\approx 85\%$)
Unpol. H,D,Ne,Kr, . . .

**Lep.-Had. Sep.** High efficiency $\approx 98\%$
Low contamination (<2%)  

**Hadron PID** 2-15 GeV
SIDIS Single Hadron Production and Transversity
HERMES Collins Moments for Pions

- Increased statistics over published results

- Non-zero transversity ($h_1$) and Collins ($H_{1\perp}$) functions

- Positive for $\pi^+$, negative for $\pi^-$, as might be expected

\[ \delta u := h_1^u > 0 \]
\[ \delta d := h_1^d > 0 \]

- Large $\pi^-$ asymmetry implies $H_{1\perp,\text{disf}} \approx -H_{1\perp,\text{fav}}$

- Isospin symmetry among pions fulfilled
HERMES Pion Kaon Comparison

- $\pi^+$ and $K^+$ consistent (u-quark dominance)
- $\pi^-$ and $K^-$ opposite sign (But $K^- = \bar{u}s$ originates from sea quarks)
Collins Pion Yield difference

Non-negligible contribution from exclusive vector meson production.

New observable “pion-difference target-spin asymmetry”

\[ A_{UT}^{\pi^+ - \pi^-} := \frac{1}{S_T} \left( \sigma_{U \uparrow}^{\pi^+} - \sigma_{U \uparrow}^{\pi^-} \right) - \left( \sigma_{U \downarrow}^{\pi^+} - \sigma_{U \downarrow}^{\pi^-} \right) \]

Vector meson contribution approximately cancels.

Non-zero asymmetries not due to vector mesons.
2D Binning of HERMES Collins Results

- Kinematic dependencies may not factorize
- Bin in as many independent variables as possible to extract the most information
Efremov/Goeke/Sweitzer Extraction

- Extract $H_1^\perp$ separately from BELLE and HERMES
- Results from both experiments consistent
- Predicted zero $\pi^0$ asymmetry

(arXiv:hep-ph/0603054v2)
Anselmino Transversity Extraction

HERMES Proton Data

BELLE $A_0$ Asymmetry

BELLE $A_{12}$ Asymmetry

COMPASS Deuteron Data

- Anselmino, et al., (PRD 75:054032, 2007) simultaneously fit data from
  - BELLE $e^+e^- \rightarrow h^+h^-X$
  - HERMES SIDIS w/ proton target
  - COMPASS SIDIS w/ deuteron target
- Extracted transversity and Collins, made prediction for COMPASS w/ proton target
As expected, transversity has opposite signs for $u$ and $d$.

COMPASS results consistent with prediction, i.e. strong agreement between all three experiments.
Transversity through Two Hadron Production
SIDIS Two Hadron and Vector Meson Production

- Can expand cross section in moments of four angles $\phi_h$, $\phi_S$, $\phi_R$, $\theta$

$$d^7 \sigma_{UT} = \sum_q \frac{\alpha^2 e_q^2}{2\pi s xy^2} B(y) |S_\perp| \left| \frac{R}{M_{hh}} \right| \sin(\phi_R + \phi_S) \sin \theta h_1(x)$$

$$\times \left( H_{1,UT}^{ZP}(z, M_{hh}^2) + \cos \theta H_{1,LT}^{ZP}(z, M_{hh}^2) \right).$$

- Transversity appears with interference fragmentation functions.
Di-hadron Results

**HERMES**

- Measure asymmetry $2 \left\langle \sin(\phi_{R\perp} + \phi_S) \sin \theta \right\rangle$ in $\pi^+, \pi^-$ pair production
- Related to $sp$ interference $FF \ H_{1,UT}^{\perp,sp}$ and transversity
- Model based on HERMES results by Bacchetta, et al. (PRD 74:114007, 2006)
- Prediction for COMPASS results yields too small of an asymmetry (arXiv:0907.0961v1)
- Both experiments indicate non-zero $H_{1,UT}^{\perp,sp}$ and non-zero transversity function

**COMPASS**

- $A_{RS}^{P}$
- $h^+h^-$ pairs, $x > 0.032$
- $h^+h^-$ pairs, $x \leq 0.032$
- COMPASS 2007 transverse proton data
- Bacchetta et al.

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Transversity at HERMES

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# TMD Two Hadron Production

- Transverse target portion of cross section much more complicated
  - Leading twist + only $ss$, $sp$, and $pp$ interference $\Rightarrow$ 27 independent $A_{UT}$ moments
  - Fourier moments of $(\phi, \phi_R, \phi_S, \theta)$ depend on $(x, y, z, P_{h\perp}, M_{hh})$.
- Clean access to 4 TMD distribution functions: $f_{1T}$, $h_{1\perp}$, $h_{1T}$, and $g_{1T}$
- Many unexplored distribution functions, including interference, two meson, and single vector meson functions
- Examples:

<table>
<thead>
<tr>
<th>Moment</th>
<th>DF</th>
<th>2 had. FF</th>
<th>VM FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin(\phi_h - \phi_S)$</td>
<td>$f_{1T}$</td>
<td>$D_{1,UU}$</td>
<td>$D_1$</td>
</tr>
<tr>
<td>$\sin(2\phi_h - \phi_R - \phi_S) \sin \theta$</td>
<td>$f_{1T}$</td>
<td>$D_{1,UT}$</td>
<td></td>
</tr>
<tr>
<td>$\sin(\phi_R - \phi_S) \sin \theta$</td>
<td>$g_{1T}$</td>
<td>$G_{1,UT}$</td>
<td></td>
</tr>
<tr>
<td>$\sin(\phi_h + \phi_S)P_2(\cos \theta)$</td>
<td>$h_1$</td>
<td>$H_{1,LL}$</td>
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<tr>
<td>$\sin(3\phi_h - \phi_S) \sin \theta$</td>
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<td>$H_{1,UT}$</td>
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</table>
Other Distribution Functions
Pretzellicity

- Non-zero Pretzellicity $h_{1T}^{\perp}$ indicates non-spherical proton, e.g. G. Miller arXiv:0802.3731v1.

- Pretzellicity moment:
  \[
  2 \left\langle \sin(3\phi_h - \phi_S) \right\rangle = -\frac{\sum_q e_q^2 h_{1T}^{\perp, q} \otimes H_{1, q}^{\perp}}{\sum_q e_q^2 f_1^q D_1^q}
  \]

- Similar to Collins moment:
  \[
  2 \left\langle \sin(\phi_h + \phi_S) \right\rangle = -\frac{\sum_q e_q^2 h_{1}^{\perp, q} \otimes H_{1, q}^{\perp}}{\sum_q e_q^2 f_1^q D_1^q}
  \]

- HERMES results just released Sept. 09

- Data imply small or identically zero $h_{1T}^{\perp}$
Final Sivers results were available June 2009 (arXiv:0906.3918v1)

\[ 2 \left\langle \sin(\phi_h - \phi_S) \right\rangle = -\frac{\sum_q e_q^2 f_{1T}^{l,q} \otimes D_{1,q}^T}{\sum_q e_q^2 f_1^q D_1^q} \]

\( \pi^+ \) significantly non-zero, rises with \( z \)

Also, \( \pi^+ \) rises and plateaus with \( P_{h\perp} \)

Slightly positive \( \pi^0 \) and zero \( \pi^- \)

\( u \) quark dominance for \( \pi^+ \) implies \( f_{1T}^u < 0 \) and \( f_{1T}^d > 0 \)

Pion yield difference \( \Rightarrow \) non-zero asymmetry is not due to vector mesons
Kaon Sivers Moments

- Similar rise with $z$ as $\pi^+$
- $K^+$ also has similar dependence on $P_{h\perp}$
- $K^-$ slightly positive
- $\pi^+ - K^+$ difference asymmetry largest where sea quarks most vary from light quarks
HERMES and COMPASS Results

- COMPASS Results from DIS ’09 (arXiv:0907.5508v1)
- Not as good agreement as for transversity and Collins moments
- COMPASS has not yet included all data
Boer Mulders and Cahn Effect

Access to Boer-Mulders function

COMPASS results from arXiv:0907.5511v1

Model prediction by Ma, et al. (arXiv:0804.3024), “a larger asymmetry in $\pi^-$ production, compared to $\pi^+$ production, would represent a signature of the Boer–Mulders effect”
Conclusion
Conclusion

- Single hadron production
  - Results from full dataset available
  - Anselmino, *et al.*, extraction of transversity and Collins FF
  - Excellent agreement between models, BELLE, COMPASS and HERMES

- Two hadron production
  - Results from COMPASS and HERMES qualitatively agree
  - Some discrepancy in magnitude of asymmetry
  - More interesting physics awaits

- Other transverse momentum distribution functions
  - First pretzelocity results
  - Final Sivers results
  - Boer-Mulders results—in process of being finalized

- HERMES has made significant contributions, with more on the way!