Tranversese Momentum and Spin: an Experimental Overview

N.C.R. Makins
University of Illinois at Urbana-Champaign

Outline

• Intro TMDs, SSAs, and the Collins & Sivers story

• Collins Fragmentation Function
  the “duct tape” of TMD analysis

• Transversity
  the “3rd” PDF

• Sivers function
  parton orbital angular momentum

• Boer-Mulders function & Cahn effect
  $L_q$ and $k_T$ with all new data!
TMDs and SSAAs

Glossary:
Transverse Momentum Dependent PDFs & FFs
Single-Spin Azimuthal Asymmetries
A particular puzzle: Where does the proton spin come from?

\[ q(x) = q^\uparrow(x) + q^\downarrow(x) \]

\[ \Delta q(x) = q^\uparrow(x) - q^\downarrow(x) \]

Only three possibilities

1. **Quark polarization**
   \[ \Delta \Sigma \equiv \int dx \left( \Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta \bar{u}(x) + \Delta \bar{d}(x) + \Delta \bar{s}(x) \right) \approx 30\% \text{ only} \]

2. **Gluon polarization**
   \[ \Delta G \equiv \int dx \Delta g(x) \quad ? \]

3. **Orbital angular momentum**
   \[ L_z \equiv L_q + L_g \quad ? \]
A particular puzzle: Where does the proton spin come from?

\[ q(x) = q^\uparrow(x) + q^\downarrow(x) \]

\[ \Delta q(x) = q^\uparrow(x) - q^\downarrow(x) \]

only three possibilities

1. Quark polarization
\[ \Delta \Sigma \equiv \int dx \ (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta \bar{u}(x) + \Delta \bar{d}(x) + \Delta \bar{s}(x)) \approx 30\% \text{ only} \]

2. Gluon polarization
\[ \Delta G \equiv \int dx \ \Delta g(x) \quad ? \]

3. Orbital angular momentum
\[ L_z \equiv L_q + L_g \quad ? \]

In friendly, non-relativistic bound states like atoms & nuclei (& constituent quark model), particles are in eigenstates of \( L \)

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

Not so for bound, relativistic Dirac particles ...
Noble “\( l \)” is not a good quantum number
Distribution Functions

\[ f_1 = \]
\[ g_1 = \]
\[ h_1 = \]
\[ g_{1T} = \]
\[ h_{1T} = \]
\[ h_{1L} = \]

Fragmentation Functions

\[ D_1 = \]
\[ G_1 = \]
\[ H_1 = \]
\[ G_{1T} = \]
\[ H_{1T} = \]
\[ H_{1L} = \]

Distribution Functions
Fragmentation Functions

Mulders & Tangerman, NPB 461 (1996) 197
Functions surviving on integration over Transverse Momentum

The others are sensitive to \textit{intrinsic} $k_T$ in the nucleon & in the fragmentation process

\textit{Mulders & Tangerman, NPB 461 (1996) 197}

\begin{align*}
\text{Distribution Functions} \\
& f_1 = \quad \text{---} \quad \text{---} \\
& g_1 = \quad \text{---} \quad \text{---} \\
& h_1 = \quad \text{---} \quad \text{---} \\
& f_{1T} = \quad \text{---} \quad \text{---} \\
& h_{1T} = \quad \text{---} \quad \text{---} \\
& h_{1L} = \quad \text{---} \quad \text{---} \\
\end{align*}

\begin{align*}
\text{Fragmentation Functions} \\
& D_1 = \quad \text{---} \quad \text{---} \\
& G_1 = \quad \text{---} \quad \text{---} \\
& H_1 = \quad \text{---} \quad \text{---} \\
& D_{1T} = \quad \text{---} \quad \text{---} \\
& H_{1T} = \quad \text{---} \quad \text{---} \\
& H_{1L} = \quad \text{---} \quad \text{---} \\
\end{align*}
One \textit{T-odd function} required to produce \textit{single-spin asymmetries} in SIDIS

Mulders & Tangerman, NPB 461 (1996) 197
Functions surviving on integration over Transverse Momentum

Distribution Functions

Weird #1

\[ f_1 = \]

\[ g_1 = \]

\[ h_1 = \]

\[ f_{1T} = \]

\[ g_{1T} = \]

\[ h_{1T} = \]

\[ h_{1L} = \]

transversity

Sivers

Boer-Mulders

Pretzelosity

Weird #2

Collins

Polarizing FF

Distribution Functions

Fragmentation Functions

One \textit{T-odd function} required to produce single-spin asymmetries in SIDIS

The others are sensitive to \textit{intrinsic }\mathbf{k}_T\textit{ in the nucleon & in the fragmentation process}

\textit{Mulders & Tangerman, NPB 461 (1996) 197}

# Measuring: Azimuthal Asymmetries

**SIDIS, at leading twist**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Azimuthal Evenness</th>
<th>Azimuthal Oddness</th>
</tr>
</thead>
<tbody>
<tr>
<td>UU</td>
<td>$\cos(2\phi_h)$</td>
<td>$f_1 = \uparrow \downarrow$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$h_{\perp}^1 = \uparrow \downarrow$</td>
</tr>
<tr>
<td>UL</td>
<td>$\sin(2\phi_h)$</td>
<td>$h_{\perp,1L} = \uparrow \downarrow$</td>
</tr>
<tr>
<td>UT</td>
<td>$\sin(\phi_h + \phi_S)$</td>
<td>$h_1 = \uparrow \downarrow$</td>
</tr>
<tr>
<td></td>
<td>$\sin(\phi_h - \phi_S)$</td>
<td>$f_{1T} = \uparrow \downarrow$</td>
</tr>
<tr>
<td></td>
<td>$\sin(3\phi_h - \phi_S)$</td>
<td>$h_{1T} = \uparrow \downarrow$</td>
</tr>
<tr>
<td>LL</td>
<td>1</td>
<td>$g_1 = \uparrow \downarrow$</td>
</tr>
<tr>
<td>LT</td>
<td>$\cos(\phi_h - \phi_S)$</td>
<td>$g_{1T} = \uparrow \downarrow$</td>
</tr>
</tbody>
</table>
### Measuring: Azimuthal Asymmetries

<table>
<thead>
<tr>
<th>Beam Pol.</th>
<th>Target Pol.</th>
<th>( \cos(2\phi_h) )</th>
<th>( \sin(2\phi_h) )</th>
<th>( \sin(\phi_h + \phi_S^l) )</th>
<th>( \sin(\phi_h - \phi_S^l) )</th>
<th>( \sin(3\phi_h - \phi_S^l) )</th>
<th>( \cos(\phi_h - \phi_S^l) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>UU</td>
<td>1</td>
<td>( f_1 = )</td>
<td>( h_1^\perp = )</td>
<td>( h_{1L} = )</td>
<td>( f_{1T} = )</td>
<td>( h_{1T}^\perp = )</td>
<td>( g_1 = )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>UL</td>
<td>( \cos(2\phi_h) )</td>
<td>( h_1^\perp = )</td>
<td>( H_1^\perp = )</td>
<td>( H_{1L}^\perp = )</td>
<td>( H_{1T}^\perp = )</td>
<td>( H_{1T}^\perp = )</td>
<td>( H_{1T}^\perp = )</td>
</tr>
<tr>
<td>UT</td>
<td>( \sin(2\phi_h) )</td>
<td>( h_{1L} = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LL</td>
<td>( \sin(\phi_h + \phi_S^l) )</td>
<td>( h_1 = )</td>
<td>( H_1^\perp = )</td>
<td>( H_{1L}^\perp = )</td>
<td>( H_{1T}^\perp = )</td>
<td>( H_{1T}^\perp = )</td>
<td>( H_{1T}^\perp = )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LT</td>
<td>( \sin(\phi_h - \phi_S^l) )</td>
<td>( h_{1T}^\perp = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
<td>( D_1 = )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*SIDIS, at leading twist*
Electro-Production of Hadrons with Transverse Target

Measure dependence of hadron production on two azimuthal angles

Electron beam defines scattering plane

Target spin transverse to beam

with respect to scattering plane
Electro-Production of Hadrons with Transverse Target

Measure dependence of hadron production on two azimuthal angles

Electron beam defines scattering plane

Target spin transverse to beam

Azimuthal angles measured around $q$ vector ...

with respect to scattering plane

$\phi_S = \text{target spin orientation}$
Electro-Production of Hadrons with Transverse Target

Measure dependence of hadron production on **two azimuthal angles**

Electron beam defines scattering plane

Target spin transverse to beam

Azimuthal angles measured around $q$ vector ...

with respect to scattering plane

$\phi_S = \text{target spin orientation}$
Electro-Production of Hadrons with Transverse Target

Measure dependence of hadron production on two azimuthal angles

Electron beam defines scattering plane

Target spin transverse to beam

Azimuthal angles measured around q vector ...

with respect to scattering plane

$\phi_S = \text{target spin orientation}$  $\phi_h = \text{hadron direction}$

Fermilab E704: $p^+ p \rightarrow \pi X$ at 400 GeV

Analyzing Power

$$A_N = \frac{1}{P_{beam}} \frac{N_{\pi}^{\text{left}} - N_{\pi}^{\text{right}}}{N_{\pi}^{\text{left}} + N_{\pi}^{\text{right}}}$$

Huge \textit{single-spin asymmetry}!

- Opposite sign for $\pi^+ = u\bar{d}$ than for $\pi^- = d\bar{u}$
- Effect larger for \textit{forward} production
- Observable: $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_\pi)$ \textit{odd} under naive Time-Reversal

\textbf{Surprising observation! ..... Why?}

SSA’s at high-energies

Now confirmed at RHIC at much higher energies

T-odd observables

SSA observables \( \sim \vec{J} \cdot (\vec{p_1} \times \vec{p_2}) \)
\( \Rightarrow odd \) under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

Can’t come from perturbative subprocess xsec:

- \( q \) helicity flip suppressed by \( m_q / \sqrt{s} \)
- need \( \alpha_s \)-suppressed loop-diagram to generate necessary phase

At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions

\[ \langle p_T \rangle = 1.0 \, 1.1 \, 1.3 \, 1.5 \, 1.8 \, 2.1 \, 2.4 \, \text{GeV/c} \]
**SSA’s at high-energies**

Now confirmed at RHIC at much higher energies

\[ p+p \rightarrow \pi^0+X \text{ at } \sqrt{s}=200 \text{ GeV} \]

\[ A_N \]

\[ \text{Star Run 6} \]

**T-odd observables**

SSA observables \( \sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2) \) \( \Rightarrow odd \) under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

\( q \) helicity flip suppressed by \( m_q/\sqrt{s} \)

need \( \alpha_s \)-suppressed loop-diagram to generate necessary phase

\( \text{At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions} \)
Now confirmed at RHIC at much higher energies

\[ p + p \rightarrow \pi^0 + X \text{ at } \sqrt{s} = 200 \text{ GeV} \]

T-odd observables

SSA observables \( \sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2) \)

\( \Rightarrow \) odd under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

Must be a spin-orbit structure either in the fragmentation process or within the proton itself

At hard (enough) scales, SSA's must arise from soft physics: T-odd distribution / fragmentation functions

The Canonical Example: Collins and Sivers
E704 Possible Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ...

\[ q(x) \quad \Delta q(x) \quad h_1(x) \]
E704 Possible Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ... transversity

\[ q(x) \quad \Delta q(x) \quad h_1(x) \]
E704 Possible Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ... \textit{transversity}

\[ q(x) \quad \Delta q(x) \]

... with a new, \textit{T-odd “Collins” fragmentation function}

\[ H_1^\perp(z, p_T) \]
E704 Possible Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ... \textbf{transversity} \[ q(x) \quad \Delta q(x) \]

... with a new, \textbf{T-odd “Collins” fragmentation function} \[ H_{1}^\perp(z, p_T) \]

\textit{spin-orbit in fragmentation!}

E704 effect:

\[ h_1(x) \otimes H_{1}^\perp(z, p_T) \]

E704 Possible Mechanism #2: The “Sivers Effect”

Need the ordinary fragmentation function $D_1(z)$
Need the ordinary fragmentation function $D_1(z)$

... with a new, $T$-odd “Sivers” distribution function $f_{1T}(x, k_T)$
E704 Possible Mechanism #2: The “Sivers Effect”

Need the ordinary fragmentation function \( D_1(z) \)

... with a new, T-odd “Sivers” distribution function \( f_{1T}^\perp(x, k_T) \)
E704 Possible Mechanism #2: The “Sivers Effect”

Need the ordinary fragmentation function $D_1(z)$

... with a new, T-odd “Sivers” distribution function $f_{1T}^\perp(x, k_T)$

Phenomenological model of Meng, Boros, Liang:
Forward $\pi^+$ produced from orbiting valence-$u$ quark by recombination at front surface of beam protons

quark orbital motion!

E704 effect:

$\pi^+$

$\pi^+ \rightarrow \pi^+ \rightarrow \pi^+:$

Forward $\pi^+$ produced from orbiting valence-$u$ quark by recombination at front surface of beam protons

$u_v$

$D_1(z)$
Electroproduction of Pions with Transverse Target

SIDIS xsec with **transverse target** polarization has two similar terms:

\[
\sin(\phi_l^h + \phi_l^S) \Rightarrow h_1 = \begin{array}{c}
\text{•} \\
\text{•} \\
\bigcirc \quad \otimes \quad H_1^\perp = \begin{array}{c}
\text{•} \\
\bigcirc
\end{array}
\end{array}
\]

\[
\sin(\phi_l^h - \phi_l^S) \Rightarrow f_{1T}^\perp = \begin{array}{c}
\text{•} \\
\bigcirc \\
\end{array} \quad \otimes \quad D_1 = \bigcirc
\]

**separate Sivers and Collins mechanisms**

- \((\phi_l^h - \phi_l^S) = \text{angle of hadron relative to initial quark spin}\)
- \((\phi_l^h + \phi_l^S) = \pi + (\phi_l^h - \phi_l''^S) = \text{hadron relative to final quark spin}\)
Electroproduction of Pions with Transverse Target

SIDIS xsec with transverse target polarization has two similar terms:

\[
\sin(\phi^l_h + \phi^l_S) \Rightarrow h_1 = \begin{array}{c}
\uparrow \\
\downarrow
\end{array} - \begin{array}{c}
\uparrow \\
\downarrow
\end{array} \otimes H^1_\perp = \begin{array}{c}
\uparrow \\
\downarrow
\end{array} - \begin{array}{c}
\uparrow \\
\downarrow
\end{array}
\]

\[
\sin(\phi^l_h - \phi^l_S) \Rightarrow f^\perp_{1T} = \begin{array}{c}
\uparrow \\
\downarrow
\end{array} - \begin{array}{c}
\uparrow \\
\downarrow
\end{array} \otimes D_1 = \begin{array}{c}
\uparrow \\
\downarrow
\end{array}
\]

seperate Sivers and Collins mechanisms

\[
(\phi^l_h - \phi^l_S) = \text{angle of hadron relative to initial quark spin}
\]

\[
(\phi^l_h + \phi^l_S) = \pi + (\phi^l_h - \phi^l_S) = \text{hadron relative to final quark spin}
\]
Electroproduction of Pions with Transverse Target

SIDIS xsec with *transverse target* polarization has *two* similar terms:

\[
\sin(\phi^l_h + \phi^l_S) \Rightarrow h_1 = \bullet - \circ \otimes H^\perp_1 = \bullet - \circ \\
\sin(\phi^l_h - \phi^l_S) \Rightarrow f^\perp_{1T} = \bullet - \circ \otimes D_1 = \bullet
\]

*separate Sivers and Collins mechanisms*

- \((\phi^l_h - \phi^l_S)\) = angle of hadron relative to *initial* quark spin
- \((\phi^l_h + \phi^l_S) = \pi + (\phi^l_h - \phi^l'_S)\) = hadron relative to *final* quark spin

Electroproduction of Pions with Transverse Target

SIDIS xsec with \textit{transverse target} polarization has \textit{two} similar terms:

\[
\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1 = \begin{array}{c}
\uparrow \quad \downarrow \quad \otimes \quad H_1^\perp = \begin{array}{c}
\uparrow \\
\downarrow 
\end{array}
\end{array}
\]

\[
\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp = \begin{array}{c}
\uparrow \quad \downarrow \quad \otimes \quad D_1 = \begin{array}{c}
\uparrow \\
\downarrow 
\end{array}
\end{array}
\]

\textbf{separate Sivers and Collins mechanisms}

\(
\bullet (\phi_h^l - \phi_S^l) = \text{angle of hadron relative to } \text{initial quark spin}
\)

\(
\bullet (\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^l) = \text{hadron relative to } \text{final quark spin}
\)
Electroproduction of Pions with Transverse Target

SIDIS xsec with *transverse target* polarization has *two* similar terms:

\[ \sin(\phi^l_h + \phi^l_S) \Rightarrow h_1 = \downarrow - \uparrow \otimes H^\perp_1 = \downarrow - \uparrow \]

\[ \sin(\phi^l_h - \phi^l_S) \Rightarrow f^\perp_{1T} = \downarrow - \uparrow \otimes D_1 = \downarrow \]

*both observed!*

*separate Sivers and Collins mechanisms*

\[ (\phi^l_h - \phi^l_S) = \text{angle of hadron relative to initial quark spin} \]

\[ (\phi^l_h + \phi^l_S) = \pi + (\phi^l_h - \phi^l_S) = \text{hadron relative to final quark spin} \]
Results from full 2002–2005 H↑ target data

Sivers Moments for π⁺ π⁻

Collins Moments for π⁺ π⁻

HERMES PRELIMINARY 2002-2005
lepton beam asymmetry, Collins amplitudes
8.1% scale uncertainty

HERMES PRELIMINARY 2002-2005
lepton beam asymmetry, Sivers amplitudes
8.1% scale uncertainty

Transversity $h_1(x)$

Photo-Album of our New Friends!

\[ h_1(x) \]
Transversity $h_1(x)$

Sivers $f_{1T}^\perp(x, k_T)$

Photo-Album of our New Friends!
Transversity $h_1(x)$

Photo-Album of our New Friends!

Boer-Mulders $h_1^\perp(x, k_T)$

Sivers $f_{1T}^\perp(x, k_T)$
Photo-Album of our New Friends!

Transversity
\( h_1(x) \)

Collins
\( H_1^\perp(z, p_T) \)

Boer-Mulders
\( h_1^\perp(x, k_T) \)

Sivers
\( f_{1T}^\perp(x, k_T) \)

Transversity $h_1(x)$

Photo-Album of our New Friends!

Collins $H_{1\perp}(z, p_T)$

Boer-Mulders $h_{1\perp}(x, k_T)$

Sivers $f_{1\perp T}(x, k_T)$

Favored / Disfavored Frag Functions

\[ D_{\text{fav}} \equiv D_{u \rightarrow \pi^+} = D_{d \rightarrow \pi^-} = \ldots \]
\[ D_{\text{dis}} \equiv D_{u \rightarrow \pi^-} = D_{d \rightarrow \pi^+} = \ldots \]
The Collins Fragmentation Function

\[ H_1^\perp(z, p_T) \]
Understanding the Collins Effect

The Collins function exists! \(\Rightarrow\) **spin-orbit** correlations in \(\pi\) formation

*Is the Artru mechanism responsible?*
Why are the Collins $\pi^-$ asymmetries so large?

DIS on proton target always dominated by \textit{u-quark scattering}

\[ A^{\pi^+}_{\text{Col}} \sim \delta u \cdot H_{\text{favored}} \quad \text{... expected: positive} \]

\[ A^{\pi^-}_{\text{Col}} \sim \delta u \cdot H_{\text{disfavored}} \quad \text{... expected: } \sim \text{ zero} \]
Why are the Collins $\pi^-$ asymmetries so large?

DIS on proton target always dominated by $u$-quark scattering

$$A_{\text{Col}}^{\pi^+} \sim \delta u \cdot H_{\text{favored}}$$  ... expected: positive

$$A_{\text{Col}}^{\pi^-} \sim \delta u \cdot H_{\text{disfavored}}$$  ... expected: $\sim$ zero

Data indicate disfavored CollinsFF is large & negative!
Why are the Collins $\pi^-$ asymmetries so large?

DIS on proton target always dominated by $u$-quark scattering

- $A_{Col}^{\pi^+} \sim \delta u \cdot H_{\text{favored}}$ ... expected: positive
- $A_{Col}^{\pi^-} \sim \delta u \cdot H_{\text{disfavored}}$ ... expected: $\sim$ zero

Data indicate disfavored CollinsFF is large & negative!

Map out solution space ... find $H_{\text{disfav}} \approx -H_{\text{fav}}$

Interpretation of Collins Results

Lund model + $^3P_0$ hypothesis once more:

- Struck quark $u$ and $d\bar{d}$ pair produced in string fragment.
  $$L = 1, S = 1 \Rightarrow J^P = 0^+$$

- Leading $\pi^+$ = favored transition, heads into page.

- Leading $\pi^+$ = subleading $\pi^+$ = disfavored transition, heads out of page.

Perhaps $H_{dis} \approx -H_{fav}$ is not only reasonable, but likely.

Leading $\pi^+ = u\bar{d}$

Heads down (into page) because of $L = 1$
Lund model + $^3P_0$ hypothesis once more:

Subleading pion heads \textbf{out} of page

struck \textbf{u}

L=1

leading $\pi^+ = \text{u}\bar{d}$

produced in string frag.
$L = 1, S = 1 \Rightarrow J^P = 0^+$

leading $\pi^+$ = \textbf{favored} transition, heads into page

subleading particle (prob $\pi^-$) = \textbf{disfavored} transition, heads out of page

$H_{\text{dis}} \approx -H_{\text{fav}}$ \textbf{is quite reasonable after all}
Collins Effect in di-Hadron Correlations In e^+e^- Annihilation into Quarks!

Collins effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

**Experimental requirements:**
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

**Measure product of two Collins FFs**
Final Charm Corrected Results for $e^+ e^- \rightarrow \pi\pi X$ (29 fb$^{-1}$, off-resonance Data)

- Significant non-zero asymmetries
- Rising behavior vs. $z$
- UL/C asymmetries about 40–50% of UL/L asymmetries
- First direct measurements of the Collins function
- UL/L data published

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0(UL/L)$</td>
<td>$(3.06 \pm 0.57 \pm 0.55)$%</td>
</tr>
<tr>
<td>$A_{12}(UL/L)$</td>
<td>$(4.26 \pm 0.68 \pm 0.68)$%</td>
</tr>
<tr>
<td>$A_0(UL/C)$</td>
<td>$(1.27 \pm 0.49 \pm 0.35)$%</td>
</tr>
<tr>
<td>$A_{12}(UL/C)$</td>
<td>$(1.75 \pm 0.59 \pm 0.41)$%</td>
</tr>
</tbody>
</table>

Fit **BELLE** $z$-dependent results to

$$H_1^{(1/2) a}_1(z) = C_a \, z \, D_1^a(z)$$

$C_{\text{fav}} = 0.15$, $C_{\text{unf}} = -0.45$

and so $H_1^{\text{fav}} \approx -H_1^{\text{unf}}$
Fit BELLE $z$-dependent results to
\[ H_1^{(1/2)a}(z) = C_a z D_1^a(z) \]

\[ C_{\text{fav}} = 0.15, \ C_{\text{unf}} = -0.45 \]
and so \( H_1^{\text{fav}} \approx -H_1^{\text{unf}} \)

Resulting Collins FF also fit HERMES data well with XQSM for \( h_1 \)

\[ A_{UT}^{\sin(\phi+\phi_S)}(z) \text{ for proton} \]

HERMES preliminary

\[ \pi^+ \]

\[ \pi^- \]
Final Charm Corrected Results for $e^+ e^- \rightarrow \pi\pi X$ (547 fb$^{-1}$, on–resonance)

- Significance largely increased
- Behavior unchanged
- Reduced systematics
- Precise measurement of Collins asymmetries in $e^+e^-$

**Integrated results:**

<table>
<thead>
<tr>
<th>$A_0$(UL/L)</th>
<th>$(2.67 \pm 0.10 \pm 0.26)$%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{12}$(UL/L)</td>
<td>$(3.55 \pm 0.08 \pm 0.15)$%</td>
</tr>
<tr>
<td>$A_0$(UL/C)</td>
<td>$(1.11 \pm 0.11 \pm 0.22)$%</td>
</tr>
<tr>
<td>$A_{12}$(UL/C)</td>
<td>$(1.46 \pm 0.09 \pm 0.13)$%</td>
</tr>
</tbody>
</table>
Transversity

$h_1(x)$
**Transversity: The Third Structure Function**

**Proton Matrix Elements**

- Vector charge:
  \[ \langle PS|\bar{\psi}\gamma^\mu\psi|PS\rangle = \int_0^1 dx \, q(x) - \bar{q}(x) \rightarrow \# \text{ valence quarks} \]

- Axial charge:
  \[ \langle PS|\bar{\psi}\gamma^\mu\gamma_5\psi|PS\rangle = \int_0^1 dx \, \Delta q(x) + \Delta \bar{q}(x) \rightarrow \text{net quark spin} \]

- Tensor charge:
  \[ \langle PS|\bar{\psi}\gamma^{\mu\nu}\gamma_5\psi|PS\rangle = \int_0^1 dx \, \delta q(x) - \delta \bar{q}(x) \rightarrow ??? \]

**Forward Helicity Amplitudes**

- \( q(x) \sim \)

- \( \Delta q(x) \sim \)

- \( \delta q(x) \sim \)

... but in transverse basis...

---

Properties of Transversity

- In Non-Relativistic Case, boosts and rotations commute:
  \[ \delta q(x) = \Delta q(x) \]
  ... but bound quarks are highly \textit{relativistic} in nature

- No Gluons
  Angular momentum conservation: \[ \Lambda - \lambda = \Lambda' - \lambda' \]
  \[ \Rightarrow \text{transversity has } \textit{no gluon} \text{ component} \]
  \[ \Rightarrow \text{different } Q^2 \textit{ evolution} \text{ than } \Delta q(x) \]

- Chiral Odd
  Helicity flip amplitudes occur only at \[ \mathcal{O}(m_q/Q) \] in inclusive DIS ...
  tensor charge = \textit{“pure valence”} object
  \[ \Rightarrow \text{promising for LQCD comparison?} \]
Collins Moments for pions from H↑

HERMES PRELIMINARY 2002-2005
lepton beam asymmetry, Collins amplitudes
8.1% scale uncertainty

$2 \langle \sin(\phi + \phi_S) \rangle_\pi$

$2 \langle \sin(\phi + \phi_S) \rangle_{\pi^0}$

$2 \langle \sin(\phi + \phi_S) \rangle_{\pi^-}$

$P_{h\perp} \text{[GeV]}$
Collins Moments for pions from $H_{\uparrow}$

-HERMES PRELIMINARY 2002-2005
lepton beam asymmetry, Collins amplitudes
8.1% scale uncertainty

NEW
Charge-difference SSA

CONTRIBUTION FROM EXCLUSIVE $\rho^0 \rightarrow \pi^+\pi^-$ LARGELY CANCELS

$A_{UT}^{\pi^+\pi^-}(\phi, \phi_S) \equiv \frac{2}{S_T} \frac{1}{(\sigma_{U\uparrow} + \sigma_{U\downarrow}^{\pi^+}) - (\sigma_{U\uparrow}^{\pi^-} + \sigma_{U\downarrow}^{\pi^-})}$

HERMES PRELIMINARY 2002-2005
lepton beam amplitudes, 8.1% scale uncertainty

Collins Moments for pions & kaons from D

\[ h_{1,u_v} \approx -h_{1,d_v} \]
Collins Moments for pions & kaons from D

\[ \frac{H_{1,\text{disfav}}}{H_{1,\text{fav}}} = -1 \]

\[ \langle \sin(\phi + \phi_S) \rangle_{H_1}^+ \sim 4\delta u_v - \delta d_v \]

\[ \langle \sin(\phi + \phi_S) \rangle_{H_1}^- \sim -4\delta u_v + \delta d_v \]

\[ \langle \sin(\phi + \phi_S) \rangle_{D}^+ \sim 3\delta u_v + 3\delta d_v \]

\[ h_{1,u_v} \approx -h_{1,d_v} \]

D target is key!
Collins Moments for pions & kaons from D

\[ H_{1,\text{disfav}} \approx -1 \]

\[ \langle \sin(\phi + \phi_S) \rangle_{H}^\pi \sim 4\delta u_v - \delta d_v \]

\[ \langle \sin(\phi + \phi_S) \rangle_{H}^{-} \sim -4\delta u_v + \delta d_v \]

\[ \langle \sin(\phi + \phi_S) \rangle_{D}^\pi \sim 3\delta u_v + 3\delta d_v \]

Deuterium results \( \approx 0 \) show

\[ h_{1,u_v} \approx -h_{1,d_v} \]
Preliminary results

Global fit to BELLE, HERMES and COMPASS

HERMES $A^\sin(\phi_h+\phi_s)_{UT}$

COMPASS $A^\sin(\phi_h+\phi_s+\pi)_{UT}$
Preliminary results

BELLE $\cos(2\varphi_0)$

BELLE $\cos(\varphi_1 + \varphi_2)$

NEW
This is the extraction of \textit{transversity} from new experimental data.

Compared to previous extraction PRD75:054032,2007

Compared to $\Delta \chi^2 = 1$ error estimate of PRD75:054032,2007

$\Delta_T u(x) > 0$ and $\Delta_T d(x) < 0$ The errors are diminished significantly.

$\Delta_T u(x)$ became larger than that of the previous fit.
Predictions from the global analysis, Collins

Update of the analysis with the most recent COMPASS Deuteron, HERMES Proton, BELLE e⁺ e⁻ data

COMPASS 2007 H↑ data!

Fabulous confirmation at higher scales of HERMES results

COMPASS proton data for h⁺ and h⁻, with the very last predictions of Anselmino et al. (DIS08 by A.Prokudin.)
Tensor charges

\[ \Delta_T u = 0.54^{+0.07}_{-0.09}, \quad \Delta_T d = -0.23^{+0.04}_{-0.05} \text{ at } Q^2 = 0.8 \text{ GeV}^2 \]

1. Quark-diquark model:
   Cloet, Bentz and Thomas
   PLB 659, 214 (2008), \( Q^2 = 0.4 \text{ GeV}^2 \)

2. CQSM:
   M. Wakamatsu, PLB B 653 (2007) 398
   \( Q^2 = 0.3 \text{ GeV}^2 \)

3. Lattice QCD:
   M. Gockeler et al.,
   Phys.Lett.B627:113-123,2005 , \( Q^2 \sim 1 \text{ GeV}^2 \)

4. QCD sum rules:
   Han-xin He, Xiang-Dong Ji,
   PRD 52:2960-2963,1995, \( Q^2 \sim 1 \text{ GeV}^2 \)
2-D moments for $\pi^\pm$ : $x-Q^2$ correlation

NEW
2-D Collins moments for $\pi^\pm$

$0.023 < x < 0.05$  
$0.05 < x < 0.09$  
$0.09 < x < 0.15$  
$0.15 < x < 0.22$  
$0.22 < x < 0.49$

$\langle Q^2 \rangle = 1.3$ GeV$^2$  
$\langle Q^2 \rangle = 1.9$ GeV$^2$  
$\langle Q^2 \rangle = 2.8$ GeV$^2$  
$\langle Q^2 \rangle = 4.2$ GeV$^2$  
$\langle Q^2 \rangle = 6.2$ GeV$^2$

HERMES PRELIMINARY 2002-2005
Lepton Beam Asymmetries — 8.1 % scale uncertainty

NEW

NEW

$0.20 < z < 0.30$  
$0.30 < z < 0.40$  
$0.40 < z < 0.50$  
$0.50 < z < 0.60$  
$0.60 < z < 0.70$

$0.00 < p_{h \perp} < 0.25$  
$0.25 < p_{h \perp} < 0.40$  
$0.40 < p_{h \perp} < 0.55$  
$0.55 < p_{h \perp} < 0.80$  
$0.80 < p_{h \perp} < 2.00$

$\sin(\theta + \phi_2)/\sqrt{r}$

Contalbrigo Marco
Transverse Spin Physics at HERMES
SPIN2008, Charlottesville, 07-10-2008
Transversity from the Interference Fragmentation Function

$h_1(x)$
Explicit dependence on transverse momentum of hadron $P_{h\perp}$

Convolution of two unknown functions

Trans. component of relative momentum survives integration over the $P_{h\perp}$ of pair

Collinear kinematics (factorization)

Simple product of unknown functions

Limited statistic power
Azimuthal $2\pi$-moment
Evidence of a T-odd and chiral-odd dihadron FF

No evidence of the sign-change at the $\rho^0$ mass


Bacchetta and Radici *hep-ph/0608037*
Two Hadron Asymmetries

2) \( z \) ordered pairs:
select in the event the two hadrons with the highest relative energy \( z \).

*Reason:* For leading hadron pairs an enhancement of the signal is predicted. Hadrons with higher energy may carry more information about the polarization of the fragmenting quark.

\[ \pi \text{ with opposite charge} \quad \pi \text{ with same charge} \]
Two Hadron Asymmetries

K/π and π/K with opposite charge

K/π and π/K with same charge

Only statistical errors shown, systematic errors considerably smaller.

Consistent with 0, despite the second bin of $\pi^0 h^-$ pairs and the last bin of $h^+ h^-$ pairs are $2\sigma$ from 0.

Systematic errors
Polarization 5%
Relative lumi. $5 \times 10^{-4}$
No systematic effects detected from bunch shuffling.

promising for RHIC future
The Sivers Function

$$f_{1T}(x, k_T)$$
The Leading-Twist Sivers Function: Can it Exist in DIS?

A T-odd function like $f_{1T}^1$ must arise from interference ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?

Brodsky, Hwang, & Schmidt 2002

It looks like higher-twist ... but no, these are soft gluons = “gauge links” required for color gauge invariance

Such soft-gluon reinteractions with the soft wavefunction are final (or initial) state interactions ... and may be process dependent! new universality issues

e.g. Drell-Yan
Understanding the Sivers Asymmetry

Trento Workshop
Summer 2004

Theoretical synthesis of field-theoretic analysis (rigour) and phenomenological thinking (intuition)
Understanding the Sivers Asymmetry

Rigorous Field Theory

Requires:

- *rescattering* via gauge link
- interference effect involving $L=0$ and $L=1$ states

Theoretical *synthesis* of field-theoretic analysis (*rigour*) and phenomenological thinking (*intuition*)
“Cartoons”

Model of Meng, Chou, Yang

\[ \pi^+ \]

\[ u_V \]

\[ \bar{d} \]

Requirements:
- rescattering via gauge link
- interference effect involving \( L=0 \) and \( L=1 \) states

Theoretical synthesis of field-theoretic analysis (rigour) and phenomenological thinking (intuition)

Understanding the Sivers Asymmetry

Rigorous Field Theory

Requires:
- rescattering via gauge link
- interference effect involving L=0 and L=1 states

Theoretical synthesis of field-theoretic analysis (rigour) and phenomenological thinking (intuition)

Model of Meng, Chou, Yang

\[ \pi^+ \]

\[ u \nu \]

\[ \bar{d} \]
Understanding the Sivers Asymmetry

Heisenberg Picture

Schroedinger Picture

Model of Meng, Chou, Yang

\[ \pi^+ + u \sqrt{d} \]

Requires:

- rescattering via gauge link
- interference effect involving L=0 and L=1 states

Theoretical synthesis of field-theoretic analysis (rigour) and phenomenological thinking (intuition)

Trento Workshop
Summer 2004

Heisenberg Picture

Schroedinger Picture

Model of Meng, Chou, Yang

\[ \pi^+ + u \sqrt{d} \]

Requires:

- rescattering via gauge link
- interference effect involving L=0 and L=1 states

Theoretical synthesis of field-theoretic analysis (rigour) and phenomenological thinking (intuition)
Sivers Moments for pions from $H^\uparrow$ Data

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{\pi^\pm} \]

HERMES PRELIMINARY 2002-2005

tepton beam asymmetry, Sivers amplitudes
- 8.1% scale uncertainty

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{\pi^0} \]

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{\pi^-} \]

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{\pi^+} \]

0.1
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

\[ P_{h\perp} \text{ [GeV]} \]

Sivers Moments for pions from H\textsuperscript{↑} Data

\begin{align*}
A_{UT}^{\pi^+\pi^-}(\phi, \phi_S) &= \frac{1}{S_T} \left( \sigma_{U^\uparrow}^{\pi^+} - \sigma_{U^\downarrow}^{\pi^+} - \sigma_{U^\uparrow}^{\pi^-} + \sigma_{U^\downarrow}^{\pi^-} \right) \\
&\text{HERMES PRELIMINARY 2002-2005} \\
&\text{lepton beam asymmetry, Sivers amplitudes} \\
&\text{8.1\% scale uncertainty}
\end{align*}

\begin{align*}
2\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+} \\
2\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^0} \\
2\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^-}
\end{align*}

\begin{align*}
\text{isolates valence} \\
2\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+\pi^-} &= -2 \frac{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4f_1^{\perp,u_v} - f_1^{\perp,d_v}}
\end{align*}

Sivers Asymmetries $\pi^\pm K^\pm$

**NEW**

**D target with RICH**

Final results, all deuteron data

hep-ex/0802.2160 (subm. PLB)

- only statistical errors shown, systematic errors considerably smaller
- small asymmetries, compatible with 0

(leading hadron: similar)
So what is the sign of $L$?

**Connection to nucleon anomalous magnetic moment**

- Constituent quark model (CQM) says $\Delta u = +4/3$, $\Delta d = -1/3$

- CQM does a great job of explaining the proton **anomalous magnetic moment**, via $\mu_p \sim \sum_q e_q/m_q \Delta q$

- ... but we know that the current quarks are **not** as polarized as in the CQM ... and they are **relativistic**: must involve $L_q \neq 0$

- Missing piece must come from $\sum_q e_q L_q$ and must be positive

- Therefore $L_u$ must be positive and $L_d$ negative
So what is the sign of $L$?

Connection to nucleon anomalous magnetic moment

- Consituent quark model (CQM) says $\Delta u = +4/3$, $\Delta d = -1/3$

- CQM does a great job of explaining the proton anomalous magnetic moment, via $\mu_p \sim \sum_q e_q/m_q \Delta q$

- ... but we know that the current quarks are not as polarized as in the CQM ... and they are relativistic: must involve $L_q \neq 0$

- Missing piece must come from $\sum_q e_qL_q$ and must be positive

- Therefore $L_u$ must be positive and $L_d$ negative

Numerous models give $L_u > 0$ and $L_d < 0$

i.e. quark angular momentum shared between spin and $L$
So what is the sign of L?

*Connection to nucleon anomalous magnetic moment*

- Constituent quark model (CQM) says $\Delta u = +4/3$, $\Delta d = -1/3$
- CQM does a great job of explaining the proton anomalous magnetic moment, via $\mu_p \sim \sum_q e_q/m_q \Delta q$
- ... but we know that the current quarks are not as polarized as in the CQM ... and they are relativistic: must involve $L_q \neq 0$
- Missing piece must come from $\sum_q e_q L_q$ and must be positive
- Therefore $L_u$ must be positive and $L_d$ negative

*Numerous models give* $L_u > 0$ *and* $L_d < 0$

*i.e. quark angular momentum shared between spin and L*

in transverse case, that is!

Lattice & GPD calculations give opposite predictions in *longitudinal-spin case*
M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ stronger for oncoming quarks

Many models predict $L_u > 0$...
Phenomenology: Sivers Mechanism

M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ stronger for oncoming quarks

We observe $\langle \sin(\phi_h - \phi_S) \rangle_{\pi^+} > 0$

(and opposite for $\pi^-$)

$\therefore$ for $\phi_S = 0$, $\phi_h = \pi/2$ preferred

Model agrees!

Many models predict $L_u > 0$ ...

$\langle \sin(\phi_l - \phi_S^l) \rangle_{\pi^-} < 0$

$\therefore$ for $\phi_S^l = 0$, $\phi_h = \pi/2$ preferred

Model agrees!
Phenomenology: Sivers Mechanism

M. Burkardt: Chromodynamic lensing

**Electromagnetic coupling** \( \sim (J_0 + J_3) \) **stronger for oncoming quarks**

\[
\langle \sin(\phi_l^h - \phi_l^S) \rangle_{\pi^+ UT} > 0
\]

We observe \( \langle \sin(\phi_l^h - \phi_l^S) \rangle_{\pi^+ UT} > 0 \)

(and opposite for \( \pi^- \))

\[\therefore \text{ for } \phi_l^S = 0, \phi_l^h = \pi/2 \text{ preferred} \]

Model agrees!

D. Sivers: Jet Shadowing

Parton energy loss considerations suggest **quenching of jets** from "near" surface of target

\[\Rightarrow \text{ quarks from "far" surface should dominate} \]

Opposite sign to data ...
For convenience: \( q_T(x) \equiv f_{1T}^{\perp,q}(x) \)

Fit HERMES \( A_{UT} \) to Sivers functions of form:

\[
\frac{u_{T}^{(1/2)}(x)}{u(x)} = S_u x(1-x), \quad \frac{d_{T}^{(1/2)}(x)}{u(x)} = S_d x(1-x)
\]

- assume no antiquark Sivers func: \( \bar{q}_T(x) = 0 \)
- unpol PDFs = GRV-LO, unpol FFs = Kretzer
For convenience: \( q_T(x) \equiv f_{1T}^{\perp,q}(x) \)

Fit HERMES \( A_{UT} \) to Sivers function of form:

\[
\frac{u_T^{(1/2)}(x)}{u(x)} = \left( S_u x (1-x) \right), \quad \frac{d_T^{(1/2)}(x)}{u(x)} = \left( S_d x (1-x) \right)
\]

- assume no antiquark Sivers func: \( \bar{q}_T(x) = 0 \)
- unpol PDFs = GRV-LO, unpol FFs = Kretzer

\[
S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28
\]
For convenience: 
\[ q_T(x) \equiv f_{1T}^{\perp,q}(x) \]

Fit HERMES \( A_{UT} \) to Sivers function of form:
\[
\frac{u_T^{(1/2)}(x)}{u(x)} = (S_u x(1-x), \quad \frac{d_T^{(1/2)}(x)}{u(x)} = (S_d x(1-x))
\]

- assume no antiquark Sivers function: \( \bar{q}_T(x) = 0 \)
- unpolarised PDFs = GRV-LO, unpolarised FFs = Kretzer

\[
S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28
\]

Fits COMPASS deuterium data well!

**But a surprise!** \( S_d \gg S_u \)!

E.g., large-\( N_C \) expectation: \( u_T(x) \approx -d_T(x) \)
For convenience: \( q_T(x) \equiv f_{1T}^{+1}(x) \)

Fit HERMES \( A_{UT} \) to Sivers function of form:

\[
\frac{u_T^{(1/2)}(x)}{u(x)} = S_u x(1-x), \quad \frac{d_T^{(1/2)}(x)}{u(x)} = S_d x(1-x)
\]

- assume no antiquark Sivers function: \( \bar{q}_T(x) = 0 \)
- unpol PDFs = GRV-LO, unpol FFs = Kretzer

\[
S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28
\]

Fits COMPASS deuterium data well!

**But a surprise!** \( S_d \gg S_u \)!

E.g., large-\( N_C \) expectation: \( u_T(x) \approx -d_T(x) \)

Hmm ... \( S_u \) actually reflects \( u_T + d_T/4 \)

... \( S_d \) actually reflects \( d_T + 4\bar{u}_T \)
Sivers Global Fit: HERMES & COMPASS

For convenience: \[ q_T(x) \equiv f_{1T}^{-1,q}(x) \]

Fit HERMES \( A_{UT} \) to Sivers function of form:
\[
\frac{u_T^{(1/2)}(x)}{u(x)} = Su x(1-x), \quad \frac{d_T^{(1/2)}(x)}{u(x)} = Sd x(1-x)
\]

- assume no antiquark Sivers func: \( \bar{q}_T(x) = 0 \)
- unpol PDFs = GRV-LO, unpol FFs = Kretzer

\[ Su = -0.81 \pm 0.07, \quad Sd = 1.86 \pm 0.28 \]

Fits COMPASS deuterium data well!

**But a surprise! \( S_d \gg S_u \)!**

e.g., large-\( N_C \) expectation: \( u_T(x) \approx -d_T(x) \)

Hmm ... \( S_u \) actually reflects \( u_T + \frac{d_T}{4} \)

... \( S_d \) actually reflects \( d_T + 4u_T \)

Could Sivers (and L) be large for antiquarks?
The Sivers effect for kaons and jets

\[ f_{1T}^\perp(x, k_T) \]
Sivers moments for Kaons from full 2002–05 Hydrogen data

HERMES PRELIMINARY 2002-2005
lepton beam asymmetry, Sivers amplitudes
8.1% scale uncertainty
Sivers moments for Kaons from full 2002–05 Hydrogen data

Sivers $K^+$ much larger than for $\pi^+$!
Sivers moments for Kaons from full 2002–05 Hydrogen data

Sivers $K^+$ much larger than for $\pi^+$!

Effect about equal for $K^- = s\bar{u}$ and $\pi^- = d\bar{u} \rightarrow$ note: same antiquark ...

Effect seems larger for $K^+ = u\bar{s}$ than $\pi^+ = u\bar{d}$ at $x \approx 0.1 \ldots$!

→ significant antiquark Sivers functions? and strongly flavor-dependent?
Fit Results

**π** production at HERMES

**K**0 fragmentation functions

\[
D_{K_S^0}^{K_S^0} = D_{d}^{K_S^0} = \frac{1}{2} \left[ D_{u}^{K^+} + D_{sea}^{K^+} \right]
\]

\[
D_{s}^{K_S^0} = D_{s}^{K_S^0} = \frac{1}{2} \left[ D_{s}^{K^+} + D_{sea}^{K^+} \right]
\]

\[
D_{u}^{K_S^0} = D_{t}^{K_S^0} = D_{sea}^{K^+} = D_{d}^{K^+} = D_{u}^{K^+} = D_{s}^{K^+} = D_{d}^{K^+}
\]

Prediction for K⁺
HERMES
Sivers asymmetries

**K** production at HERMES

NEW global fit

29 May 2008
Transversity 2008 - Ferrara

Elena Boglione
Fit Results

π production at COMPASS

K production at COMPASS

Prediction for π⁰ COMPASS Sivers asymmetries

K⁰ data are not fitted

Elena Boglione
Note:

- large d-quark Sivers
- antiquark Sivers needed to explain data
- anti-s Sivers saturated to positivity bounds
Predictions: Sivers

Latest prediction of Anselmino et al.

COMPASS 2007 H↑ data

COMPASS proton data for h+ and h-, with the latest prediction of Anselmino et al.


S. Levorato, Transversity 2008 May 28-31 - Ferrara, Italy
Origins of SSA in $p^+p \rightarrow \pi^0+X$ at RHIC

STAR: arXiv:hep-ex/0801.2990 accepted for publication in PRL

Hints of Sivers function universality?

How to separate Sivers and Collins contributions?
Origins of SSA in $p^+p \rightarrow \pi+X$ at RHIC

20x times increase in acceptance to isolate Sivers contributions
Universality of $k_T$-dependent Functions

These processes have similar gauge-link topology:

**Expectation:** $T$-odd functions will change sign between spacelike (SIDIS) and time-like ($e^+e^-$ and DY) processes

**Sivers sign-change**

- Sivers effect should change sign between SIDIS and DY
- Exciting new prospect: measure with photon-jet at RHIC

Universality of E704 / RHIC

$p^+p \rightarrow \pi X$ not yet clear ...

3 “soft blobs” ... gauge-link topology more complex
The Boer-Mulders function

\[ h_{\perp}^1(x, k_T) \]

... and the Cahn effect ...
A \cos(\Phi) modulation in the \textit{unpolarized xsec} for SIDIS

\textit{kinematic effect} for massless eq→eq scattering due to \textit{parton} $k_T$

\[
\sigma \propto s^2 + u^2 \propto \left( 1 - \frac{k_T}{Q} \sqrt{1 - y \cos \phi} \right)^2 + (1 - y)^2 \left( 1 - \frac{k_T}{Q \sqrt{1 - y}} \cos \phi \right)^2
\]

in eq system

Cahn, PLB 78 (1978) 269

The Cahn Effect

A \( \cos(\Phi) \) modulation in the **unpolarized xsec** for SIDIS

\( \rightarrow \) **kinematic effect** for massless \( eq \rightarrow eq \) scattering due to parton \( k_T \)

\[ \sigma \propto s^2 + u^2 \propto \left( 1 - \frac{k_T}{Q} \sqrt{1 - y \cos \phi} \right)^2 + (1 - y)^2 \left( 1 - \frac{k_T}{Q \sqrt{1 - y}} \cos \phi \right)^2 \]

in eq system
The Cahn Effect

A \cos(\Phi) modulation in the \textit{unpolarized xsec} for SIDIS → \textit{kinematic effect} for massless eq→eq scattering due to parton $k_T$

\[
\sigma \propto s^2 + u^2 \propto \left(1 - \frac{k_T}{Q} \sqrt{1 - y \cos \phi}\right)^2 + (1 - y)^2 \left(1 - \frac{k_T}{Q \sqrt{1 - y}} \cos \phi\right)^2
\]

beam $k$

$q$-vector

parton $k_T \rightarrow \Phi=0^\circ$

slide = lepton scattering plane

photon–target

CM frame

A $\cos(\Phi)$ modulation in the unpolarized xsec for SIDIS

→ kinematic effect for massless eq→eq scattering due to parton $k_T$

The Cahn Effect

\[ \sigma \propto s^2 + u^2 \propto \left(1 - \frac{k_T}{Q}\sqrt{1-y\cos}\phi\right)^2 + (1-y)^2 \left(1 - \frac{k_T}{Q\sqrt{1-y}}\cos\phi\right)^2 \]

Cahn, PLB 78 (1978) 269

beam $k$

$q$-vector

parton $k_T \rightarrow \Phi=180^\circ$

slide = lepton scattering plane

photon–target

CM frame

parton $k_T \rightarrow \Phi=0^\circ$
A \cos(\Phi) modulation in the \textbf{unpolarized xsec} for SIDIS
\rightarrow \textbf{kinematic effect} for massless eq\rightarrow eq scattering due to \textbf{parton} \textit{k}_T

\[ \sigma \propto s^2 + u^2 \propto \left(1 - \frac{k_T}{Q} \sqrt{1 - y \cos \phi} \right)^2 + (1 - y)^2 \left(1 - \frac{k_T}{Q \sqrt{1 - y}} \cos \phi \right)^2 \]

\textbf{\Phi=180° preferred}: higher \textit{s}, \textit{u} in beam-quark system
reflected in azimuthal distribution of produced hadrons

\[ \langle \cos \phi \rangle = - \left( \frac{2k_T}{Q} \right) \frac{(2 - y) \sqrt{1 - y}}{1 + (1 - y)^2} \]

\[ \langle \cos 2\phi \rangle = \left( \frac{2k_T^2}{Q^2} \right) \frac{(1 - y)}{1 + (1 - y)^2} \]

First DIS data with charge-separated hadrons!

\( \cos(\Phi) \) moment for positive hadrons

\[ A_{\cos \Phi_h} \]

\[ h^+ \]

\( x \quad z \quad P^h \ [\text{GeV/c}] \)

Hermes Preliminary
First DIS data with charge-separated hadrons!

**$\cos(\Phi)$ moment for positive hadrons**

**NEW**

**$A_{\cos \phi_h}$**

**$h^+$**

**COMPASS** 2004 $^6$LiD (part)

**charge-separation + different targets may offer insight into $<k_T>$ for different quark flavours**

Comparison with Theory

\[ A_{\cos \phi}^D \]

\[ h^+ \]

**COMPASS 2004 \(^6\)LiD (part)**

*preliminary*

errors shown are statistical only

M. Anselmino, M. Boglione, A. Prokudin, C. Türk
does not include Boer – Mulders contribution

Wolfgang Käfer, Traversity08 @ Ferrara
Cahn effect for negative hadrons

$\cos(\Phi)$ moment for **negative** hadrons

$A_{\cos \phi_h}$

![Graph showing $A_{\cos \phi_h}$ for different values of $x$, $z$, and $p^h$ for hydrogen and deuterium.]

**apparent discrepancy for $h^-$! ... different kinematics ...?**

The Boer-Mulders distribution function

\[ h_1^+(x, k_T) \otimes H_1^+(z, p_T) \rightarrow \cos(2\phi) \text{ modulation} \]

Boer-Mulders: correlation between \( S_q \) and \( L_q \)

assume \( S_u \parallel L_u \)
The Boer-Mulders distribution function

\[ h_1^{+}(x, k_T) \otimes H_1^{+}(z, p_T) \rightarrow \cos(2\phi) \text{ modulation} \]

Boer-Mulders: correlation between \( S_q \) and \( L_q \)

**assume** \( S_u \parallel L_u \)

1 oncoming quarks
scatter most ...
\( h_1^{\perp} \) sets spin direc’s
The Boer-Mulders distribution function

\[ h_1^+(x, k_T) \otimes H_1^+(z, p_T) \rightarrow \cos(2\phi) \] modulation

Boer-Mulders: correlation between \( S_q \) and \( L_q \)

1. oncoming quarks scatter most ...
   \( h_1^\perp \) sets spin direc’s

2. \( \gamma^* \) absorbed

assume \( S_u \parallel L_u \)
The Boer-Mulders distribution function

\[ h_1^\perp (x, k_T) \otimes H_1^\perp (z, p_T) \rightarrow \cos(2\phi) \text{ modulation} \]

Boer-Mulders: correlation between \( S_q \) and \( L_q \)

1. oncoming quarks scatter most ...
   \( h_1^\perp \) sets spin direc’s

2. \( \gamma^* \) absorbed

3. FSI kick back to remnant

assume \( S_u \parallel L_u \)
The Boer-Mulders distribution function

\[ h_1^+(x, k_T) \otimes H_1^+(z, p_T) \rightarrow \cos(2\phi) \text{ modulation} \]

Boer-Mulders: correlation between \( S_q \) and \( L_q \)

1. Oncoming quarks scatter most ... \( h_1^\perp \) sets spin direc’ts
2. \( \gamma^* \) absorbed
3. FSI kick back to remnant
4. Collins!

Assume \( S_u \parallel L_u \)

Favoured \( u \rightarrow \pi^+ \)

\(< \cos 2\phi \> \text{ negative} \)
The Boer-Mulders distribution function

\[ h_1^+(x, k_T) \otimes H_1^+(z, p_T) \rightarrow \cos(2\phi) \text{ modulation} \]

Boer-Mulders: correlation between \( S_q \) and \( L_q \)

1. **oncoming quarks** scatter most ...
   \( h_1^- \) sets spin direc’s

2. **\( \gamma^* \) absorbed**

3. **FSI kick** back to remnant

4. **Collins!**

\[ \langle \cos 2\phi \rangle \text{ negative} \]

\[ \text{favoured} \quad u \rightarrow \pi^+ \]

\[ \text{disfavoured} \quad u \rightarrow \pi^- \]

\[ \langle \cos 2\phi \rangle \text{ positive} \]

\[ \theta \text{ lepton plane} \]
Expected sign of Boer-Mulders

**Widely expected** that $h_{1\perp}$ has the *same sign* for $u$ and $d$

- **Transversity**: $h_{1,u} > 0 \ h_{1,d} < 0$
  $\rightarrow$ same as $g_{1,u}$ and $g_{1,d}$ in NR limit

- **Sivers**: $f_{1T\perp,u} < 0 \ f_{1T\perp,d} > 0$
  $\rightarrow$ relat$^n$ to *anomalous magnetic moment*$^*$
  
  $f_{1T\perp,q} \sim \kappa_q$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$

  values achieve $\kappa^p,n = \Sigma q e_q \kappa_q$ with $u,d$ only

- **Boer-Mulders**: should *follow* that $h_{1\perp,u}$ and $h_{1\perp,d} < 0$ !
  $\rightarrow$ relat$^n$ to *tensor magnetic moment*$^*$
  $\rightarrow$ possible analogue to Sokolov-Ternov?

---

Expected sign of Boer-Mulders

Widely expected that $h_{1 \perp}$ has the **same sign** for $u$ and $d$

- **Transversity**: $h_{1,u} > 0$, $h_{1,d} < 0$
  \[ \rightarrow \text{same as } g_{1,u} \text{ and } g_{1,d} \text{ in NR limit} \]

- **Sivers**: $f_{1T\perp,u} < 0$, $f_{1T\perp,d} > 0$
  \[ \rightarrow \text{related to anomalous magnetic moment}^* \]
  \[ f_{1T\perp,q} \sim \kappa_q \quad \text{where } \kappa_u \approx +1.67, \quad \kappa_d \approx -2.03 \]
  \[ \text{values achieve } \kappa^{p,n} = \sum_q e_q \kappa_q \text{ with } u,d \text{ only} \]

- **Boer-Mulders**: should follow that $h_{1\perp,u}$ and $h_{1\perp,d} < 0$!
  \[ \rightarrow \text{related to tensor magnetic moment}^* \]
  \[ \rightarrow \text{possible analogue to Sokolov-Ternov?} \]


**but these TMDs are all independent**

\[ \langle \vec{s}_u \cdot \vec{S}_p \rangle = +0.5 \quad \langle \vec{l}_u \cdot \vec{S}_p \rangle = +0.5 \]
Expected sign of Boer-Mulders

Widely expected that $h_1^\perp$ has the **same sign** for $u$ and $d$

- **Transversity**: $h_{1,u} > 0 \quad h_{1,d} < 0$
  $\rightarrow$ same as $g_{1,u}$ and $g_{1,d}$ in NR limit

- **Sivers**: $f_{1T^\perp,u} < 0 \quad f_{1T^\perp,d} > 0$
  $\rightarrow$ relat$^n$ to **anomalous magnetic moment**$^*$
  $f_{1T^\perp,q} \sim \kappa_q$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$
  values achieve $\kappa^{p,n} = \sum_q e_q \kappa_q$ with $u,d$ only

- **Boer-Mulders**: should **follow** that $h_{1^\perp,u}$ and $h_{1^\perp,d} < 0$ !
  $\rightarrow$ relat$^n$ to **tensor magnetic moment**$^*$
  $\rightarrow$ possible analogue to Sokolov-Ternov?


\[ \langle \mathbf{s}_u \cdot \mathbf{S}_p \rangle = +0.5 \quad \langle \mathbf{l}_u \cdot \mathbf{S}_p \rangle = +0.5 \quad \langle \mathbf{s}_u \cdot \mathbf{l}_u \rangle = 0 \]
First charge-separated data #1: HERMES

\[ h_1^+(x, k_T) \otimes H_1^-(z, p_T) \rightarrow \cos(2\phi) \text{ modulation} \]

- **hydrogen** → u-quark dominance ...
  → opposite signs for \( h^+ \) and \( h^- \) due to Collins favored-vs-disfav
- **deuterium \approx hydrogen** values! can we understand?
Back-of-envelope estimates for $\langle \cos(2\Phi) \rangle(x)$

Using

$$\delta q(x) \equiv h_{1,q}^\perp(x)$$

for convenience

$$\eta \equiv \frac{\int D_{1,\text{disfav}}}{\int D_{1,\text{fav}}} \simeq 0.35 \quad \frac{\int H_{1,\text{disfav}}^\perp}{\int H_{1,\text{fav}}^\perp} = -1$$

$$\langle \cos(2\Phi) \rangle_H^{\pi_+} \sim \frac{4\delta u_v - \delta d_v}{4u + \eta d + 4\eta \bar{u} + \bar{d}}$$

$$\langle \cos(2\Phi) \rangle_H^{\pi_-} \sim \frac{-4\delta u_v + \delta d_v}{4\eta u + d + 4\bar{u} + \eta \bar{d}}$$

$$\langle \cos(2\Phi) \rangle_D^{\pi_+} \sim \frac{3\delta u_v + 3\delta d_v}{(4 + \eta)(u + d) + (4\eta + 1)(\bar{u} + \bar{d})}$$

$$\langle \cos(2\Phi) \rangle_D^{\pi_-} \sim \frac{-3\delta u_v - 3\delta d_v}{(4\eta + 1)(u + d) + (4 + \eta)(\bar{u} + \bar{d})}$$
Back-of-envelope estimates for $\langle \cos(2\Phi) \rangle(x)$

Using

$\delta q(x) \equiv h_{1,q}^\perp(x)$ for convenience

$\eta \equiv \frac{\int D_{1,\text{disfav}}}{\int D_{1,\text{fav}}} \approx 0.35 \quad \frac{\int H_{1,\text{disfav}}^\perp}{\int H_{1,\text{fav}}^\perp} = -1$

$\langle \cos(2\Phi) \rangle_H^+ \sim \frac{4\delta u_v - \delta d_v}{4u + \eta d + 4\eta \bar{u} + \bar{d}}$

$\langle \cos(2\Phi) \rangle_D^+ \sim \frac{3\delta u_v + 3\delta d_v}{(4 + \eta)(u + d) + (4\eta + 1)(\bar{u} + \bar{d})}$

$\langle \cos(2\Phi) \rangle_H^- \sim \frac{-4\delta u_v + \delta d_v}{4\eta u + d + 4\bar{u} + \eta \bar{d}}$

$\langle \cos(2\Phi) \rangle_D^- \sim \frac{-3\delta u_v - 3\delta d_v}{(4\eta + 1)(u + d) + (4 + \eta)(\bar{u} + \bar{d})}$

$\eta = 0.35$

Model: $h_{1,q}^\perp = -q$ for all flavours $q$
Back-of-envelope estimates for $\langle \cos(2\phi) \rangle(x)$

Using $\delta q(x) \equiv h_{1,q}^\perp(x)$ for convenience

$$\langle \cos(2\phi) \rangle_H^+ \sim \frac{4\delta u_v - \delta d_v}{4u + \eta d + 4\eta \bar{u} + \bar{d}}$$

$$\langle \cos(2\phi) \rangle_H^- \sim \frac{-4\delta u_v + \delta d_v}{4\eta u + d + 4\bar{u} + \eta \bar{d}}$$

$$\langle \cos(2\phi) \rangle_D^+ \sim \frac{3\delta u_v + 3\delta d_v}{(4 + \eta)(u + d) + (4\eta + 1)(\bar{u} + \bar{d})}$$

$$\langle \cos(2\phi) \rangle_D^- \sim \frac{-3\delta u_v - 3\delta d_v}{(4\eta + 1)(u + d) + (4 + \eta)(\bar{u} + \bar{d})}$$

$$\eta \equiv \frac{\int D_{1,\text{disfav}}}{\int D_{1,\text{fav}}} \simeq 0.35 \quad \frac{\int H_{1,\text{disfav}}}{\int H_{1,\text{fav}}} = -1$$

Model: $h_{1,q}^\perp = -q$ for all flavours $q$

Model: $h_{1,q}^\perp = -q$ for $u, \bar{u}$, $h_{1,q}^\perp = -1.6q$ for $d, \bar{d}$

Using $\delta q(x) \equiv h_{1,q}^\perp(x)$ for convenience,

$$\langle \cos(2\phi) \rangle_H^+ \sim \frac{4\delta u_v - \delta d_v}{4u + \eta d + 4\eta \bar{u} + \bar{d}}$$

$$\langle \cos(2\phi) \rangle_H^- \sim \frac{-4\delta u_v + \delta d_v}{4\eta u + d + 4\bar{u} + \eta \bar{d}}$$

$$\eta \equiv \frac{\int D_{1,\text{disfav}}}{\int D_{1,fav}} \simeq 0.35$$

$$\frac{\int H_{1,\text{disfav}}}{\int H_{1,fav}} = -1$$

$$\langle \cos(2\phi) \rangle_D^+ \sim \frac{3\delta u_v + 3\delta d_v}{(4 + \eta)(u + d) + (4\eta + 1)(\bar{u} + \bar{d})}$$

$$\langle \cos(2\phi) \rangle_D^- \sim \frac{-3\delta u_v - 3\delta d_v}{(4\eta + 1)(u + d) + (4 + \eta)(\bar{u} + \bar{d})}$$

**Hydrogen–Deuterium similarity $\rightarrow$ same sign for Boer-Mulders $u$ & $d$!**
very
different
picture!

First charge-separated data #2: COMPASS

COMPASS 2004 $^6 \text{LiD}$ (part)

$A^D_{\cos 2\phi}$

$h^+$

$p\text{preliminary}$

$A^D_{\cos 2\phi}$

$h^-$

$10^{-2}$

$10^{-1}$

$x$

$0.4$

$0.6$

$z$

V. Barone, A. Prokudin, B.Q. Ma

errors shown are statistical only

Wolfgang Käfer, Traversity08 @ Ferrara
very different picture!

**COMPASS**

First charge-separated data #2: COMPASS

\[ A_D \cos 2\phi \]

\[ h^+ \quad \text{preliminary} \]

\[ h^- \]

\[ \cos(2\phi) \] well explained by dominant Cahn effect!

... while Cahn contribution seems small at HERMES!

Challange for theory!

V. Barone, A. Prokudin, B. Q. Ma

errors shown are statistical only

Wolfgang Käfer, Traversity08 @ Ferrara
Summary: Newest Highlights in Transverse Spin

New COMPASS results 2007 H↑ target & 2003-04 D↑ with RICH

- D↑ target essential complement to HERMES H↑
- H↑ Collins: confirms HERMES results @ higher scales
- H↑ Sivers: consistent with zero \(\rightarrow\) unexpected

New BELLE results on Collins and (soon) many other fragmentation functions essential to analysis of DIS and pp data

First charge-separated data on \(\cos(\Phi)\) and \(\cos(2\Phi)\) from HERMES and COMPASS

- Cahn effect more-or-less as expected for \(h^+\)
- Cahn effect discrepancy for \(h^-\) betw HERMES & COMPASS
- \(\cos(2\Phi)\) from HERMES agrees with Boer-Mulders expectations
- \(\cos(2\Phi)\) from COMPASS indicates dominant Cahn contribution!

Many new results skipped ... please see C.Aidala → pp, J.C.Peng → DY ... and all the other fabulous talks at SPIN08!