Recent Measurements of the $\cos(n\phi_h)$ Azimuthal Modulations of the Unpolarized Deep Inelastic Scattering Cross-section at HERMES

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on behalf of the HERMES collaboration

Theory & Experimental Introduction
Procedure
$\cos(\phi_h)$ Results & Model
$\cos(2\phi_h)$ Results & 3 Models
Spin, orbital motion, quarks, and protons

- Cahn
  \[ f(x)D(z) \]
  - Kinematic effect
  - Known since EMC
  - Sensitive to \(<k_T>\)

Cahn \( \Rightarrow \cos(\phi_h) \)

Boer-Mulders

Boer-Mulders \( \Rightarrow \cos(2\phi_h) \)

Unpolarized target
The LO, subleading twist (3) unpolarized SIDIS cross section

\[
\frac{d\sigma}{dx \, dy \, dz \, dP_{h\perp}^2 \, d\phi_h} =
\]

\[
2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left[ F_{UU,T} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} \right]
\]

\[
F_{UU,T} = C[f_1D_1]
\]

\[
F_{UU}^{\cos\phi_h} = \frac{2M}{Q} C \left[ -\frac{\hat{P}_{h\perp} \cdot k_T}{M_h} \frac{p_T^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp} \cdot p_T}{M} f_1D_1 + \ldots \right]
\]

\[
F_{UU}^{\cos(2\phi_h)} = C \left[ -\frac{2(\hat{P}_{h\perp} \cdot k_T)(\hat{P}_{h\perp} \cdot p_T) - k_T \cdot p_T}{MM_h} h_1^\perp H_1^\perp \right]
\]
The LO, subleading twist (3) unpolarized SIDIS cross section

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\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} = 2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left[ F_{UU,T} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} \right]
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\[
F_{UU}^{\cos(2\phi_h)} = C \left[ -\frac{2(\hat{P}_{h\perp} \cdot k_T)(\hat{P}_{h\perp} \cdot p_T) - k_T \cdot p_T}{MM_h} \right] h_1^\perp H_1^\perp
\]
The LO, subleading twist (3) unpolarized SIDIS cross section

\[ \frac{d\sigma}{dx
dy
dz
dP_{h\perp}^2
d\phi_h} = \]

\[ 2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \left[ F_{UU,T} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} \right] \]

\[ F_{UU,T} = C[f_1 D_1] \]

\[ F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ -\frac{\hat{P}_h \cdot k_T}{M_h} p_T^2 h_1^\perp H_1^\perp - \frac{\hat{P}_h \cdot p_T}{M} f_1 D_1 + \ldots \right] \]

\[ F_{UU}^{\cos(2\phi_h)} = C \left[ -\frac{2(\hat{P}_h \cdot k_T)(\hat{P}_h \cdot p_T) - k_T \cdot p_T}{M M_{h}} h_1^\perp H_1^\perp \right] \]
The LO, subleading twist (3) unpolarized SIDIS cross section

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\frac{d\sigma}{dx
dy
dz
dP_{h\perp}^2
d\phi_h} =
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\[
2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left[F_{UU,T} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}\right]
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F_{UU,T} = C[f_1D_1]
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\[
F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[-\frac{\hat{P}_{h\perp} \cdot k_T}{M_h} \frac{p_T^2}{M^2} h_1^+ H_1^+ - \frac{\hat{P}_{h\perp} \cdot p_T}{M} f_1 D_1 + \ldots\right]
\]

\[
F_{UU}^{\cos(2\phi_h)} = C \left[-\frac{2(\hat{P}_{h\perp} \cdot k_T)(\hat{P}_{h\perp} \cdot p_T) - k_T \cdot p_T}{M M_h} h_1^+ H_1^+\right]
\]
The LO, subleading twist (3) unpolarized SIDIS cross section

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\frac{d\sigma}{dx\, dy\, dz\, dP^2_{h\perp}\, d\phi_h} = 2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left[F_{UU,T} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}\right]
\]

\[F_{UU,T} = C[f_1D_1]\]

\[F_{UU}^{\cos\phi_h} = \left(\frac{2M}{Q}\right) C \left[ -\frac{\hat{P}_{h\perp} \cdot k_T}{M_h} \frac{p_T^2}{M^2} h_{1\perp}^\perp H_{1\perp}^\perp - \frac{\hat{P}_{h\perp} \cdot p_T}{M} f_1D_1 + \ldots \right]
\]

\[F_{UU}^{\cos(2\phi_h)} = C \left[ -\frac{2(\hat{P}_{h\perp} \cdot k_T)(\hat{P}_{h\perp} \cdot p_T) - k_T \cdot p_T}{MM_h} h_{1\perp}^\perp H_{1\perp}^\perp \right]
\]
The LO, subleading twist (3) unpolarized SIDIS cross section

\[
\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} = 2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \epsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left[F_{UU,T} + \sqrt{2\epsilon(1 + \epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}\right]
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F_{UU,T} = C[f_1D_1]
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F_{UU}^{\cos\phi_h} = \left(\frac{2M}{Q}\right) C \left[-\frac{\hat{P}_{h\perp} \cdot k_T}{M_h} \frac{p_T^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp} \cdot p_T}{M} \frac{f_1 D_1}{M} + \ldots\right]
\]

\[
F_{UU}^{\cos(2\phi_h)} = C \left[-\frac{2(\hat{P}_{h\perp} \cdot k_T)(\hat{P}_{h\perp} \cdot p_T) - k_T \cdot p_T}{MM_h} h_1^\perp H_1^\perp\right] + X \frac{1}{Q^2} f_1 D_1
\]
The unpolarized SIDIS cross section

\[
\frac{d\sigma}{dx \, dy \, dz \, dP_{h\perp}^2 \, d\phi_h} = 2\pi \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \epsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left[F_{UU,T} + \sqrt{2\epsilon(1 + \epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}\right]
\]

\[= A + B \cos(\phi_h) + C \cos(2\phi_h)\]

\[
2\langle\cos(\phi_h)\rangle = 2 \frac{\int \cos(\phi_h) d^5\sigma}{\int d^5\sigma} = \frac{B}{A}
\]

\[
2\langle\cos(2\phi_h)\rangle = 2 \frac{\int \cos(2\phi_h) d^5\sigma}{\int d^5\sigma} = \frac{C}{A}
\]
The HERA Accelerator at DESY
Hamburg Germany
The HERMES Spectrometer

27.6 GeV $e^\pm$ beam

Rebecca Lamb

CIPANP San Diego, CA May 29, 2009
The HERMES Spectrometer

- Field Clamps
- Drift Chambers
- Trigger Hodoscope H1
- Preshower (H2)
- Luminosity Monitor
- Steel Plate
- Gas Target
- 27.6 GeV $e^\pm$ Beam
- 10M DIS unpolarized H 0.0006e-
- 10M DIS unpolarized D 0.0005

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The HERMES Spectrometer

27.6 GeV $e^\pm$ beam

27.6 GeV $e^\pm$ beam

10M DIS unpol $H$ 00.06e-

10M DIS unpol $D$ 00.05

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The HERMES Spectrometer

- Tracking Chambers
- Lepton / Hadron identification >98% efficiency

27.6 GeV $e^\pm$ beam

10M DIS unpol H 00,06\(e^-\)
10M DIS unpol D 00,05
Procedure
Analysis Challenge!

Monte Carlo:

- Generated in $4\pi$
- Measured inside acceptance

Our acceptance and QED radiation generate $\cos(n\phi_h)$ moments which depend on $x$, $y$, $z$, $p_{h\perp}$, and so does PHYSICS!
Azimuthal Moments due to QED Initial and Final State Radiation

**ISR**

\[ q = k - k' \]
\[ w = k' - k_{\text{meas}} \]
\[ q_{\text{meas}} = k - k_{\text{meas}} = k - k' + w = q + w \]

**FSR**

\[ q = k - k' \]
\[ w = k_{\text{meas}} - k \]
\[ q_{\text{meas}} = k_{\text{meas}} - k' = k + w - k' = q + w \]
Azimuthal Moments due to QED Initial and Final State Radiation

**ISR**

\[ q = k - k' \]
\[ w = k' - k_{meas} \]
\[ q_{meas} = k - k_{meas} = k - k' + w = q + w \]

\[ \phi_{h(true)} = 0^\circ \]
\[ \phi_{h(meas)} = 180^\circ \]

**FSR**

\[ q = k - k' \]
\[ w = k_{meas} - k \]
\[ q_{meas} = k_{meas} - k' = k + w - k' = q + w \]

\[ \phi_{h(true)} = 0^\circ \]
\[ \phi_{h(meas)} = 180^\circ \]
Unfolding for detector and QED radiative effects

Probability that an event at true born kinematics $j_{\text{born}}$ is measured at kinematics $i_{\text{meas}}$

$$
\sigma_{\text{meas}}(i_{\text{meas}}) = \sum_{j=1}^{N} S(i_{\text{meas}}, j_{\text{born}}) \sigma_{\text{true}}(j_{\text{born}}) + \sigma_{\text{bkg}}(i)
$$

What we actually measure

What we'd like to know!

Events smeared in from outside DIS cuts (MC)

Fully tracked Pythia MC

$$
S(i_{\text{meas}}, j_{\text{born}}) = \frac{\sigma_{\text{meas}}(i_{\text{meas}}, j_{\text{born}})}{\sigma_{\text{born}}(j_{\text{born}})}
\quad 4\pi \text{ Pythia MC}
$$
Five Dimensional Binning

- A **model independent** correction can be made with
  - bins in all 5 independent variables (max # for SIDIS!)
  - infinitely small bins sizes
  - no smearing in from outside DIS region (background)

- Given limited statistics, we have bin edges:

  \[
  \begin{align*}
  x &= 0.023 \ 0.042 \ 0.078 \ 0.145 \ 0.27 \ 1 \\
  y &= 0.3 \ 0.45 \ 0.6 \ 0.7 \ 0.85 \\
  z &= 0.2 \ 0.3 \ 0.45 \ 0.6 \ 0.75 \ 1 \\
  P_{h\perp} &= 0.05 \ 0.2 \ 0.35 \ 0.5 \ 0.75 \\
  \phi &= 12 \text{ bins}
  \end{align*}
  \]

  **400 kinematic bins \times 12 \phi_h \text{ bins} = 4800 \text{ bins}**
  - Highest z bin not included in projections vs other variables

- With the additional DIS cuts
  - $Q^2 > 1 \text{ GeV}$
  - $W^2 > 10 \text{ GeV}$
Analysis Summary

1. 4800 measurements are unfolded and fit in 400 bins

\[
\frac{d\sigma}{dx \, dy \, dz \, dP_{h\perp}^2 \, d\phi_h} = A + B \cos(\phi_h) + C \cos(2\phi_h)
\]

2. 400 moments are calculated

\[
2\langle \cos(\phi_h) \rangle = \frac{B}{A} \quad \quad 2\langle \cos(2\phi_h) \rangle = \frac{C}{A}
\]

3. 1-dimensional projections are calculated as the integral over the other 3 variables

\[
\langle \cos(\phi_h) \rangle(x) = \frac{\sum_{y,z,P_{h\perp}} \sigma^{4\pi}(x,y,z,P_{h\perp}) \, \langle \cos \phi_h \rangle(x,y,z,P_{h\perp})}{\sum_{y,z,P_{h\perp}} \sigma^{4\pi}(x,y,z,P_{h\perp})}
\]
Analysis Summary

1. 4800 measurements are unfolded and fit in 400 bins

\[
\frac{d\sigma}{dx
dx dy dz
dP_{h\perp}^2 d\phi_h} = A + B \cos(\phi_h) + C \cos(2\phi_h)
\]

2. 400 moments are calculated

\[
2\langle \cos(\phi_h) \rangle = \frac{B}{A} \\
2\langle \cos(2\phi_h) \rangle = \frac{C}{A}
\]

3. 1-dimensional projections are calculated as the integral over the other 3 variables

\[
\langle \cos(\phi_h) \rangle(x) = \frac{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp} \sigma_{4\pi}^4(x, y, z, P_{h\perp}) \langle \cos \phi_h \rangle(x, y, z, P_{h\perp})}{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp} \sigma_{4\pi}^4(x, y, z, P_{h\perp})}
\]
Monte Carlo test

- One MC production as “data” $<\cos(\phi_h)> = \text{Cahn Model}$
- A different MC production used to unfold $<\cos(\phi_h)> = 0$

Unfolded in 5D
- Cahn Model in $4\pi$
- Unfolded in 1D -> Inaccurate!!
Monte Carlo test

- One MC production as “data” $\langle \cos(\phi_\text{h}) \rangle =$ Cahn Model
- A different MC production used to unfold $\langle \cos(\phi_\text{h}) \rangle =$ 0

Unfolded in 5D

Unfolded in 1D $\rightarrow$ Inaccurate!!

$\blacksquare$ Unfolded in 5D

$\blacksquare$ Cahn Model in $4\pi$

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$\langle \cos(\phi_h) \rangle$ Results and Interpretation

\[
F_{UU}^{\cos \phi_h} = \left( \frac{2M}{Q} \right) C \left[ -\frac{\hat{P}_{h\perp} \cdot k_T}{M_h} \frac{p_T^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp} \cdot p_T}{M} f_1 D_1 + \ldots \right]
\]

Cahn+Boer-Mulders

interaction dependent terms
\[ \langle \cos(\phi_h) \rangle \] Results and Interpretation

![Graph showing results and interpretation](image-url)
<\cos(\phi_h)> Results and Interpretation

Data:
- H and D results very similar
- h+ and h- results differ

Questions:
- What can we learn about intrinsic \( <k_T> \) of quarks?

\[
F^{\cos \phi_h}_{UU} = \left( \frac{2M}{Q} \right) C \left[ -\frac{\hat{P}_h \cdot k_T}{M_h} \frac{p_T^2}{M^2} h_\perp^1 H_\perp^1 - \frac{\hat{P}_h \cdot p_T}{M} f_1 D_1 + \ldots \right]
\]

Cahn+Boer-Mulders

interaction dependent terms
\[ \langle \cos(\phi_h) \rangle \] Results and Interpretation

M. Anselmino et al., Phys Rev D71:074006, 2005

\[ \langle \cos(\phi_h) \rangle \]

<cos(\phi_h)> Results and Interpretation

M. Anselmino et al., Phys Rev D71:074006, 2005
$\langle \cos(\phi_h) \rangle$ Results and Interpretation

M. Anselmino et al., Phys Rev D71:074006, 2005
\[ \langle \cos(\phi_h) \rangle \] Results and Interpretation

M. Anselmino et al., Phys Rev D71:074006, 2005

Hydrogen
\[ \langle \cos(\phi_h) \rangle_{uu} \]

HERMES Preliminary
\[ \langle \cos(\phi_h) \rangle \] Results and Interpretation

M. Anselmino et al., Phys Rev D71:074006, 2005

Cahn-only doesn’t describe data. Too large?
\[ <\cos(2\phi_h)> \text{ Results and Interpretation} \]

\[ F_{UU}^{\cos(2\phi_h)} = C \left[ -\frac{2(\hat{P}_h \perp \cdot k_T)(\hat{P}_h \perp \cdot p_T)}{M M_h} - k_T \cdot p_T \right] + X \frac{1}{Q^2} f_1 D_1 \]

- Boer-Mulders
- Collins
- Boer-Mulders
- twist-4 Cahn
<cos(2φ_h)> Results and Interpretation

\(<\cos(2\phi_h)\>\) Results and Interpretation

Data:
- H and D results very similar
- \(h^+ \sim 0\), slightly negative
- \(h^-\) clearly positive

Questions:
- Is \(<\cos(2\phi)\>\) a clean probe of \(h_{1\perp}^1\)?
- What is the relative sign of \(h_{1\perp}^{1u}\) and \(h_{1\perp}^{1d}\)?

\[
F_{UUU}^{\cos(2\phi_h)} = C \left[ -\frac{2(\hat{P}_{h\perp} \cdot k_T)(\hat{P}_{h\perp} \cdot p_T) - k_T \cdot p_T}{M M_h} h_{1\perp}^1 H_{1\perp}^1 \right] + X \frac{1}{Q^2} f_1 D_1
\]
Model 1

\( \langle \cos(2 \phi_h) \rangle \): Model 1
Gamberg et al.

Same sign u and d Boer–Mulders function from a diquark spectator model

Collins calculated in the spectator framework
\[ \langle \cos(2\phi_h) \rangle: \text{Model 1} \]

Gamberg et al.


\[\begin{align*}
\langle \cos(2\phi_h) \rangle & = \text{Model 1} \\
\end{align*}\]
\[ \langle \cos(2\phi_h) \rangle: \text{Model 1} \]

Gamberg et al.


Diquark spectator model does well... without Cahn term
\[ \langle \cos(2\phi_h) \rangle : \text{Model 1} \]

Gamberg et al.


Update in the works!

Diquark spectator model does well... without Cahn term
Model 2

$\langle \cos(2\phi_h) \rangle$: Model 2
Barone et al.

Same sign $u$ and $d$ Boer-Mulders function
taken as a scaled Sivers function

Collins parameterization to SIDIS and $e^+e^-$ from

Sivers fit to SSA data taken from
M. Anselmino et al.,

anomalous tensor magnetic moment
anomalous magnetic moment

$$h_1^q \sim -\kappa_T^q$$
$$f_{1T}^q \sim -\kappa^q$$

$$h_1^q(x, k_T^2) = \frac{\kappa_T^q}{\kappa^q} f_{1T}^q(x, k_T^2)$$

$$h_1^u = 1.80 f_{1T}^u$$
$$h_1^d = -0.94 f_{1T}^d$$
\[ \langle \cos(2\phi_h) \rangle \text{: Model 2} \]


Barone et al.

Same sign $u$ and $d$ Boer-Mulders function taken as a scaled Sivers function

\[ h_1^{\perp q}(x, k_T^2) = \frac{\kappa_T^q}{\kappa_T^q} f_{1T}^{\perp q}(x, k_T^2) \]

\[ h_1^{\perp u} = 1.80 f_{1T}^{\perp u} \]

\[ h_1^{\perp d} = -0.94 f_{1T}^{\perp d} \]

anomalous tensor magnetic moment

anomalous magnetic moment

PLUS Cahn twist-4 contribution
\[ \langle \cos(2\phi_h) \rangle: \text{Model 2} \]

Barone et al.

\[ \langle \cos(2\phi_h) \rangle \]

- All contributions
- Boer-Mulders
- Cahn (twist 4)

Hydrogen
\[ \langle \cos(2\phi_h) \rangle \]

- \( h^- \)
- \( h^+ \)

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\[ <\cos(2\phi_h)>: \text{Model 2} \]

Barone et al.

\[ \begin{align*}
&\cos(2\phi_h) \\
&\text{All contributions} \\
&\text{Boer-Mulders} \\
&\text{Cahn (twist 4)}
\end{align*} \]

Cahn (twist 4) too large?


\[ <\cos(2\phi_h)>: \text{Model 2} \]

\[ \begin{align*}
&\text{Hydrogen} \\
&h^- \\
&h^+
\end{align*} \]

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NEW work to update the twist-4 Cahn contribution

"standard" values $\langle k_\perp^2 \rangle = 0.25 \text{ GeV}^2$ $\langle p_\perp^2 \rangle = 0.2 \text{ GeV}^2$
NEW work to update the twist-4 Cahn contribution

\[ \langle k_T^2 \rangle = 0.18 \text{ GeV}^2 \quad \langle p_{\perp}^2 \rangle = 0.42 \cdot (1 - z)^{0.54} \cdot z^{0.37} \text{ GeV}^2 \]

More work needs to be done to understand \( \langle k_T^2 \rangle \) before BM can be cleanly extracted.
Model 3

\[ \langle \cos(2 \phi_h) \rangle : \text{Model 3} \]

Zhang et al.

Boer-Mulders extracted from unpolarized p+D Drell-Yan data

\[ h_{1,q}^\perp(x, k_T^2) = h_{1,q}^\perp(x) \exp(-k_T^2/p_{bm}^2), \]

\begin{align*}
  h_{1,u}^\perp(x) &= \omega H_u x_c (1 - x) f_1^u(x), \\
  h_{1,d}^\perp(x) &= \omega H_d x_c (1 - x) f_1^d(x), \\
  h_{1,\bar{u}}^\perp(x) &= \frac{1}{\omega} H_{\bar{u}} x_c (1 - x) f_1^{\bar{u}}(x), \\
  h_{1,\bar{d}}^\perp(x) &= \frac{1}{\omega} H_{\bar{d}} x_c (1 - x) f_1^{\bar{d}}(x),
\end{align*}

Set II:

Boer-Mulders extracted assuming

\( h_{1,u}^\perp \) and \( h_{1,d}^\perp \) of opposite signs

\( \rightarrow \) results in large \( h_{1}^\perp \) for antiquarks

Collins parameterization to SIDIS and e+e- from


\( f_1 \) MRST2001 LO

D₁ Kretzer
$<\cos(2\phi_h)>$: Model 3

Zhang et al.

Same sign $u$ and $d$
\[ \langle \cos(2\phi_h) \rangle: \text{Model 3} \]

Opposite sign \( u \) and \( d \)

\[
\langle \cos(2\phi_h) \rangle: \text{Hydrogen vs Deuterium}
\]

in the (roughly implemented) Zhang model

Caveats of this rough version of the model

- PDFs
  - \( k_T \) dependence not included
  - Different unpolarized PDFs used

- FFs
  - Full Collins functions not included
  - Just a constant ratio of favored/disfavored used

- Overall normalization missing
- Extra(??) -1 needed to get sign
- \( \nu \leftrightarrow \langle \cos(2\phi) \rangle \) ??
- sign of Collins??

Using:

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

\[
\eta \equiv \frac{\int D_{1,\text{disf}}}{\int D_{1,\text{fav}}} \simeq 0.35
\]

\[
\langle \cos(2\phi) \rangle_H^+ \sim \frac{4\delta_{uv} - \delta_{dv}}{4u + \eta d + 4\eta \bar{u} + \bar{d}}
\]

\[
\langle \cos(2\phi) \rangle_H^- \sim \frac{-4\delta_{uv} + \delta_{dv}}{4\eta u + d + 4\bar{u} + \eta \bar{d}}
\]

\[
\langle \cos(2\phi) \rangle_D^+ \sim \frac{3\delta_{uv} + 3\delta_{dv}}{(4 + \eta)(u + d) + (4\eta + 1)(\bar{u} + \bar{d})}
\]

\[
\langle \cos(2\phi) \rangle_D^- \sim \frac{-3\delta_{uv} - 3\delta_{dv}}{(4\eta + 1)(u + d) + (4 + \eta)(\bar{u} + \bar{d})}
\]
Set 1 & Set 2 similar shape & relative size

\begin{align*}
\langle \cos(2\phi_h) \rangle: \text{Hydrogen vs Deuterium} \\
in the (roughly implemented) Zhang model
\end{align*}
$\langle \cos(2\phi_h) \rangle$: Hydrogen vs Deuterium
in the (roughly implemented) Zhang model

So given that we are doing something reasonable for $H$, let's calculate $D$...

Set 1
Like the data
$H \sim D$

Set 2
Not like the data
$H \sim \text{large } D \sim 0$

We MUST use $H$ AND $D$ data to determine the u/d sign!!!
What's next?

- Our dual-radiator RICH has **improved** software for beautifully identified **pions**, kaons, and protons.

- This analysis: \(~1.5\text{M SIDIS on both H and D}\)
  
  Additional \(~5\text{M SIDIS on both H and D available}\)

- Novel 1D projections that
  - Reach to higher \(P_{h\perp}\)
  - Strive to disentangle our \(x - Q^2\) dependence
Conclusions

NEW HERMES results!

• $<\cos(\phi_h)>$ and $<\cos(2\phi_h)>$ on Hydrogen and Deuterium

• $<\cos(\phi_h)>$
  • $h^+ \neq h^-$
    • $<k_T>^u \neq <k_T>^d$ ??
    • $(h_1^\perp \times H_1^\perp)^{\pi^+} \neq (h_1^\perp \times H_1^\perp)^{\pi^-}$ significant??

• $<\cos(2\phi_h)>$
  • Sensitive to Boer–Mulders DF
  • Twist–4 Cahn term must be taken into account!!
  • Models for D essential in determining $u / d$ relative sign

• Cahn and BM both contribute to both $<\cos(\phi_h)>$ and $<\cos(2\phi_h)>$

• Comprehensive models needed (BM+Cahn, H&D, $<\cos(\phi_h)>$&$<\cos(2\phi_h)>$

• Challenge: reconcile HERMES and COMPASS results
  • Different kinematic range?
Backup Slides
Existing Measurements

\[ 2(\cos(2\phi_h))_{UU} \]

Deuterium

- \( h^- \)
- \( h^+ \)

\[ A_{\cos 2\phi} \]

\[ P_T \]

HERMES Preliminary

Rebecca Lamb

CIPANP San Diego, CA May 29, 2009
Existing Measurements

\[ \cos(2\phi_h) \]
Existing Measurements

\( \cos(\phi_h) \)

- **E665**
  - Plot showing data points and curves for \( \langle \cos(\phi_h) \rangle \) vs. \( P_T^{\text{cut}} \) (GeV/c).

- **ZEUS**
  - Plot showing data points and curves for \( \langle \cos(\phi_h) \rangle \) vs. \( P_T^{\text{cut}} \) (GeV/c).

- **EMC**
  - Plot showing data points and curves for \( \langle \cos(\phi_h) \rangle \) vs. \( x_F \).
Existing Measurements

COMPASS  2004 $^6$LiD (part)

$A_D$ vs $x$, $z$, $P_T$ [GeV/c]

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Semi-Inclusive
Deep Inelastic Scattering

\[ Q^2 = -q^2 \]
\[ x = \frac{Q^2}{2P \cdot q} \quad \text{lab} \quad \frac{Q^2}{2M \nu} \]
\[ y = \frac{P \cdot q}{P \cdot k} = \frac{\nu}{E} \]
\[ z = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{\nu} \]
\[ \gamma = \frac{2Mx}{Q} \]
\[ W^2 = (P + q)^2 \quad \text{lab} \quad M^2 + 2M \nu - Q^2 \]