Measurement of azimuthal asymmetries of the unpolarized cross-section at HERMES

Francesca Giordano
Ferrara, Transversity 08
Unpolarized Semi Inclusive DIS (SIDIS)
Unpolarized SIDIS: collinear approximation

\[
\frac{d^3 \sigma}{dx \, dy \, dz} = \frac{\alpha^2}{xyQ^2} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ A(y) \, F_{UU,T} + B(y) \, F_{UU,L} \right\}
\]

\[
F_{\ldots} = F_{\ldots}(x, Q^2, z)
\]

\[
A(y) \approx (1 - y + 1/2y^2) \quad B(y) \approx (1 - y)
\]
Unpolarized SIDIS: non-collinear cross-section

\[
\frac{d^5 \sigma}{dx \ dy \ dz \ d\phi \ dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \left(1 + \frac{\gamma^2}{2x}\right) \left\{A(y) \ F_{UU,T} + B(y) \ F_{UU,L} + C(y) \ \cos \phi \ F_{UU}^{\cos \phi} + B(y) \ \cos 2\phi \ F_{UU}^{\cos 2\phi}\right\}
\]

\[
F_\ldots = F_\ldots (x, Q^2, z, P_{h\perp})
\]

\[
\begin{align*}
A(y) &\approx (1 - y + 1/2 y^2) \\
B(y) &\approx (1 - y) \\
C(y) &\approx (2 - y)\sqrt{1 - y}
\end{align*}
\]
Unpolarized SIDIS:
non-collinear cross-section

\[
\frac{d^5 \sigma}{dx \, dy \, dz \, d\phi \, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ \begin{array}{c}
A(y) \ F_{UU,T} + B(y) \ F_{UU,L} \\
+ C(y) \ \cos \phi \ F_{UU}^{\cos \phi} + B(y) \ \cos 2\phi \ F_{UU}^{\cos 2\phi} \end{array} \right\}
\]

\[
\langle \cos n \phi \rangle = \frac{\int \cos n \phi \ d^5 \sigma}{\int d^5 \sigma}
\]

\[
\int d^5 \sigma = \int dx \, dy \, dz \, dP_{h\perp}^2 \, d\phi \frac{d^5 \sigma}{dx \, dy \, dz \, dP_{h\perp}^2 \, d\phi}
\]
Leading twist expansion

<table>
<thead>
<tr>
<th>Distribution Functions (DF)</th>
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</thead>
<tbody>
<tr>
<td>N / q</td>
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$h_1^\perp = \text{Boer-Mulders function}$

CHIRAL-ODD

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$h_1 \perp = \text{Boer-Mulders function}$

**CHIRAL-ODD**

$h_1 \perp \otimes H_1 \perp$

chiral-odd DF

chiral-odd FF

**CHIRAL-EVEN!**
Structure functions expansion at leading twist

\[ F_{UU}^{\cos2\phi} = C \left[ -\frac{2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right] h_1^\perp H_1^\perp \]
Structure functions expansion at twist 3

\[ F_{UU}^{\cos 2\phi} = C \left[ -\frac{2(\hat{h} \cdot \bar{k}_T)(\hat{h} \cdot \bar{p}_T) - \bar{k}_T \cdot \bar{p}_T}{MM_h} h_1 H_1 \right] \]

\[ F_{UU}^{\cos \phi} = \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot \bar{p}_T}{M_h} \left( xhH_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{D}^\perp}{z} \right) - \frac{\hat{h} \cdot \bar{k}_T}{M} \left( xf_1^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{H}}{z} \right) \right] \]
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F_{UU}^{\cos 2\phi} = C \left[ -\frac{2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} h_1^\perp H_1^\perp \right]
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\]

\[
F_{UU}^{\cos \phi} = \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot \vec{p}_T}{M_h} \left( x\tilde{h} + \frac{\kappa_T^2}{M^2} h_1^\perp \right) \left( x\hat{h}H_1^\perp + \frac{M_h}{M} \frac{\tilde{D}^\perp}{\tilde{z}} \right) - \frac{\hat{h} \cdot \vec{k}_T}{M} \left( xf_1^\perp + f_1 \right) \left( xf_1^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{H}}{\tilde{z}} \right) \right]
\]
Cahn and Boer-Mulders effects

$$F^{\cos^2\phi}_{UU} = C \left[ -\frac{2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right] h_1^\perp H_1^\perp$$

$$F^{\cos\phi}_{UU} = \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot \vec{p}_T}{M_h} x h_1^\perp H_1^\perp - \frac{\hat{h} \cdot \vec{k}_T}{M} x f_1 D_1 \right]$$
Cahn and Boer-Mulders effects

\[ F_{UU}^{\cos 2\phi} = C \left[ -\frac{2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{M M_h} \cdot h_1^\perp H_1^\perp \right] \]

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Experimental status: $\langle \cos \phi \rangle$

- Negative results in all the existing measurements
- No distinction between hadron type or charge
Experimental status: $\langle \cos 2\phi \rangle$

- Positive results in all the existing measurements
- No distinction between hadron type or charge (in SIDIS experiments)
- Indication of small Boer-Mulders function for the sea quark (from Drell-Yan experiments)
HERa MEasurement of Spin

HERA storage ring @ DESY
HERMES spectrometer

Resolution: $\Delta p/p \sim 1\text{-}2\%$ $\Delta \theta < 0.6$ mrad

Electron-hadron separation efficiency $\sim 98\text{-}99\%$

Hadron identification with dual-radiator RICH
HERMES spectrometer

Resolution: $\Delta p/p \sim 1\text{-}2\%$, $\Delta \theta < \sim 0.6\text{ mrad}$

Electron-hadron separation efficiency $\sim 98\text{-}99\%$

Hadron identification with dual-radiator RICH
HERMES spectrometer

Electron-hadron separation efficiency ~ 98-99%

Hadron identification with dual-radiator RICH

2% $\Delta \theta < \sim 0.6$ mrad
Possible Measurements @

- Flavour sensitive results:
  - Distinction of hadron type and charge (thanks to the RICH identification)
  - Results from scattering off different targets (Hydrogen, Deuterium, ...)

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Possible Measurements @ hermes

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Possible access to quark intrinsic transverse momenta via the cahn effect
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Information about the Boer-Mulders distribution function
Possible Measurements @ hermes

Flavour sensitive results:
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Possible access to quark intrinsic transverse momenta via the cahn effect

Information about the Boer-Mulders distribution function

Possible sensitivity to functions related to graphs with an additional gluon ( $\tilde{f}^{\perp}, \tilde{D}^{\perp}, \tilde{h}, \tilde{H}$ )
Extraction method

\[ n^{\text{EXP}} = \int \sigma_0 L(1 + A \cos \phi + B \cos 2\phi) \]

\[ A = 2 \langle \cos \phi \rangle \]

\[ B = 2 \langle \cos 2\phi \rangle \]
Extraction method

\[ n^{\text{EXP}} = \int \sigma_0 L (1 + A \cos \phi + B \cos 2\phi) \varepsilon_{\text{acc}}(\phi) \varepsilon_{\text{RAD}}(\phi) \]
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\[ n^{\text{EXP}} = \int \sigma_0 L (1 + A \cos \phi + B \cos 2\phi) \varepsilon_{\text{acc}} (\phi) \varepsilon_{\text{RAD}} (\phi) \]

\[ n^{\text{EXP}} = \int \sigma_0 L (1 + A_{F_{UU}}) \varepsilon_{\text{acc}} \varepsilon_{\text{RAD}} \]
Extraction method

\[ n^{\text{EXP}} = \int \sigma_0 L (1 + A \cos \phi + B \cos 2\phi) \varepsilon_{\text{acc}}(\phi) \varepsilon_{\text{RAD}}(\phi) \]

\[ n_{\text{MC}} = \int \sigma_0^{\text{MC}} L^{\text{MC}} \varepsilon_{\text{acc}}^{\text{MC}} \varepsilon_{\text{RAD}}^{\text{MC}} \]
Extraction method

\[ n^{\text{EXP}} = \int \sigma_0 L (1 + A \cos \phi + B \cos 2\phi) \varepsilon_{\text{acc}}(\phi) \varepsilon_{\text{RAD}}(\phi) \]

\[ n^{\text{MC}} = \int \sigma_0 L \varepsilon_{\text{MC}}^{\text{MC}} \varepsilon_{\text{acc}}^{\text{MC}} \varepsilon_{\text{RAD}}^{\text{MC}} \]
Extraction method

\[ n^{\text{CAHN}} = \int \sigma_0 L (1 + A \cos \phi + B \cos 2\phi) \varepsilon_{\text{acc}}(\phi) \varepsilon_{\text{RAD}}(\phi) \]

\[ n^{\text{CAHN}} = \int \sigma_0 L (1 + A_{FUU}) \varepsilon_{\text{acc}} \varepsilon_{\text{RAD}} \]

\[ n^{\text{MC}} = \int \sigma_0^{\text{MC}} L^{\text{MC}} \varepsilon^{\text{MC}}_{\text{acc}} \varepsilon^{\text{MC}}_{\text{RAD}} \]

Model for the ‘Cahn effect’ in Monte Carlo
Extraction method

\[ n^{CAHN} = \int \sigma_0 L (1 + A \cos \phi + B \cos 2\phi) \varepsilon_{acc}(\phi) \varepsilon_{RAD}(\phi) \]

Monte Carlo + Cahn model

Standard Monte Carlo
Extraction method

\[
\frac{n_{\text{CAHN}}^{MC}}{n_{\text{MC}}} = \frac{\int \sigma_0 \varepsilon_{acc} \varepsilon_{RAD} L \left(1 + A \cos \phi + B \cos 2\phi\right)}{\int \sigma_0^M C \varepsilon_{acc}^M \varepsilon_{RAD}^M L^M}
\]

(MC+Cahn)/MC
Extraction method

\[
\frac{n^{CAHN}}{n^{MC}} = \frac{\int \sigma_0 \varepsilon_{acc} \varepsilon_{RAD} L \left(1 + A \cos \phi + B \cos 2\phi\right)}{\int \sigma_0^{MC} \varepsilon_{acc}^{MC} \varepsilon_{RAD}^{MC} L^{MC}}
\]

\[
(MC+Cahn)/MC
\]

\[
\sigma_0 = \sigma_0(\bar{x}) \quad \varepsilon_i = \varepsilon_i(\bar{x})
\]

\[
A = A(\bar{x}) \quad B = B(\bar{x})
\]

\[
\bar{x} = (x, y, z, P_{h\perp})
\]
Extraction method

\[ n^{\text{CAHN}} = \frac{\int \sigma_0 \varepsilon_{\text{acc}} \varepsilon_{\text{RAD}} L (1 + A \cos \phi + B \cos 2\phi)}{\int \sigma_0^{MC} \varepsilon_{\text{acc}}^{MC} \varepsilon_{\text{RAD}}^{MC} L^{MC}} \]

\[(\text{MC+Cahn})/\text{MC} \]

\[ \sigma_0 = \sigma_0(\bar{x}) \quad \varepsilon_i = \varepsilon_i(\bar{x}) \]

\[ A = A(\bar{x}) \quad B = B(\bar{x}) \]

\[ \bar{x} = (x, y, z, P_{h\perp}) \]
Extraction method

\[
\frac{n^{\text{CAHN}}}{n^{\text{MC}}} = \frac{\sigma_0 \varepsilon_{\text{acc}} \varepsilon_{\text{RAD}} L}{\sigma_0^{\text{MC}} \varepsilon_{\text{acc}}^{\text{MC}} \varepsilon_{\text{RAD}}^{\text{MC}} L^{\text{MC}}} (1 + A \cos \phi + B \cos 2\phi)
\]

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A = A(\bar{x}) \quad B = B(\bar{x})
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\[
\bar{x} = (x, y, z, P_{h\perp})
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Extraction method

\[ \frac{n^{CAHN}}{n^{MC}} \bar{x} = \frac{\sigma_0 \varepsilon_{acc} \varepsilon_{RAD} L}{\sigma_0^{MC} \varepsilon_{acc}^{MC} \varepsilon_{RAD}^{MC} L^{MC}} (1 + A \cos \phi + B \cos 2\phi) \]

**Fully differential analysis**

<table>
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<th>BINNING</th>
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<tr>
<td>500 kinematical bins × 12 ( \phi )-bins</td>
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<table>
<thead>
<tr>
<th>Variable</th>
<th>Bin limits</th>
<th>#</th>
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<tr>
<td>( y_{bj} )</td>
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<tr>
<td>( z )</td>
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<td>1 5</td>
</tr>
<tr>
<td>( P_{hT} )</td>
<td>0.05 0.2 0.35 0.5 0.75 1.41</td>
<td>5</td>
</tr>
</tbody>
</table>
The method

$P_{h\perp}$

\[ Z \]

\[ \phi \]
The method

\[ P_{h_\perp} \]

\[ Z \]

\[ \phi \]
The method

\[
\langle \cos \phi \rangle (x) = \frac{\sum_i \sigma_i^{4\pi} (x) \langle \cos \phi \rangle_i}{\sum_i \sigma_i^{4\pi} (x)}
\]
The method

$P_{h \perp}$

$Z$

$2 \langle \cos \phi \rangle$

$2 \langle \cos 2\phi \rangle$

Bins

Bins
Fake asymmetries

\[
\frac{n^{MC_1}}{n^{MC_2}} = \frac{\int \sigma_0^{MC_1} \epsilon^{MC}_{acc} \epsilon^{MC}_{RAD} L^{MC_1}}{\int \sigma_0^{MC_2} \epsilon^{MC}_{acc} \epsilon^{MC}_{RAD} L^{MC_2}}
\]
Fake asymmetries

\[
n_{MC_1}^{MC} = \frac{\int \sigma_0^{MC_1} \varepsilon_{acc}^{MC} \varepsilon_{RAD}^{MC} L^{MC_1}}{\int \sigma_0^{MC_2} \varepsilon_{acc}^{MC} \varepsilon_{RAD}^{MC} L^{MC_2}}
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Fake asymmetries

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\frac{n_{MC1}}{n_{MC2}} = \frac{\int \sigma_0^{MC1} \epsilon_{acc}^{MC} \epsilon_{RAD}^{MC} L^{MC1}}{\int \sigma_0^{MC2} \epsilon_{acc}^{MC} \epsilon_{RAD}^{MC} L^{MC2}}
\]
Fake asymmetries

\[
\frac{n^{MC\ 1}}{n^{MC\ 2}} = \int \sigma^{0\ MC\ 1} \ \varepsilon^{MC\ acc} \ \varepsilon^{MC\ RAD} \ L^{MC\ 1} \\
= \int \sigma^{0\ MC\ 2} \ \varepsilon^{MC\ acc} \ \varepsilon^{MC\ RAD} \ L^{MC\ 2}
\]

- ■ One-dimensional analysis
- △ Multidimensional analysis
Fake asymmetries

\[
\frac{n_{MC1}}{n_{MC2}} = \frac{\int \sigma_0^{MC1} \varepsilon_{acc}^{MC} \varepsilon_{RAD}^{MC} L^{MC1}}{\int \sigma_0^{MC2} \varepsilon_{acc}^{MC} \varepsilon_{RAD}^{MC} L^{MC2}}
\]

One-dimensional analysis

Multidimensional analysis

Fully differential analysis is needed
Monte Carlo check

\[ \frac{n_{CAHN}^{MC}}{n_{MC}^{MC}} = \frac{\sigma_0 \varepsilon_{acc} \varepsilon_{RAD} L_{MC}}{\sigma_0^{MC} \varepsilon_{acc}^{MC} \varepsilon_{RAD}^{MC} L_{MC}^{MC}} (1 + A \cos \phi + B \cos 2\phi) \]
Monte Carlo check: $\langle \cos \phi \rangle$

- Cahn Model
- Extracted values
Monte Carlo check: $\langle \cos 2\phi \rangle$
Unfolding procedure

\[ n_{\text{CORR}} = S_{PY}^{-1} \left[ n_{\text{EXP}} - Bg_{PY} \right] \]
Unfolding procedure

\[ n_{\text{CORR}} = S_{PY}^{-1} \left[ n_{\text{EXP}} - Bg_{PY} \right] \]

\[ S_{PY}^{-1} = \text{Inverted Smearing Matrix} \]
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\[ S_{PY}^{-1} = \text{Inverted Smearing Matrix} \]

Depends only on instrumental and radiative effects
Inverted Smearing Matrix

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\[ n_{\text{CORR}} = S_{\text{PY}}^{-1} \left[ n_{\text{EXP}} - Bg_{\text{PY}} \right] \]

Depends only on instrumental and radiative effects
Unfolding procedure
Monte Carlo check

\[ n_{\text{CORR}} = S_{\text{PY}}^{-1} \left[ n_{\text{CAHN}} - Bg_{\text{PY}} \right] \]

Depends only on instrumental and radiative effects
Monte Carlo check: $\langle \cos \phi \rangle$

- Cahn Model
- Extracted values
Monte Carlo check: $\langle \cos 2\phi \rangle$
Accounting for the intrinsic **quark transverse motion** in the unpolarized cross-section gives origin to an azimuthal asymmetry in the hadron production direction; in particular it was stressed the existence of the

- **Cahn effect**: an (higher twist) azimuthal modulation related to the existence of quark intrinsic motion;

- **Boer-Mulders effect**: a leading twist asymmetry originated by the correlation between the quark transverse motion and spin (a kind of *spin-orbit effect*).
Summary & Outlook

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Monte Carlo studies show that:

- A fully differential analysis together with an unfolding procedure is able to disentangle the ‘physical’ azimuthal asymmetry from the acceptance and radiative modulations of the cross-section.
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**Possibilities @ HERMES**

- Information about the Boer-Mulders distribution function;
- Possible access to quark intrinsic transverse momenta via the cahn effect;
- Possible sensitivity to processes with an additional gluon;
- **Flavour sensitive results:**
  - Distinction of hadron type and charge
  - Results from scattering off different targets (Hydrogen, Deuterium, …);
- HERMES collected enough statistics for a fully differential analysis!
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- Possible sensitivity to higher twist effect;
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  - Distinction of hadron type and charge
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