HERMES results on azimuthal modulations in the spin-independent SIDIS cross section

Madrid, DIS 2009

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DESY, Hamburg

For the HERMES collaboration
Unpolarized Semi-Inclusive DIS

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

Collinear approximation

\[ F_\gamma = F_\gamma(x, y, z) \]
Unpolarized Semi-Inclusive DIS

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

Collinear approximation

\[ F_{\ldots} = F_{\ldots}(x, y, z) \]
Unpolarized Semi-Inclusive DIS

\[
\frac{d^5\sigma}{dx\ dy\ dz\ d\phi_h\ dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ A(y)\ F_{UU,T} + B(y)\ F_{UU,L} \right\} \\
+ C(y)\ \cos\phi_h\ F_{UU}^{\cos\phi_h} + B(y)\ \cos2\phi_h\ F_{UU}^{\cos2\phi_h} \right\}
\]

\[
F_{\ldots} = F_{\ldots}(x, y, z, P_{h\perp})
\]
Unpolarized Semi-Inclusive DIS

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

\[
\langle \cos n \phi_h \rangle(x, y, z, P_{h\perp}) = \frac{\int \cos n \phi_h \sigma^{(5)} d\phi_h}{\int \sigma^{(5)} d\phi_h}
\]
Leading twist expansion

\[ F_{UU,T} \propto C[f_1D_1] \]
Leading twist expansion

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

**Distribution Functions (DF)**

<table>
<thead>
<tr>
<th>N / q</th>
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**Fragmentation Functions (FF)**

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Leading twist expansion

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\[ F_{UU,T} \propto C[f_1D_1] \]
Leading twist expansion

\[ h_1 \] = Boer-Mulders function

**CHIRAL-ODD**

\[ C \left[ h_1^\perp H_1^\perp \right] \]

**chiral-odd**

DF

**CHIRAL-EVEN!**

FF

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Leading twist azimuthal modulation

\[ F_{UU}^{\cos 2\phi_h} = C \left[ -\frac{2(\vec{P}_h \cdot \vec{k}_T)(\vec{P}_h \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right] h_{1^\perp} H_{1^\perp} \]

(Implicit sum over quark flavours)
Leading & next to leading twist azimuthal modulation

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

\[ F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ -\frac{\vec{P}_{h\perp} \cdot \vec{p}_T}{M_h} x h_1^\perp H_1^\perp - \frac{\vec{P}_{h\perp} \cdot \vec{k}_T}{M} x f_1 D_1 + \ldots \right] \]

...neglecting interaction dependent terms....

(Implicit sum over quark flavours)
Cahn and Boer-Mulders effects

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

\[
F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ -\frac{\hat{P}_{h\perp} \cdot \vec{p}_T}{M_h} x h_1 H_1 \right] - \frac{\hat{P}_{h\perp} \cdot \vec{k}_T}{M} x f_1 D_1 + \ldots
\]

CAHN EFFECT
Cahn and Boer-Mulders effects

\[ F_{UU}^{\cos \phi} = \frac{2M}{Q} C \left[ -\frac{\vec{P}_{h \perp} \cdot \vec{p}_T}{M_h} x h_1^\perp H_1^\perp - \frac{\vec{P}_{h \perp} \cdot \vec{k}_T}{M} x f_1 D_1 + \ldots \right] \]

\[ F_{UU}^{\cos 2\phi} = C \left[ -\frac{2(\vec{P}_{h \perp} \cdot \vec{k}_T)(\vec{P}_{h \perp} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} h_1^\perp H_1^\perp \right] \]
HERa MEasurement of Spin

HERA storage ring @ DESY
HERMES spectrometer

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

Electron-hadron separation efficiency ~ 98-99%

Hadron identification with dual-radiator RICH
HERMES spectrometer

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

Electron-hadron separation efficiency $\sim 98-99\%$

Hadron identification with dual-radiator RICH
HERMES spectrometer

Aerogel $n=1.03$

$C_4F_{10}$ $n=1.0014$

$p/\Delta \theta \sim 1-2\%$  $\Delta \theta \sim 0.6$ mrad

Electron-hadron separation efficiency $\sim 98-99\%$

Hadron identification with dual-radiator RICH
Experimental extraction

\[ n^{\text{EXP}} = \int \sigma_0(w) \left[ 1 + A(w) \cos \phi_h + B(w) \cos 2\phi_h \right] L \, dw \]

\[ w = (x, y, z, P_{h\perp}) \]

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

\[ B = 2 \langle \cos 2\phi_h \rangle \]
Experimental extraction

\[ n^{\text{EXP}} = \int \sigma_0(w) \left[ 1 + A(w)\cos\phi_h + B(w)\cos2\phi_h \right] \epsilon_{\text{acc}}(w, \phi_h)\epsilon_{\text{RAD}}(w, \phi_h) \ L \ dw \]

\[ w = (x, y, z, P_{h\perp}) \]
Experimental extraction

\[ n^{\text{EXP}} = \int \sigma_0(w) \left[ 1 + A(w) \cos \phi_h + B(w) \cos 2\phi_h \right] \varepsilon_{\text{acc}}(w, \phi_h) \varepsilon_{\text{RAD}}(w, \phi_h) \, L \, dw \]

w = (x, y, z, P_{h\perp})

unfolding procedure
Experimental extraction

\[ n^{\text{EXP}} = \int \sigma_0(w) \left[ 1 + A(w) \cos \phi_h + B(w) \cos 2\phi_h \right] \varepsilon_{\text{acc}}(w, \phi_h) \varepsilon_{\text{RAD}}(w, \phi_h) L \, dw \]

\[ w = (x, y, z, P_{h\perp}) \]

Multidimensional \( (w) \) unfolding procedure
The unfolding procedure

\[ n_{\text{EXP}} = S \ n_{\text{BORN}} + n_{\text{Bg}} \]
The unfolding procedure

\[ n_{\text{EXP}} = S \cdot n_{\text{BORN}} + n_{\text{Bg}} \]

Probability that an event generated with kinematics \( w \) is measured with kinematics \( w' \)
The unfolding procedure

\[ n_{\text{EXP}} = S n_{\text{BORN}} + n_{\text{Bg}} \]

Probability that an event generated with kinematics \( w \) is measured with kinematics \( w' \)

Accounts for acceptance, radiative and smearing effects

\( \Rightarrow \) depends only on instrumental and radiative effects
The unfolding procedure

\[ n_{\text{EXP}} = S \cdot n_{\text{BORN}} + n_{Bg} \]

- Probability that an event generated with kinematics \( w \) is measured with kinematics \( w' \)
- Accounts for acceptance, radiative and smearing effects
- Depends only on instrumental and radiative effects

Includes the events smeared into the acceptance
The unfolding procedure

\[ n_{\text{EXP}} = S \cdot n_{\text{BORN}} + n_{\text{Bg}} \]

\[ n_{\text{BORN}} = S^{-1} \left[ n_{\text{EXP}} - n_{\text{Bg}} \right] \]
Why a multi-dimensional analysis?

\[
n^{MC+Cahn} = \int \sigma_0(w) \left[1 + A(w)\cos\phi_h + B(w)\cos2\phi_h\right] \epsilon_{acc}(w,\phi_h)\epsilon_{RAD}(w,\phi_h) \ L \ dw
\]
Why a multi-dimensional analysis?
Why a multi-dimensional analysis?

4D binned in \((x, y, z, P_{h\perp})\)
The multi-dimensional analysis

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The multi-dimensional analysis
The multi-dimensional analysis

\[
\langle \cos \phi_h \rangle = \frac{\sum \sigma^{A\pi}(\omega_{x_i=x_b}) \langle \cos \phi \rangle_{x_i=x_b}}{\sum \sigma^{A\pi}(\omega_{x_i=x_b})}
\]

projection

First y bin

\( z \)

\( P_{h,\perp} \)

x bin=1

x bin=2

x bin=3

x bin=4

x bin=5
The multi-dimensional analysis

\[
\langle \cos \phi_h \rangle (x_b) = \frac{\int_{0.3}^{0.85} dy \int_{0.05}^{0.2} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma_{A\pi} (\omega_{x_i=x_b}) \langle \cos \phi \rangle (x_i=x_b) \langle \cos \phi \rangle (x_i=x_b)}{\sum \sigma_{A\pi} (\omega_{x_i=x_b}) \langle \cos \phi \rangle (x_i=x_b)}
\]

First y bin

x bin=1
x bin=2
x bin=3
x bin=4
x bin=5
Results
Hydrogen data
Hydrogen data

\[ H_{1}^{\perp, u \rightarrow \pi^{+}} \approx -H_{1}^{\perp, u \rightarrow \pi^{-}} \]

M. Anselmino et al.,
Hydrogen data

\[ F_{UU}^{\cos 2\phi_h} = C \left[ -\frac{2(\hat{P}_{h\perp} \cdot \vec{k}_T)(\hat{P}_{h\perp} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right] \]

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Hydrogen data

\[
F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ -\frac{\hat{P}_{h \perp} \cdot \vec{p}_T}{M_h} x h_1^{\perp} H_1^{\perp} - \frac{\hat{P}_{h \perp} \cdot \vec{k}_T}{M} x f_1 D_1 + \ldots \right]
\]

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H_1^{\perp, u \rightarrow \pi^-} \approx -H_1^{\perp, u \rightarrow \pi^+}
\]
$\cos 2\phi_h$ interpretation

L. P. Gamberg and G. R. Goldstein,
\[ \cos 2\phi_h \] interpretation

\[ \begin{align*}
\pi^+ & \quad \text{HERMES} \\
\pi^- & \\
\end{align*} \]

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

V. Barone et al.
cos2φ_h interpretation

B. Zhang et al.,
\[ \cos \phi_h \] interpretation

**M. Anselmino et al.,**

*Phys. Rev. D71:074006, 2005*

cosφₕ interpretation

\[ F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ -\frac{\vec{P}_{h\perp} \cdot \vec{P}_T}{M_h} x \ h_1^\perp H_1^\perp - \frac{\vec{P}_{h\perp} \cdot \vec{k}_T}{M} x \ f_1 D_1 + \ldots \right] \]
Hydrogen vs. Deuterium data

$h^+_{1,u} \approx h^+_{1,d}$
Hydrogen vs. Deuterium data

\[ h_{1,u} \approx h_{1,d} \]
The existence of an intrinsic **quark transverse motion** gives origin to an azimuthal asymmetry in the hadron production direction:

- **Cahn effect**: an (higher twist) azimuthal modulation related to the existence of intrinsic quark motion;
- **Boer-Mulders effect**: a leading twist asymmetry originated from the correlation between the quark transverse motion and transverse spin (a kind of **spin-orbit effect**).
Summary

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  - A **fully differential unfolding procedure** is essential to disentangle the ‘physical’ azimuthal asymmetry from the acceptance and radiative modulations of the cross-section.
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- **Flavour dependent experimental results:**
  - Negative $<\cos\phi_h>$ **moments** are extracted for positive and negative hadrons, with a larger absolute value for the positive ones
  - The results for the $<\cos2\phi_h>$ **moments** are negative for the positive hadrons and positive for the negative hadrons
    - Evidence of a non-zero Boer-Mulders function
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Compass results
Experimental status: $\langle \cos \phi_h \rangle$

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

- **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)**