The HERMES view on the nucleon's TMD partonic structure
- a small selection from many results -

Gunar.Schnell @ desy.de
[on behalf of the HERMES collaboration]
The HERMES Experiment (†2007)

27.6 GeV polarized $e^+ / e^-$ beam scattered off ...

unpolarized (H, D, He,..., Xe) as well as transversely (H) and longitudinally (H, D) polarized (pure) gas targets
Last* time at LightCone ... 

* HERMES’ previous appearance: August 6th, 2002
First glimpse of transversity?

HERMES 1996/97: longitudinal polarized proton target

transverse component \( S_T \)
of target spin (w.r.t. virtual photon):

\[
S_T \propto \sin \Theta_\gamma \approx \frac{2Mx}{Q} \sqrt{1 - y} \sim 0.15
\]

\( \Rightarrow \) glimpse on transversity?!

Longitudinal target SSA:

\[
A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}
\]
First glimpse of transversity?

HERMES 1996/97: longitudinal polarized proton target

transverse component $S_T$ of target spin (w.r.t. virtual photon):

$$S_T \propto \sin \Theta_\gamma \simeq \frac{2Mx}{Q} \sqrt{1-y} \sim 0.15$$

⇒ glimpse on transversity?!

Longitudinal target SSA:

$$A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

Gunar Schnell (DESY), HERMES Collaboration
First glimpse of transversity?

HERMES 1996/97: longitudinal polarized proton target

transverse component $S_T$ of target spin (w.r.t. virtual photon):

$$S_T \propto \sin \Theta \gamma \approx \frac{2Mx}{Q} \sqrt{1 - y} \sim 0.15$$

⇒ glimpse on transversity?!

Longitudinal target SSA:

$$A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

... or Sivers?
First glimpse of transversity?

**Outlook**

New Target Magnet for HERMES

- Transverse target ($B = 0.295T$)
- High uniformity along beam direction: $\Delta B \leq 4.5 \cdot 10^{-5}T$
- Transversely polarized hydrogen
- Target polarization above 80%

- $\langle \sin \phi \rangle_{UT}$ becomes dominant
- Sivers and Collins distinguishable
- $h_1$ and $H_{1T}^\perp$ as well as $f_{1T}^\perp$ accessible
First glimpse of transversity?

**Outlook**

New Target Magnet for HERMES

- **Transverse target** \((B = 0.295T)\)
- **High uniformity along beam direction:** \(\Delta B \leq 4.5 \cdot 10^{-5}T\)
- **Transversely polarized hydrogen**
- **Target polarization above 80%**

- \(\langle \sin \phi \rangle_{UT}\) becomes dominant
- Sivers and Collins distinguishable
  \(\leftrightarrow h_1\) and \(H_1^T\) as well as \(f_{1T}^\perp\) accessible
First glimpse of transversity?

**Outlook**

**New Target Magnet for HERMES**
- Transverse target \((B = 0.295T)\)
- High uniformity along beam direction:
  \[ \Delta B \leq 4.5 \cdot 10^{-5}T \]
- Transversely polarized hydrogen
- Target polarization above 80%

\[ S_T \propto \sin \Theta_\gamma \simeq \frac{2Mx}{Q} \sqrt{1 - y} \sim 0.15 \]

⇒ glimpse on transversity?!

**HERMES 1996/97**
- Longitudinal polarized proton target
  \( S_T \) of target spin (w.r.t. virtual photon):
  \[ S_T \propto \sin \Theta_\gamma \simeq \frac{2Mx}{Q} \sqrt{1 - y} \sim 0.15 \]

⇒ glimpse on transversity?

**Longitudinal target SSA**

\[ A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi)}{N^-(\phi)} \]

\[ A(\phi) = P_1 + P_2 \sin(\phi) \]

\[ P_1 = -0.001 \pm 0.005 \]

\[ P_2 = 0.019 \pm 0.007 \]

\[ \langle \sin \phi \rangle_{UL} \text{ becomes dominant} \]

\[ \text{Sivers and Collins distinguishable} \]

\[ h_1 \text{ and } H_1^\perp \text{ as well as } f_{1T}^\perp \text{ accessible} \]
... and now the conclusion
Spin-Momentum Structure of the Nucleon

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^+ + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right]
\]

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^+ + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^+ + s^i S^i h_1 \right.
\]

\[
+ s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T}^+ + \Lambda s^i k^i \frac{1}{m} h_{1L}^+ \right]
\]

<table>
<thead>
<tr>
<th>nucleon pol.</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>(f_1)</td>
<td>(g_{1L})</td>
<td>(h_1^+)</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>(f_{1T}^+)</td>
<td>(g_{1T})</td>
<td>(h_1, h_{1T}^+)</td>
</tr>
</tbody>
</table>

- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

quark pol.
Spin-Momentum Structure of the Nucleon

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^{\perp} + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right]
\]

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^{\perp} + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^{\perp} + s^i S^i h_1 
+ s^i (2 k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T}^{\perp} + \Lambda s^i k^i \frac{1}{m} h_{1L}^{\perp} \right]
\]

<table>
<thead>
<tr>
<th>nucleon pol.</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>(f_1)</td>
<td></td>
<td>(h_1^{\perp})</td>
</tr>
<tr>
<td>L</td>
<td>(g_{1L})</td>
<td>(h_{1L}^{\perp})</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>(f_{1T}^{\perp})</td>
<td>(g_{1T})</td>
<td>(g_{1T}, h_{1T}^{\perp})</td>
</tr>
</tbody>
</table>

**Boer-Mulders**
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

**Sivers**
- Twist-2 TMDs

**Worm-gear**

**Transversity**

**Twist-2 TMDs**
1-Hadron Production ($ep \rightarrow ehX$)

\[ d\sigma = d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} + \frac{1}{Q} \cos \phi \, d\sigma^2_{UU} + \lambda_e \frac{1}{Q} \sin \phi \, d\sigma^3_{LU} \]

\[ + S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \frac{1}{Q} \sin \phi \, d\sigma^5_{UL} + \lambda_e \left[ d\sigma^6_{LL} + \frac{1}{Q} \cos \phi \, d\sigma^7_{LL} \right] \right\} \]

\[ + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \right. \]

\[ \left. + \frac{1}{Q} \left( \sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin \phi_S \, d\sigma^{12}_{UT} \right) \right\} \]

\[ + \lambda_e \left[ \cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q} \left( \cos \phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \}

Bacchetta et al., JHEP 0702 (2007) 093
1-Hadron Production \((ep \rightarrow ehx)\)

\[
d\sigma = d\sigma_0^{U} + \cos 2\phi \, d\sigma_1^{U} + \frac{1}{Q} \cos \phi \, d\sigma_2^{U} + \lambda_e \frac{1}{Q} \sin \phi \, d\sigma_3^{L}
\]

\[
+S_L \left\{ \sin 2\phi \, d\sigma_4^{U} + \frac{1}{Q} \sin \phi \, d\sigma_5^{U} + \lambda_e \left[ d\sigma_6^{L} + \frac{1}{Q} \cos \phi \, d\sigma_7^{L} \right] \right\}
\]

\[
+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_8^{U} + \sin(\phi + \phi_S) \, d\sigma_9^{U} + \sin(3\phi - \phi_S) \, d\sigma_{10}^{U} \right. \\
+ \left. \frac{1}{Q} (\sin(2\phi - \phi_S) \, d\sigma_{11}^{U} + \sin \phi_S \, d\sigma_{12}^{U}) \right\}
\]

\[
+ \lambda_e \left[ \cos(\phi - \phi_S) \, d\sigma_{13}^{L} + \frac{1}{Q} \left( \cos \phi_S \, d\sigma_{14}^{L} + \cos(2\phi - \phi_S) \, d\sigma_{15}^{L} \right) \right] \}
\]


Bacchetta et al., JHEP 0702 (2007) 093

1-Hadron Production (ep→ehX)

\[ d\sigma = d\sigma_{UU}^0 + \cos 2\phi \, d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi \, d\sigma_{UU}^2 + \lambda_e \frac{1}{Q} \sin \phi \, d\sigma_{LU}^3 \]

\[ + S_L \left\{ \sin 2\phi \, d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi \, d\sigma_{UL}^5 + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi \, d\sigma_{LL}^7 \right] \right\} \]

\[ + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^8 + \sin(\phi + \phi_S) \, d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right\} \]

Collins Effect:

sensitive to quark transverse spin
1-Hadron Production (ep→ehX)

\[ d\sigma = d\sigma_{UU}^0 + \cos 2\phi \, d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi \, d\sigma_{UU}^2 + \lambda_e \frac{1}{Q} \sin \phi \, d\sigma_{LU}^3 \]

\[ + S_L \left\{ \sin 2\phi \, d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi \, d\sigma_{UL}^5 + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi \, d\sigma_{LL}^7 \right] \right\} \]

\[ + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^8 + \sin(\phi + \phi_S) \, d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right\} \]

\[ + \cos(2\phi - \phi_S) \, d\sigma_{UT}^{12} \]
The HERMES Collins amplitudes

\[ 2 \left( \frac{\sin(\theta + \phi_s)}{V} \right) \nu \]

\[ \pi^+ \]

\[ \pi^- \]

The HERMES Collins amplitudes

Non-zero Collins effect observed!

The HERMES Collins amplitudes

non-zero Collins effect observed!

both Collins FF and transversity sizeable

The HERMES Collins amplitudes

- Published† results confirmed with much higher statistical precision
- Overall scale uncertainty of 8.1%
- Positive for $\pi^+$ and negative for $\pi^-$ as maybe expected ($\delta u \equiv h_1^u > 0$
  †
- Unexpected large $\pi^-$ asymmetry
  ⇒ role of disfavored Collins FF
- Most likely: $H_{1}^{\perp, disf} \approx -H_{1}^{\perp, fav}$
- Isospin symmetry among charged and neutral pions fulfilled

† [A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]
Sivers amplitudes for pions

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{\text{UT}} = - \frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes W D_{1}^q(z, k_T^2)}{\sum_q e_q^2 f_{1}^q(x, p_T^2) \otimes D_{1}^q(z, k_T^2)} \]

7.3% scale uncertainty
Sivers amplitudes for pions

\[ 2 \langle \sin (\phi - \phi_S) \rangle_{UT} = - \frac{\sum_q e_q^2 f_{1T}^{q}(x, p_T^2) \otimes W D_{1}^{q}(z, k_T^2)}{\sum_q e_q^2 f_{1T}^{q}(x, p_T^2) \otimes D_{1}^{q}(z, k_T^2)} \]

\[ \pi^+ \] dominated by u-quark scattering:

\[ \sum_q e_q^2 f_{1T}^{q}(x, p_T^2) \otimes W D_{1}^{q}(z, k_T^2) \]

\[ \approx \frac{f_{1T}^{u}(x, p_T^2) \otimes W D_{1}^{u \rightarrow \pi^+}(z, k_T^2)}{f_{1T}^{u}(x, p_T^2) \otimes D_{1}^{u \rightarrow \pi^+}(z, k_T^2)} \]

\( \begin{align*}
\pi^+ \quad \text{dominated by u-quark Sivers DF} \quad < 0
\end{align*} \)
Sivers amplitudes for pions

\[
2 \langle \sin (\phi - \phi_S) \rangle_{UT} = - \frac{\sum_q e_q^2 f_{1T}^{q}(x, p_T^2) \otimes \nu W D_{1}^{q}(z, k_T^2)}{\sum_q e_q^2 f_{1}^{q}(x, p_T^2) \otimes D_{1}^{q}(z, k_T^2)}
\]

\(\pi^+\) dominated by \(u\)-quark scattering:

\[
\simeq - \frac{f_{1T}^{u}(x, p_T^2) \otimes \nu W D_{1}^{u \rightarrow \pi^+}(z, k_T^2)}{f_{1}^{u}(x, p_T^2) \otimes D_{1}^{u \rightarrow \pi^+}(z, k_T^2)}
\]

\(\blacktriangleright\) \(u\)-quark Sivers DF < 0

\(\blacktriangleright\) \(d\)-quark Sivers DF > 0
(cancellation for \(\pi^-\))
Sivers amplitudes for pions

\[ 2\langle \sin (\phi - \phi_S) \rangle_{UT} = - \frac{\sum_q e_q^2 f_{1T}^{q}(x, p_T^2) \otimes W D^q_1(z, k_T^2)}{\sum_q e_q^2 f_{1T}^{q}(x, p_T^2) \otimes D^q_1(z, k_T^2)} \]

\[ \pi^+ \text{ dominated by } u\text{-quark scattering:} \]

\[ \sim - \frac{f_{1T}^{u}(x, p_T^2) \otimes W D^{u \rightarrow \pi^+}_1(z, k_T^2)}{f^{u}(x, p_T^2) \otimes D^{u \rightarrow \pi^+}_1(z, k_T^2)} \]

\[ L_z^u > 0 \]

**Sivers “difference asymmetry”**

- Transverse single-spin asymmetry of pion cross-section difference:

\[
A^{\pi^+ - \pi^-}_{UT}(\phi, \phi_S) \equiv \frac{1}{S_T} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}
\]

\[
\langle \sin(\phi - \phi_S) \rangle^{\pi^+ - \pi^-}_{UT}(\phi, \phi_S) \propto -\frac{4f_{1T}^{u\nu} - f_{1T}^{d\nu}}{4f_{1T}^{u\nu} - f_{1T}^{d\nu}}
\]
Sivers "difference asymmetry"

- Transverse single-spin asymmetry of pion cross-section difference:

\[ A_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) \equiv \frac{1}{S_T} \frac{\left( \sigma_{U \uparrow}^{\pi^+} - \sigma_{U \uparrow}^{\pi^-} \right) - \left( \sigma_{U \downarrow}^{\pi^+} - \sigma_{U \downarrow}^{\pi^-} \right)}{\left( \sigma_{U \uparrow}^{\pi^+} - \sigma_{U \uparrow}^{\pi^-} \right) + \left( \sigma_{U \downarrow}^{\pi^+} - \sigma_{U \downarrow}^{\pi^-} \right)} \]

\[ \langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) \propto -\frac{4f_{1T}^{\perp,u,v} - f_{1T}^{\perp,d,v}}{4f_1^{u,v} - f_1^{d,v}} \]

access to Sivers u-valence distribution
The kaon Sivers amplitudes

\[ 2 \langle \sin(\phi - \phi_s) \rangle_{ur} \]

\( x \quad 0.4 \quad 0.6 \quad z \quad 0.5 \quad P_{h \perp} \quad [\text{GeV}] \)

\( \pi^+ \)

\( \pi^0 \)

\( \pi^- \)

\( K^+ \)

\( K^- \)
The kaon Sivers amplitudes

![Graphs showing the kaon Sivers amplitudes for different particle types and kinematic variables.](image)
The kaon Sivers amplitudes
The “Kaon Challenge”

\[ \frac{\pi^+}{K^+} \text{ production dominated by scattering off } u\text{-quarks: } \approx - \frac{f_{1T}^{u}(x, p_T^2) \otimes \mathcal{W} \; D_{1}^{u \rightarrow \pi^+/K^+}(z, k_T^2)}{f_{1}^{u}(x, p_T^2) \otimes D_{1}^{u \rightarrow \pi^+/K^+}(z, k_T^2)} \]
The “Kaon Challenge”

$\pi^+/K^+$ production dominated by scattering off $u$-quarks: $\sim - \frac{x f_{1T,u}(x, p_T^2) \otimes \mathcal{W} D_{1u \rightarrow \pi^+/K^+}(z, k_T^2)}{f_{1u}(x, p_T^2) \otimes D_{1u \rightarrow \pi^+/K^+}(z, k_T^2)}$
The “Kaon Challenge”

\[ \frac{\pi^+}{K^+} \text{ production dominated by scattering off } u\text{-quarks: } \sim -\frac{f_{1T}^u(x, p_T^2) \otimes W D_{1}^{u\rightarrow\pi^+/K^+}(z, k_T^2)}{f_{1T}^u(x, p_T^2) \otimes D_{1}^{u\rightarrow\pi^+/K^+}(z, k_T^2)} \]

\[ K^+ = |u\bar{s}\rangle \quad \pi^+ = |u\bar{d}\rangle \quad \Rightarrow \text{non-trivial role of sea quarks?} \]
The “Kaon Challenge”

\[ \pi^+/K^+ \] production dominated by scattering off u-quarks:

\[ \approx - \frac{f_{1T}u(x, p_T^2) \otimes W D_{1}^{u \rightarrow \pi^+/K^+}(z, k_{T}^2)}{f_{1T}u(x, p_T^2) \otimes D_{1}^{u \rightarrow \pi^+/K^+}(z, k_{T}^2)} \]

\[ K^+ = |u \bar{s}\rangle \& \pi^+ = |u \bar{d}\rangle \]  \( \Rightarrow \) non-trivial role of sea quarks?

Convolution integrals depend on \( k_T \) dependence of fragmentation functions.
The “Kaon Challenge”

$$\pi^+ / K^+$$ production dominated by scattering off $u$-quarks: $\mathcal{N} \sim - f_{1T}^u(x, p_T^2) \otimes W D_{1u}^{u \rightarrow \pi^+/K^+}(z, k_T^2)\| s$$

- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ $\Rightarrow$ non-trivial role of sea quarks?
- Convolution integrals depend on $k_T$ dependence of fragmentation functions
- Possible difference in dependences on the kinematics integrated over
Role of sea quarks

[A. Airapetian et al., PLB 666, 446 (2008)]

\[ xS(x) \]

\[ K^+ - \pi^+ \]

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

\[ 10^{-1} \]
Role of sea quarks

[A. Airapetian et al., PLB 666, 446 (2008)]

\[
xS(x)
\]

\[
0 \quad 0.2 \quad 0.4
\]

\[
0 \quad 0.1 \quad 0.6 \quad x
\]

\[
2 \langle \sin(\phi_{-s}) \rangle _{u}^K + 2 \langle \sin(\phi_{-s}) \rangle _{u}^\pi
\]

\[
K^+ - \pi^+
\]

\[
x \quad 10^{-1}
\]

differences biggest in region where strange sea is most different from light sea
Cancelation of fragmentation function

\[ \langle \sin(\phi - \phi_S) \rangle_{\pi^+ - \pi^-}^{\pi^+ - \pi^-} (\phi, \phi_S) \propto -\frac{4 f_{1T}^{u\nu} - f_{1T}^{d\nu}}{4 f_{1T}^{u\nu} - f_{1T}^{d\nu}} \]
Cancelation of fragmentation function

\[ \langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-} (\phi, \phi_S) \propto \frac{4f_{1T}^{u\perp} u_v - f_{1T}^{d\perp} d_v}{4f_1^{u\perp} u_v - f_1^{d\perp} d_v} \]

should be flat
\( Q^2 \) dependence of amplitudes

- separate each \( x \)-bin into two \( Q^2 \) bins:

- only in low-\( Q^2 \) region significant (>90% c.l.) deviation
$Q^2$ dependence of amplitudes

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{\ell r} \]

\[ \langle Q^2 \rangle \ [\text{GeV}^2] \]

\[ x \]

\[ \pi^+ \]

$Q^2 < \langle Q^2(x_i) \rangle$
$Q^2$ dependence of amplitudes

\[ 2 \langle \sin(\phi_S) \rangle_{ur} \]

\[ \langle Q^2 \rangle_{[\text{GeV}^2]} \]

\[ \pi^+ \]

- $Q^2 < \langle Q^2(x_i) \rangle$
- $Q^2 > \langle Q^2(x_i) \rangle$

$x$
Q^2 dependence of amplitudes

\[ 2 \langle \sin(\phi - \phi_S) \rangle_{\mu r} \]

\[ \langle Q^2 \rangle [\text{GeV}^2] \]

\[ Q^2 < \langle Q^2(x_i) \rangle \]

\[ Q^2 > \langle Q^2(x_i) \rangle \]

\[ \pi^+ \]

\[ K^+ \]
Q² dependence of amplitudes

hint of Q² dependence of kaon amplitude
The “others”
Pretzelosity - \( \sin(3\phi - \phi_s) \)

- no significant non-zero signal observed
- suppressed by two powers of \( P_{h\perp} \) (compared to, e.g., Sivers)
Subleading twist I - $\sin(2\phi + \phi_S)$

- no significant non-zero signal observed except maybe $K^+$
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- related to worm-gear $h_{1L}^\perp$
- arises solely from longitudinal component of target-spin ($\leq 15\%$)

![Graph showing $2\langle \sin(2\phi + \phi_S) \rangle_{u_\perp}$ for different particles]

HERMES: PRELIMINARY

7.3% scale uncertainty
Subleading twist II - $\sin(2\phi - \phi_s)$

- no significant non-zero signal observed
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- various terms related to pretzelosity, worm-gear, Sivers etc.:
Subleading twist III - $\sin(\phi_s)$

- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and $z$, and summation over all hadrons
significant non-zero signal observed for negatively charged mesons

must vanish after integration over $P_{h\perp}$ and $z$, and summation over all hadrons

HERMES 7.3% scale uncertainty

PRELIMINARY

HERMES 9.3% scale uncertainty


$e^+ p \rightarrow e^+ X$

Elastic fraction

$\langle Q^2 \rangle [\text{GeV}^2]$
significant non-zero signal observed for negatively charged mesons

must vanish after integration over $P_{h\perp}$ and $z$, and summation over all hadrons

Subleading twist III - $\sin(\phi_s)$


**Subleading twist III - \( \sin(\phi_s) \)**

- Significant non-zero signal observed for negatively charged mesons.
- Must vanish after integration over \( P_{h \perp} \) and \( z \), and summation over all hadrons.
- Various terms related to transversity, worm-gear, Sivers etc.:

\[
\propto \left( x f_T^+ D_1 - \frac{M_h}{M} h_1^+ \tilde{H} \right) - \mathcal{W}(p_T, k_T, P_{h \perp}) \left[ \left( x h_T^+ H_1^+ + \frac{M_h}{M} g_{1T}^+ \tilde{G}^+ \right) - \left( x h_T^+ H_1^+ - \frac{M_h}{M} f_{1T}^+ \tilde{D}^+ \right) \right]
\]
Subleading twist III - $\sin(\phi_s)$

$Q^2$ dependence seen in signal for negative pions
Back to the beginning of Sivers effect

$p^+ p \rightarrow \pi X$
Back to the beginning of Sivers effect

\[ \sqrt{S} = 4.9 \text{ GeV} \]

\[ 6.6 \text{ GeV} \]

\[ 19.4 \text{ GeV} \]

\[ 62.4 \text{ GeV} \]

\[ \pi^+ \]

\[ \pi^- \]

\[ p \cdot p \]

\[ A_N \]

\[ \text{Measurement of } A_N \text{ in } p p \text{-scattering for different center of mass energies:} \]

\[ 1976 \]

\[ 2002 \]

\[ 1991 \]

\[ 2008 \]

\[ N_R - N_L \]

\[ N_R + N_L \]

\[ A_N = \]

\[ \text{Only two models consistently describing the data:} \]

\[ * \text{TMDs (Transverse Momentum Dependent)} \]

\[ * \text{high-twist correlations} \]

\[ \text{Interpretation not yet completely satisfactory} \]

\[ \text{All available models predict } A_N \text{ goes to zero at high } p_T \text{ values.} \]

\[ \text{BUT: not yet DATA at such kinematic region} \]

\[ \text{All available data coming from } p p \text{ scattering} \]
Inclusive hadron electro-production

\[ e p \uparrow \rightarrow h X \]

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected
- lepton kinematics unknown

\[ ep^\uparrow \rightarrow hX \]

lepton beam going into the page
Inclusive hadron electro-production

- scattered lepton undetected ➜ lepton kinematics unknown
- dominated by quasi-real photo-production (low $Q^2$) ➜ hadronic component of photon relevant?

\[ ep \uparrow \rightarrow hX \]
Inclusive hadron electro-production

- scattered lepton undetected ➜ lepton kinematics unknown
- dominated by quasi-real photo-production (low $Q^2$) ➜ hadronic component of photon relevant?
- cross section proportional to $S_N (k \times p_h) \sim \sin \phi$

\[ ep^\uparrow \rightarrow hX \]
Inclusive hadron electro-production

- scattered lepton undetected
  - lepton kinematics unknown
- dominated by quasi-real photo-production (low $Q^2$)
  - hadronic component of photon relevant?
- cross section proportional to
  $S_N$ ($k \times p_h$) $\sim \sin \phi$

$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin \phi}(p_T, x_F) \sin \phi$$

lepton beam going into the page

$e p^\uparrow \rightarrow h X$
Inclusive hadron electro-production

- scattered lepton undetected ➞ lepton kinematics unknown
- dominated by quasi-real photo-production (low \( Q^2 \)) ➞ hadronic component of photon relevant?
- cross section proportional to \( S_N (k \times p_h) \sim \sin \phi \)

\[
A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin \phi}(p_T, x_F) \sin \phi
\]

where \( A_N \) is defined as:

\[
A_N = \frac{\int_0^{2\pi} d\phi \, \sigma_{UT} \sin \phi - \int_0^{\pi} d\phi \, \sigma_{UT} \sin \phi}{\int_0^{2\pi} d\phi \, \sigma_{UU}} = -\frac{2}{\pi} A_{UT}^{\sin \phi}
\]

The complete analysis [x] with further information can be found in Florian's thesis [yx].
$x_F$ dependence of $A_{UT} \sin \phi$ amplitude

$e^\pm p \rightarrow \pi^\pm + X$ HERMES preliminary

$e^\pm p \rightarrow K^\pm + X$

8.8% scale uncertainty

$e^\pm p \rightarrow \pi^- + X$

$e^\pm p \rightarrow K^- + X$

$\langle p_T \rangle \text{ (GeV)}$
$x_F$ dependence of $A_{UT} \sin \phi$ amplitude

- opposite in sign to pp
- increasing amplitudes
$x_F$ dependence of $A_{UT} \sin \phi$ amplitude

- opposite in sign to pp
- increasing amplitudes

increasing $p_T$
$p_T$ dependence of $A_{UT} \sin \phi$ amplitude

Increasing amplitudes with turnover
$p_T$ dependence of $A_{UT} \sin \phi$ amplitude

Increasing amplitudes with turnover

Sign change
$p_T$ dependence of $A_{UT} \sin \phi$ amplitude

behavior and size similar to SIDIS Sivers

G. Schnell - DESY Zeuthen
Summary & Outlook

- clear signals for Sivers function observed
- indication of positive (negative) u-quark (d-quark) orbital angular momentum
- pretzelosity either too small or its contribution to semi-inclusive DIS too much suppressed
- no sizable $\sin(2\phi \pm \phi_S)$ modulations seen
- significant (and surprising?) non-zero $\sin(\phi_S)$ modulation for $\pi^-$
- SSA in inclusive hadron electro-production resemble Sivers effect but different in sign to pp collision
- final Collins results coming out soon