measurements of the transverse spin structure

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Università degli studi di Ferrara

For the HERMES collaboration
HERA MEasurement of Spin

HERA storage ring @ DESY
HERa MEasurement of Spin

Lepton (Electron/Positron) beam (27.6GeV/c) off a transversely polarised hydrogen target

$<P> \sim 72.5 \pm 0.053\%$
Lepton (Electron/Positron) beam (27.6GeV/c) off a transversely polarised hydrogen target \[<P> \sim 72.5 \pm 0.053\%\]
**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**

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

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

Hadron identification with dual-radiator RICH
HERMES spectrometer

Aerogel $n=1.03$

$\text{C}_4\text{F}_{10}$ $n=1.0014$

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

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

Hadron identification with dual-radiator RICH
### Leading twist Distribution Functions

<table>
<thead>
<tr>
<th></th>
<th>quark</th>
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<tbody>
<tr>
<td><strong>U</strong></td>
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<tr>
<td><strong>T</strong></td>
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</table>

**Legend:**
- `q`: Quark
- `Δq`: Quark distribution
- `δq`: Quark distribution change

---

**Francesca Giordano**

**Gordon08**
Leading twist Distribution Functions

<table>
<thead>
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Transversity DF
Transversity

As Transversity is a chiral-odd function it can be probed only in conjunction with another chiral-odd function

In Semi Inclusive Deep Inelastic Scattering it is coupled to a chiral-odd Fragmentation Function
Semi Inclusive Deep Inelastic Scattering

1-hadron production

\[ \sigma_{UT} \propto S_T \sin(\phi_h + \phi_S) \sum_q e_q^2 \left[ \frac{k_T \cdot \hat{P}_{h\perp}}{M} \delta q \cdot H_{q,q}^{\perp} \right] \]

2-hadron production

\[ \sigma_{UT} \propto \left| S_T \right| \sin \theta \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 \delta q \cdot H_{q,q}^{\perp} \]
Semi Inclusive Deep Inelastic Scattering

1-hadron production

Collins Fragmentation Function

$$\sigma_{UT} \propto S_T \sin(\phi + \phi_S) \sum_q e_q^2 \int \left[ \frac{k_T \cdot \hat{P}_{h\perp}}{M} \delta q \cdot H_{i,q} \right]$$
Semi Inclusive Deep Inelastic Scattering

1-hadron production

Collins Fragmentation Function

\[ \sigma_{UT} \propto S_T \sin(\phi + \phi_S) \sum_q e_q^2 \int \frac{k_T \cdot \hat{P}_{h\perp}}{M} \delta q \cdot H_{1,q} \]

Collins signature
1-hadron production

\[ A_{UT}^h = \frac{\sigma_\downarrow - \sigma_\uparrow}{\sigma_\downarrow + \sigma_\uparrow} \]

\[
A_{UT}^h \propto 2|S_T| \sin(\varphi + \varphi_S) \sum_q e_q^2 \frac{I[\langle \vec{k}_T \cdot \hat{P}_h \rangle]}{M_h} \delta q(x, p_T^2) H_1^\perp q(z, k_T^2) \]

\[
A_{UT}^h \frac{A(y) \sum_q e_q^2 q(x, p_T^2) D_1^q(z, k_T^2)}{A(y) \sum_q e_q^2 q(x, p_T^2) D_1^q(z, k_T^2)}
\]
1-hadron production

\[ A^h_{UT} = \frac{\sigma_{h}^{\downarrow} - \sigma_{h}^{\uparrow}}{\sigma_{h}^{\downarrow} + \sigma_{h}^{\uparrow}} \]

\[ A^h_{UT} \propto 2|S_T| \sin(\varphi + \varphi_S) \]

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\[ A_T^h \propto 2|S_T| \sin(\varphi - \varphi_S) \sum_q e_q^2 I\left(\frac{\vec{p}_T \cdot \hat{P}_{h\perp}}{M}\right) f_{1T}^\perp q(x, k_T^2) D_1^q(z, k_T^2) \]

Collins signature
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\[ A_{UT}^h = \frac{\sigma_\downarrow^h - \sigma_\uparrow^h}{\sigma_\downarrow^h + \sigma_\uparrow^h} \]

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Collins signature

\[ + 2|S_T| \sin(\varphi - \varphi_S) \sum_q e_q^2 I\left(\frac{\vec{p}_T \cdot \hat{P}_{h\perp}}{M}\right) f_{1T}^{\perp q}(x, k_T^2) D_1^q(z, k_T^2) \]

\[ A(y) \sum_q e_q^2 q(x, p_T^2) D_1^q(z, k_T^2) \]
A^h_{UT} = \frac{\sigma_{h}^{\downarrow} - \sigma_{h}^{\uparrow}}{\sigma_{h}^{\downarrow} + \sigma_{h}^{\uparrow}}

A^h_{UT} \propto 2|S_T| \sin(\varphi + \varphi_S)

Collins signature

+ 2|S_T| \sin(\varphi - \varphi_S)

Sivers signature
# Leading twist Distribution Functions

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**Transversity DF**
The TMD Distribution Functions

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Transversity DF
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<td>$h_{1u}$</td>
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<td>$\Delta q$</td>
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**Sivers DF**

**Transversity DF**
Sivers mechanism

The Sivers function $f_{1T}^{q}(x, p_{T}^{2})$ describes the correlation between the transverse polarization of the nucleon and the transverse momentum of the struck quark $\Rightarrow$ spin-orbit structure of the nucleon

a non-zero Sivers function requires a non-vanishing orbital angular momentum inside the nucleon
Collins amplitudes for pions

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

- Large positive for $\pi^+$
- Large negative for $\pi^-$
- Consistent with zero for $\pi^0$

\[ u \rightarrow \pi^+ H_{1}^\perp, \text{fav} \]
\[ u \rightarrow \pi^- H_{1}^\perp, \text{unfav} \]
Collins amplitudes for pions

\[ \to \text{Large positive for } \pi^+ \]
\[ \to \text{Large negative for } \pi^- \]
\[ \to \text{Consistent with zero for } \pi^0 \]

\[ u \to \pi^+ \quad H_1^\perp, \text{ fav} \]
\[ u \to \pi^- \quad H_1^\perp, \text{ unfav} \]

\[ H_{1,\text{unfav}} \approx -H_{1,\text{fav}} \]
Collins amplitudes for pions

→ Large positive for $\pi^+$
→ Large negative for $\pi^-$
→ Consistent with zero for $\pi^0$

$u \to \pi^+ \ H_1^\perp , \text{fav}$
$u \to \pi^- \ H_1^\perp , \text{unfav}$

$H_1^\perp , \text{unfav} \approx -H_1^\perp , \text{fav}$

Isospin symmetry fulfilled for $\pi$-meson SSA amplitudes!
Collins amplitudes for charged kaons

→ No significant non-zero

Collins amplitudes for Kaons
Collins amplitudes for charged kaons

→ No significant non-zero Collins amplitudes for Kaons

→ Collins amplitudes for $K^+$ compatible with $\pi^+$
Sivers amplitudes for pions

→ Large positive for $\pi^+$
→ Consistent with zero for $\pi^-$
→ Positive for $\pi^0$

Isospin symmetry fulfilled for $\pi$-meson SSA amplitudes!
Sivers amplitudes for pions

→ Large positive for $\pi^+$
→ Consistent with zero for $\pi^-$
→ Positive for $\pi^0$

Non zero quark orbital angular momentum!

Isospin symmetry fulfilled for $\pi$-meson SSA amplitudes!
Sivers amplitudes for charged kaons

- Large positive for $K^+$
- Consistent with zero for $K^-$
Sivers amplitudes for charged kaons

- Large positive for $K^+$
- Consistent with zero for $K^-$
- $K^+$ amplitudes are larger than the $\pi^+$ amplitudes!
Sivers amplitudes for charged kaons

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

→ Large positive for $K^+$

→ Consistent with zero for $K^-$

→ $K^+$ amplitudes are larger than the $\pi^+$ amplitudes!

Suggests a significant sea quark contribution
Semi Inclusive Deep Inelastic Scattering

Independent method to extract $\delta q$

Direct product of transversity and Fragmentation function
(no convolution involved!)

**BUT:**

- poorer statistics
- increased number of variables

$$\sigma_{UT} \propto |S_T| \sin \theta \sin (\phi_{R\perp} + \phi_S) \sum_q e_q^2 \delta q \cdot H_{1,q}$$

Azimuthal dependence

**2-hadron production**

CMS frame
2-hadron production

\[ A_{UT} \equiv \frac{\sigma_{UT}}{\sigma_{UU}} \propto |S_T| \sin(\phi_{R\perp} + \phi_S) \]

\[
\sin \theta \sum_q e_q^2 \delta q(x) \left[ \frac{H_{1,q}^{sp} (z, M_{\pi\pi}^2) \cos \theta + H_{1,q}^{sp} (z, M_{\pi\pi}^2) \cos \theta}{D_{1,q}^{pp} (z, M_{\pi\pi}) + (3 \cos^2 \theta - 1) D_{1,q}^{pp} (z, M_{\pi\pi})} \right] \]

The contribution to the Asymmetry is due to interference of different partial waves of the final state h^+h^-.
2-hadron production

\[
A_{UT} \equiv \frac{\sigma_{UT}}{\sigma_{UU}} \propto |S_T| \sin(\phi_{R\perp} + \phi_S)
\]

\[
\sin \theta \sum_q e_q^2 \delta q(x) \left[ H_{1,q}^{\xi,sp}(z, M_{\pi\pi}^2) + \cos \theta \ H_{1,q}^{\xi,pp}(z, M_{\pi\pi}^2) \right]
\]

\[
\sum_q e_q^2 q(x) \left[ D_{1,q}(z, M_{\pi\pi}) + \cos \theta \ D_{1,q}^{sp}(z, M_{\pi\pi}) + (3 \cos^2 \theta - 1) D_{1,q}^{pp}(z, M_{\pi\pi}) \right]
\]

\[
\theta' \equiv \left| \theta - \frac{\pi}{2} \right| - \frac{\pi}{2}
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2-hadron production

\[ A_{UT} \equiv \frac{\sigma_{UT}}{\sigma_{UU}} \propto \left| S_T \right| \sin(\phi_R + \phi_S) \]

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\]

\[
\theta' = \left| \theta - \frac{\pi}{2} \right| - \frac{\pi}{2}
\]

The azimuthal moments are extracted from \( A_{UT} \) using a 2-dimensional \( \chi^2 \) fit

\[
A_{UT} = \sin(\phi_R + \phi_S) \frac{a \sin \theta'}{1 + b (3 \cos^2 \theta' - 1)}
\]
\[ A_{UT} \equiv \frac{\sigma_{UT}}{\sigma_{UU}} \propto |S_T| \sin(\phi_{R\perp} + \phi_S) \]

\[
\sin \theta \sum_q e_q^2 \delta q(x) \left[ H_{1,q}^{\perp,sp} (z, M_{\pi\pi}^2) + \cos \theta \ H_{1,q}^{\perp,pp} (z, M_{\pi\pi}^2) \right]
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\[
\sum_q e_q^2 q(x) \left[ D_{1,q} (z, M_{\pi\pi}) + \cos \theta \ D_{1,q}^{sp} (z, M_{\pi\pi}) + (3 \cos^2 \theta - 1) D_{1,q}^{pp} (z, M_{\pi\pi}) \right]
\]

\[
A_{UT} = \sin(\phi_{R\perp} + \phi_S) \frac{a \sin \theta'}{1 + b (3 \cos^2 \theta' - 1)}
\]

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2-hadron production

First evidence of a T-odd and chiral-odd dihadron fragmentation function!

(A. Airapetian et al, JHEP 06 (2008) 017)
2-hadron production

**POSITIVE ASYMMETRY**
in the whole range of $M_{\pi\pi}$-mass

![Graph showing positive asymmetry in the whole range of $M_{\pi\pi}$-mass](image)
2-hadron production

POSITIVE ASYMMETRY
in the whole range of $M_{\pi\pi}$-mass

No evidence of the sign-change at the $\rho^0$ mass
predicted by Jaffe et al.
(Phys.Rev.Lett.80,(1998))
2-hadron production

POSITIVE ASYMMETRY in the whole range of $M_{\pi\pi}$-mass

Prediction by Bacchetta & Radici consistent with mass dependence

\textit{(Phys. Rev. D 74,(2006))}
The TMD Distribution Functions

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Sivers DF

Transversity DF
Unpolarized Semi Inclusive Deep Inelastic Scattering

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

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\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) \{A(y) \ F_{UU,T} + B(y) \ F_{UU,L}\} \\
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\]

\[F_{UU}^{\cos 2\phi} = I \left[ -\frac{2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \ h_1^\perp H_1^\perp \right]\]
Unpolarized Semi Inclusive Deep Inelastic Scattering

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

\[
F_{UU}^{\cos 2\phi} = I \left[ -2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T \right]_{\text{MM}_h}^{(\perp)}
\]

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Unpolarized Semi Inclusive Deep Inelastic Scattering

Multi-dimensional unfolding procedure in progress!

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

\[
F_{UU}^{\cos 2\phi} = I \left[-\frac{2(\hat{h} \cdot \vec{k}_T)(\hat{h} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right]
\]
Conclusion

1-hadron production:

- First evidence of a significant SSA Collins amplitudes for $\pi$-mesons

allowed the first extraction of the transversity function!

$\sin(\phi + \phi_S) \propto \delta q(x) \otimes H_{1/q}(z)$


A.Airapetian et al.

E.S.Ageev et al.

R.Seidl et al.
Conclusion

1-hadron production:

- First evidence of a significant SSA Collins amplitudes for $\pi$-mesons
  allowed the first extraction of the transversity function!
- Significant SSA Sivers amplitudes for $\pi^+$ and $K^+$
  non-zero quark orbital angular momenta!
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2-hadron production:

• Significative non-zero asymmetries for $\pi^+\pi^-$-pairs :
  independent probe of transversity!
Conclusion

1-hadron production:
• First evidence of a significant SSA Collins amplitudes for $\pi$-mesons:
  \[\text{allowed the first extraction of the transversity function!}\]
• Significant SSA Sivers amplitudes for $\pi^+$ and $K^+$:
  \[\text{non-zero quark orbital angular momenta!}\]

2-hadron production:
• Significative non-zero asymmetries for $\pi^+\pi^-$-pairs:
  \[\text{independent probe of transversity!}\]
  \[\text{first evidence for a non-zero chiral-odd interference fragmentation function! (to be measured in $e^+e^-$ machines)}\]
Conclusion

1-hadron production:
- First evidence of a significant SSA Collins amplitudes for $\pi$-mesons:
  - allowed the first extraction of the transversity function!
- Significant SSA Sivers amplitudes for $\pi^+$ and $K^+$:
  - non-zero quark orbital angular momenta!

2-hadron production:
- Significant non-zero asymmetries for $\pi^+\pi^-$-pairs:
  - independent probe of transversity!
  - first evidence for a non-zero chiral-odd interference fragmentation function! (to be measured in $e^+e^-$ machines)
- No evidence of a sign change of SSA at $\rho^0$ mass
Thank you!
Vector meson contamination

\[ \text{VM fraction} \]

\[ \begin{array}{c}
\text{\pi}^+, \text{\pi}_0, \text{\pi}^- \\
\text{K}^-, \text{K}^+ \\
\end{array} \]

\[ \begin{array}{c}
x, z, P_{h\perp} [\text{GeV}] \\
\end{array} \]