The HERMES measurement of transverse single-spin asymmetries

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on behalf of the hermes collaboration

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The spin structure of the nucleon:

Angular momentum sum rule:

\[ \frac{s_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g \]

HERMES contributions to the spin puzzle:

Measurement of transverse spin phenomena:

\[ L_q \]

\[ \text{transversity measurements} \]
The HERMES experiment:

- polarised **gas target** internal to the HERA storage ring
- background-free measurements from highly polarised nucleons
- **2002–2005: transversely polarised hydrogen** target
- very clean lepton-hadron separation and hadron identification
Transverse single-spin asymmetries:

- **naive time reversal odd** (naive-T-odd) **functions**
- involve interference of amplitudes with different helicities
  - suppressed in perturbative QCD
  - assigned to distribution and fragmentation functions
- **associated with spin/orbit effects** \((S \cdot (P_1 \times P_2))\)
- observed in semi-inclusive DIS on a transversely polarised target:
  - **single-hadron production** \((ep^{\uparrow} \rightarrow e'hX)\):
  - **dihadron production** \((ep^{\uparrow} \rightarrow e'h_1h_2X)\):
    - \(S_q \cdot (p_q \times R)\)
    - transfer of transverse quark spin to relative orbital angular momentum of hadron pair \((2R = P_{h_1} - P_{h_1})\)
    - sensitive to \(h_1^q(x)H_{1,q}^{\ll}(z,M_{\pi\pi}, \cos \theta)\)
    - dihadron fragmentation function \(H_{1,q}^{\ll}(z,M_{\pi\pi}, \cos \theta)\)
      (leading twist, chiral-odd, naive T-odd)
The semi-inclusive production of $\pi^+\pi^-$ pairs:

azimuthal angles $\phi_S$ and $\phi_{RT}$:

$$\phi_S \equiv \frac{(q \times k) \cdot S_T}{|(q \times k) \cdot S_T|} \arccos \left( \frac{(q \times k) \cdot (q \times S_T)}{|(q \times k)| \cdot |q \times S_T|} \right)$$

$$\phi_{RT} \equiv \frac{(q \times k) \cdot R_T}{|(q \times k) \cdot R_T|} \arccos \left( \frac{(q \times k) \cdot (q \times R_T)}{|(q \times k)| \cdot |q \times R_T|} \right)$$

$$P_h \equiv P_{\pi^+} + P_{\pi^-}$$

$$R \equiv \frac{P_{\pi^+} - P_{\pi^-}}{2}$$

$$R_T \equiv R - (R \cdot \hat{P}_h) \hat{P}_h$$
SSA in semi-inclusive $\pi^+\pi^-$ production:

- Fourier and Legendre expansion:

$$A_{UT} \sin(\phi_{R\perp} + \phi_S) \sin \theta \sim \sum_q e_q^2 \frac{h^q_1(x)}{f^q_1(x)} \frac{H^{\langle,sp}_{1,q}(z,M_{\pi\pi})}{D_{1,q}(z,M_{\pi\pi})}$$

- Focus on sp- and pp-interference ($M_{\pi\pi} < 1.5$ GeV):
  - $D_{1,q} \approx D_{1,q} + D^{sp}_{1,q} \cos \theta + D^{pp}_{1,q} \frac{1}{4}(3\cos^2 \theta - 1)$
  - $H^{\langle,sp}_{1,q} \approx H^{\langle,pp}_{1,q} \cos \theta$

- Symmetrisation around $\theta = \pi/2$ implies $D^{sp}_{1,q}$ and $H^{\langle,pp}_{1,q}$ drop out.
Functional form of the $\chi^2$ fit:

- Extraction of $a \equiv A_{UT}^{\sin(\phi_{R\perp}+\phi_S)} \sin \theta$ in a linear fit

\[
A_{U\perp}(\phi_{R\perp} + \phi_S, \theta') = \sin(\phi_{R\perp} + \phi_S) \frac{a \sin \theta'}{1 + b \frac{1}{4}(3 \cos^2 \theta' - 1)}
\]

- While varying $b$ within positivity limits

\[
\frac{-3D_{1,q}^{pp}(z,M_{\pi\pi})}{2D_{1,q}(z,M_{\pi\pi})} \leq b \leq \frac{3D_{1,q}^{pp}(z,M_{\pi\pi})}{D_{1,q}(z,M_{\pi\pi})}
\]

- Limits estimated with PYTHIA6 (tuned for HERMES kinematics)
- Systematic uncertainty due to “b-scan”:
  - Central value in the ranges of $a \Rightarrow$ SSA amplitude
  - Standard deviation $\Rightarrow$ systematic uncertainty
Published Results (JHEP 0806:017, 2008):

\[ A_{U \perp} \sin(\phi_R + \phi_S) \sin \theta = 0.018 \pm 0.005_{\text{stat}} \pm 0.002_{\text{b-scan}} + 0.004_{\text{acc}} \]

- additional 8.1% scale uncertainty (target polarisation)
- first evidence for \( H_{1,q} \)
- transversity can be studied in dihadron production
SSA in single-hadron production:

- **single-hadron production** \((ep^{\uparrow} \rightarrow e'hX)\):

- **azimuthal asymmetry** in the momentum distribution of the produced hadrons (transverse to the nucleon spin)
  - Collins mechanism \((S_q \cdot (p_q \times P_h))\)
    - sensitive to transversity
  - Sivers mechanism \((S_N \cdot (P \times p_q))\)
    - sensitive to \(L_q\)
The Collins amplitudes for pions:

Results of the Collins amplitude:

\[ h^q_1 (x) \otimes H^\perp_1 q (z) \]

from 2002–2005 data:

- positive amplitudes for \( \pi^+ \)
- large negative \( \pi^- \) amplitudes is unexpected
- \( H^\perp_1,\text{unfav} (z) \approx -H^\perp_1,\text{fav} (z) \)
- isospin symmetry of \( \pi \)-mesons is fulfilled
- information from another process on the Collins fragmentation function (BELLE) permits extraction of transversity (e.g. Anselmino et al, Phys.Rev.D75:054032,2007)
The Sivers mechanism:

- **non-zero Sivers distribution** $f_{1T}^{\perp}$ involves non-zero Compton amplitude $N^{\uparrow}q^{\uparrow} \rightarrow N^{\downarrow}q^{\uparrow}$

- **orbital angular momentum of quarks:** (M. Burkardt, *Phys.Rev.D66:114005,2002*)

  \[
  \gamma^* b \gamma^* b \rightarrow u_X (x,b_{\perp}):
  \]

- **final state interactions (naive-T-odd):**
  - left-right asymmetry of quark distribution
  - left-right asymmetry of momentum distribution of produced hadron
The Sivers amplitudes for pions:

Results of the Sivers amplitude:

\[ f_{1T}^q (x) \otimes D_1^q (z). \]

from 2002–2005 data:

- significantly positive for \( \pi^+ \)
- implies non-zero \( L_z^q \)
- \( \pi^- \) amplitude consistent with zero
- isospin symmetry of \( \pi \)-mesons is fulfilled

- extraction of the Sivers function is possible as spin-independent fragmentation function \( D_1^q (z) \) is known
In a nutshell:

- (most) precise data on a transversely polarised hydrogen target
- significant Collins amplitudes for $\pi$-mesons
  - enables quantitative extraction of transversity distribution

- significant Sivers amplitudes for $\pi^+$ and $K^+$
  - clear (and first) evidence of a naive-T-odd parton distribution
  - enables quantitative extraction of the Sivers function

- first evidence for a naive-T-odd dihadron fragmentation function
  - provides alternative probe for transversity distribution