The HERMES *measurement of transverse single-spin asymmetries*

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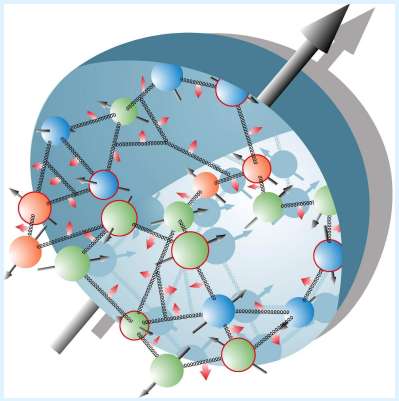
The spin structure of the nucleon:

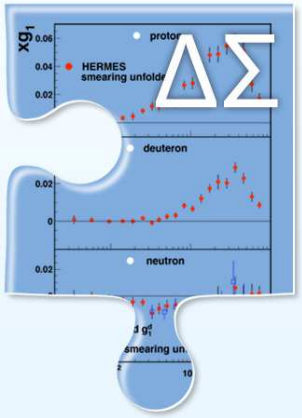
Angular momentum sum rule:

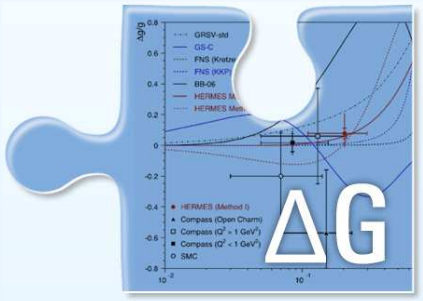
$$\frac{s_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

Spin of the nucleon



HERMES contributions to the spin puzzle:



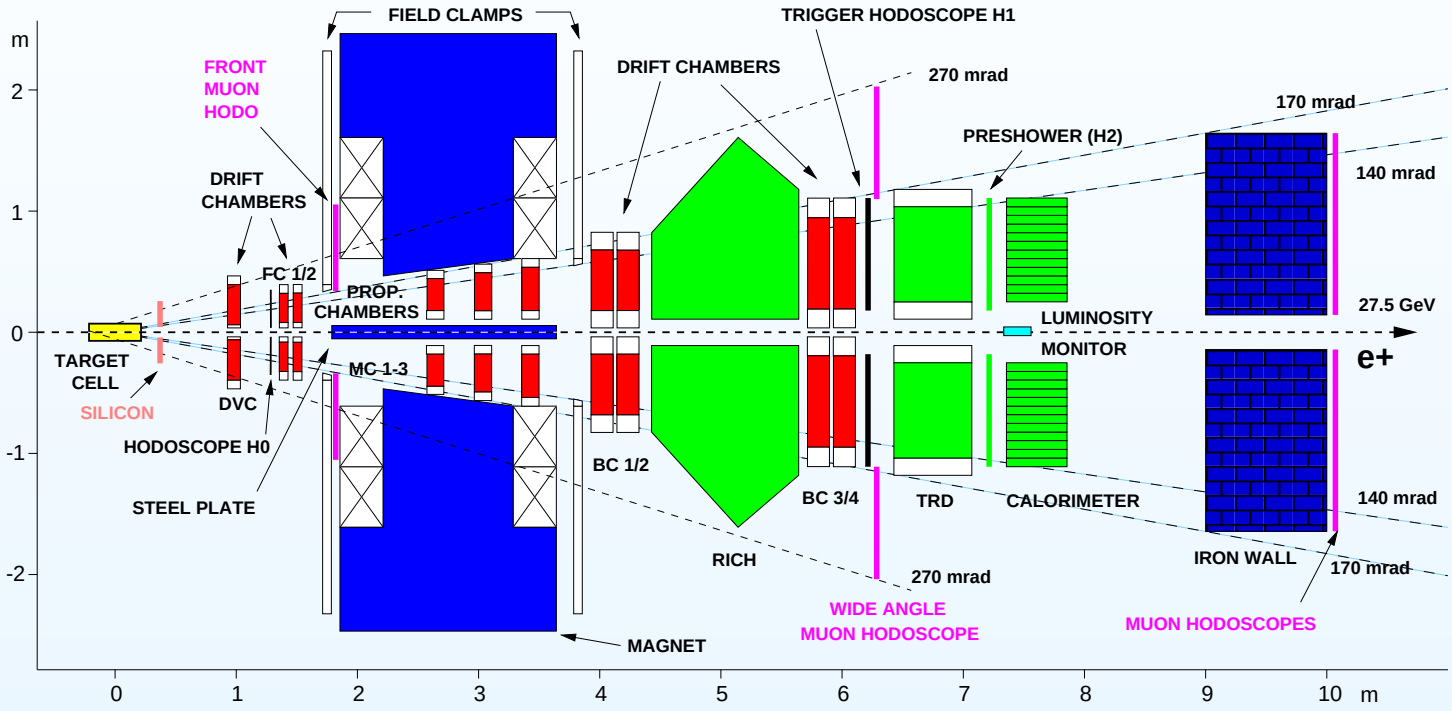


Measurement of transverse spin phenomena:

➥ L_q

➥ transversity measurements

The HERMES experiment:

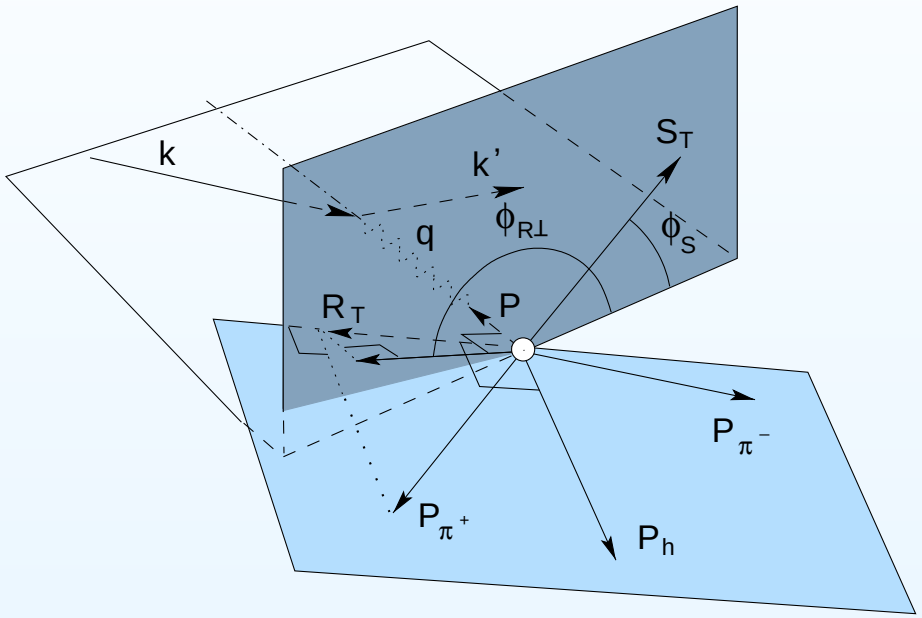


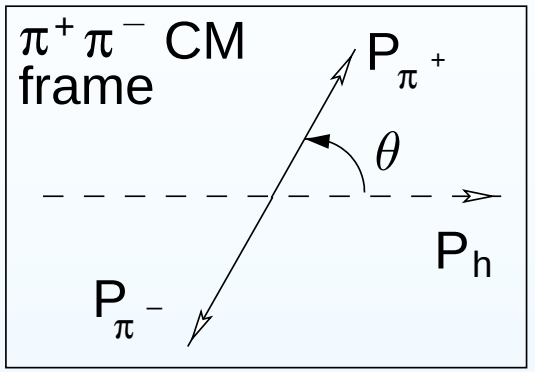
- polarised **gas target** internal to the HERA storage ring
- background-free measurements from highly polarised nucleons
- **2002–2005: transversely polarised hydrogen** target
- very clean lepton-hadron separation and hadron identification

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 ($\boldsymbol{S \cdot (P_1 \times P_2)}$)**
- observed in semi-inclusive DIS on a transversely polarised target:
  - **single-hadron production** ($ep^{\Uparrow} \to e'hX$):
  - **dihadron production** ($ep^{\Uparrow} \to e'h_1h_2X$):
    - $\boldsymbol{S_q \cdot (p_q \times R)}$
    - transfer of transverse quark spin to relative orbital angular momentum of hadron pair ($\boldsymbol{2R = P_{h_1} - P_{h_1}}$)
    - sensitive to $\boldsymbol{h_1^q(x) H_{1,q}^{\sphericalangle}(z, M_{\pi\pi}, \cos\theta)}$
    - dihadron fragmentation function $\boldsymbol{H_{1,q}^{\sphericalangle}(z, M_{\pi\pi}, \cos\theta)}$
      (leading twist, chiral-odd, naive T-odd)

The semi-inclusive production of $\pi^+\pi^-$ pairs:





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

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

$$\boldsymbol{R_T} \equiv \boldsymbol{R} - (\boldsymbol{R}\cdot\hat{\boldsymbol{P}}_{\boldsymbol{h}})\hat{\boldsymbol{P}}_{\boldsymbol{h}}$$

azimuthal angles ϕ_S and ϕ_{R_T}:

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

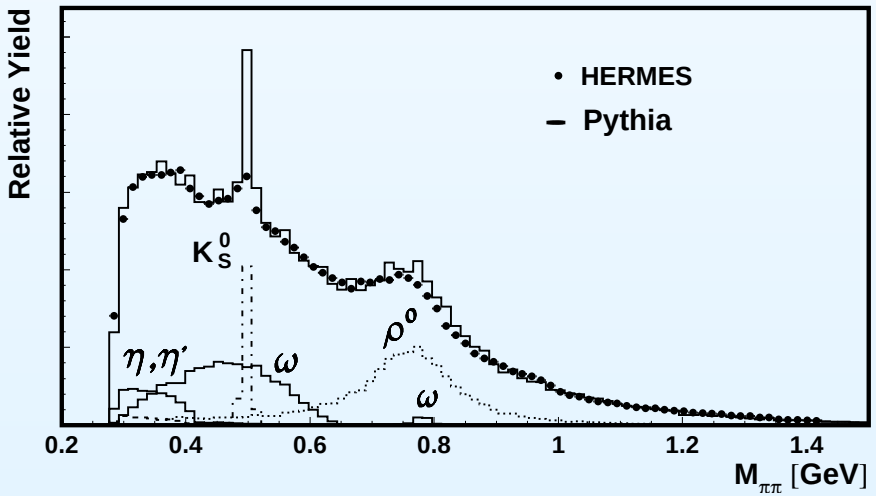
$$\phi_{\boldsymbol{R}_\perp} \equiv \frac{(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{R_T}}{|(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{R_T}|}\arccos\left(\frac{(\boldsymbol{q}\times\boldsymbol{k})\cdot(\boldsymbol{q}\times\boldsymbol{R_T})}{|(\boldsymbol{q}\times\boldsymbol{k})|\,|\boldsymbol{q}\times\boldsymbol{R_T}|}\right)$$

SSA in semi-inclusive $\pi^+\pi^-$ production:

- **Fourier and Legendre expansion:**

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} \sim \frac{\sum_q e_q^2\, h_1^q(x)\, H_{1,q}^{\sphericalangle,sp}(z,M_{\pi\pi})}{\sum_q e_q^2\, f_1^q(x)\, D_{1,q}(z,M_{\pi\pi})}$$

- focus on **sp- and pp-interference** ($M_{\pi\pi} < 1.5\,\text{GeV}$):
  - ➥ $D_{1,q} \simeq D_{1,q} + D_{1,q}^{sp}\cos\theta + D_{1,q}^{pp}\frac{1}{4}(3\cos^2\theta - 1)$
  - ➥ $H_{1,q}^{\sphericalangle} \simeq H_{1,q}^{\sphericalangle,sp} + H_{1,q}^{\sphericalangle,pp}\cos\theta$



- symmetrisation around $\theta = \pi/2$ ➥ $D_{1,q}^{sp}$ and $H_{1,q}^{\sphericalangle,pp}$ drop out

Functional form of the χ^2 fit:

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

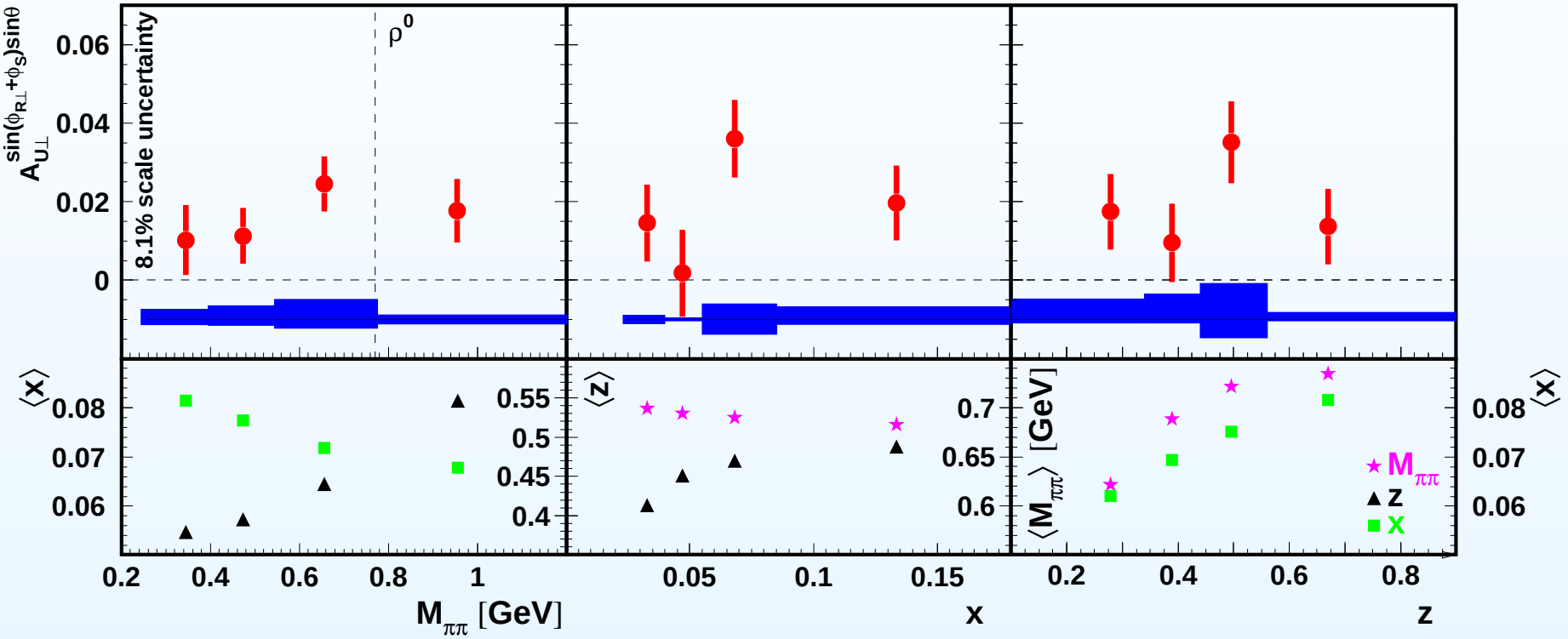
$$A_{U\perp}(\phi_{R\perp}+\phi_S,\theta') = \sin(\phi_{R\perp}+\phi_S)\frac{a\sin\theta'}{1+b\frac{1}{4}(3\cos^2\theta'-1)}$$

- 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 ➥ SSA amplitude
  - standard deviation ➥ systematic uncertainty

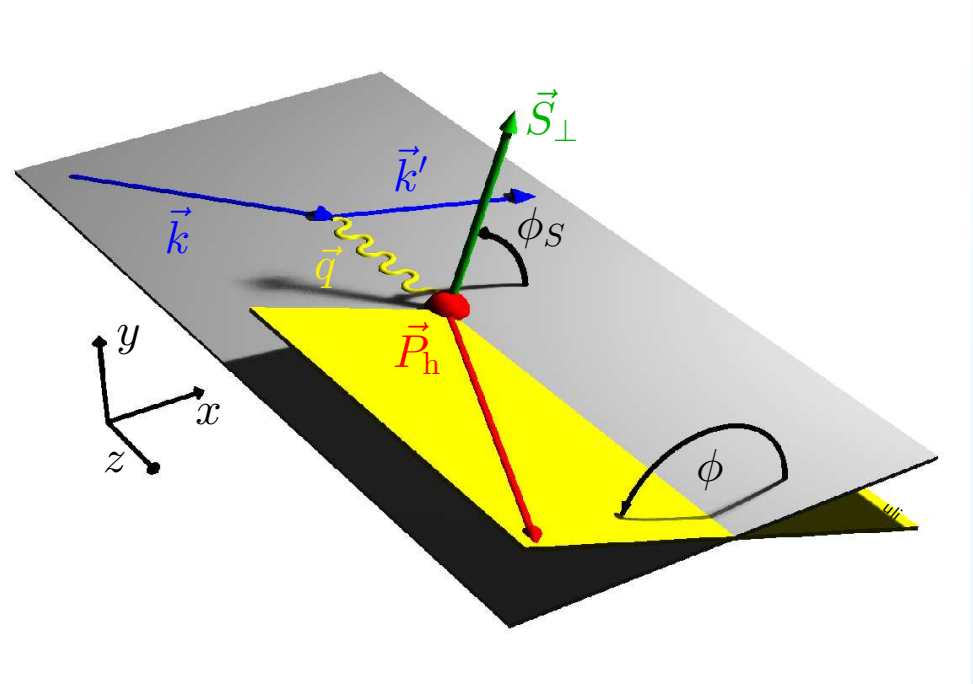
Published Results (**JHEP 0806:017,2008**):



- $A_{U\perp}^{\sin(\phi_{R\perp}+\phi_S)\,\sin\theta} = 0.018 \pm 0.005_{\mathrm{stat}} \pm 0.002_{\mathrm{b-scan}} + 0.004_{\mathrm{acc}}$
- additional 8.1% scale uncertainty (target polarisation)
- first evidence for $H_{1,q}^{\sphericalangle}$
- transversity can be studied in dihadron production

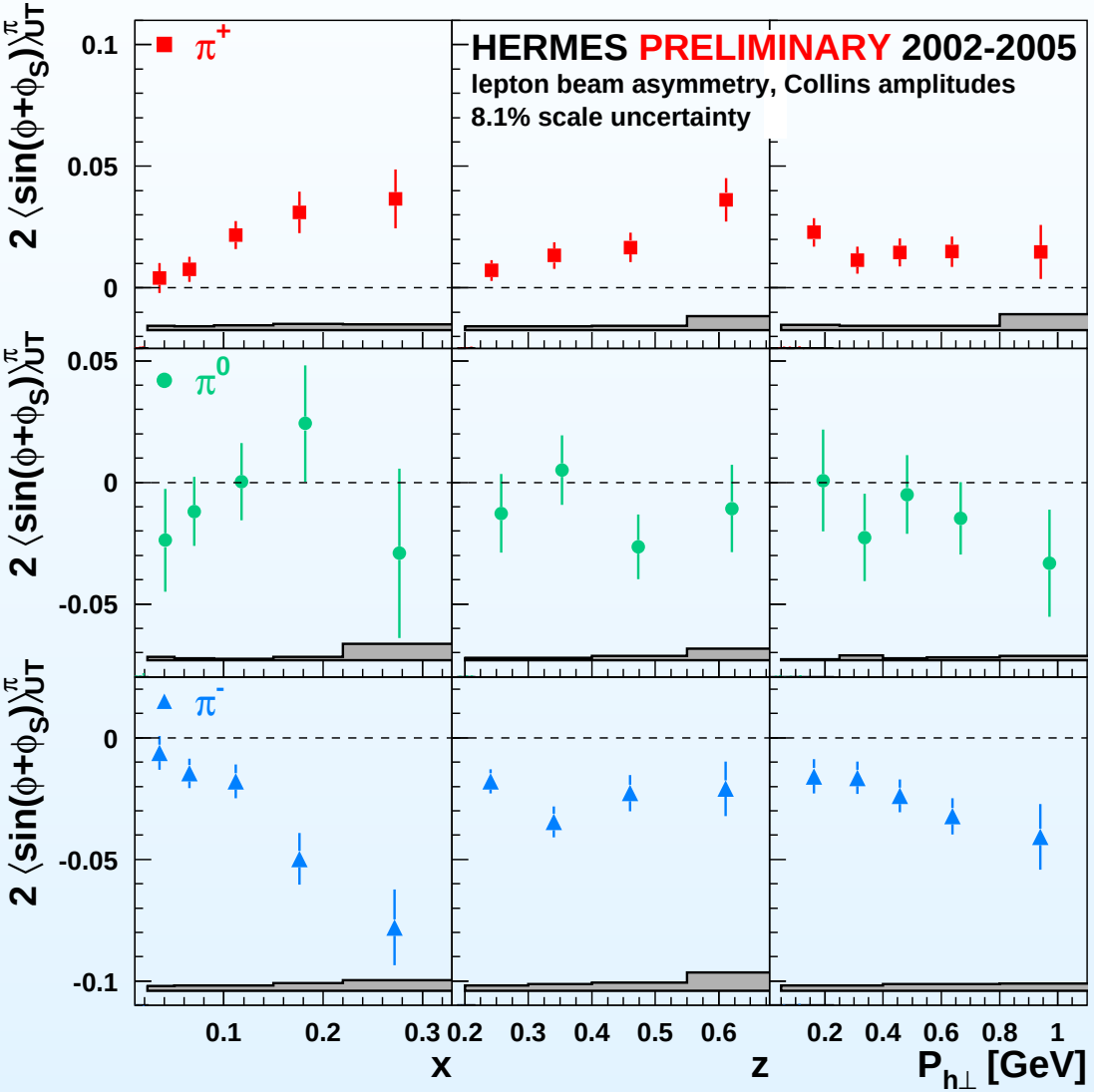
SSA in single-hadron production:

- **single-hadron production** ($ep^{\Uparrow} \to e'hX$):



- **azimuthal asymmetry** in the momentum distribution of the produced hadrons (transverse to the nucleon spin)
  - **Collins mechanism** $(\boldsymbol{S_q} \cdot (\boldsymbol{p_q} \times \boldsymbol{P_h}))$
    ➥ sensitive to transversity
  - **Sivers mechanism** $(\boldsymbol{S_N} \cdot (\boldsymbol{P} \times \boldsymbol{p_q}))$
    ➥ sensitive to L_q

The Collins amplitudes for pions:



Results of the Collins amplitude:

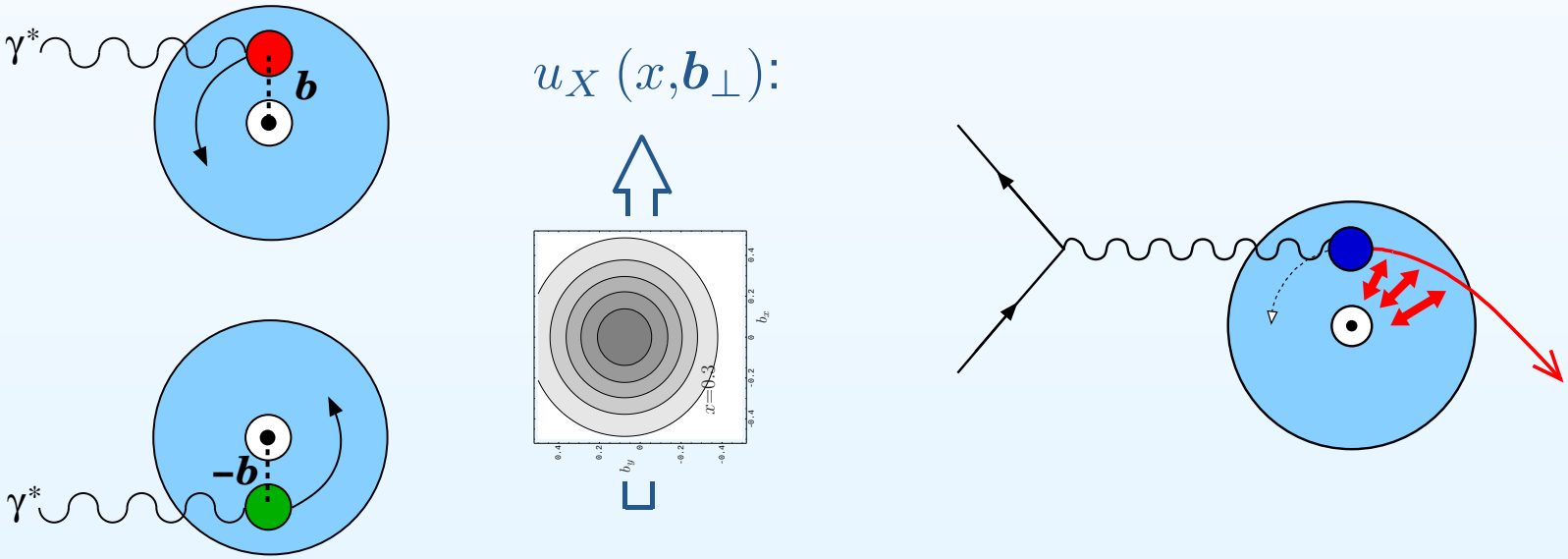
$$h_1^q(x) \otimes H_1^{\perp q}(z)$$

from 2002–2005 data:

- positive amplitudes for π^+
- large negative π^- amplitudes is unexpected
- $H_1^{\perp,\text{unfav}}(z) \approx -H_1^{\perp,\text{fav}}(z)$
- isospin symmetry of π-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**))

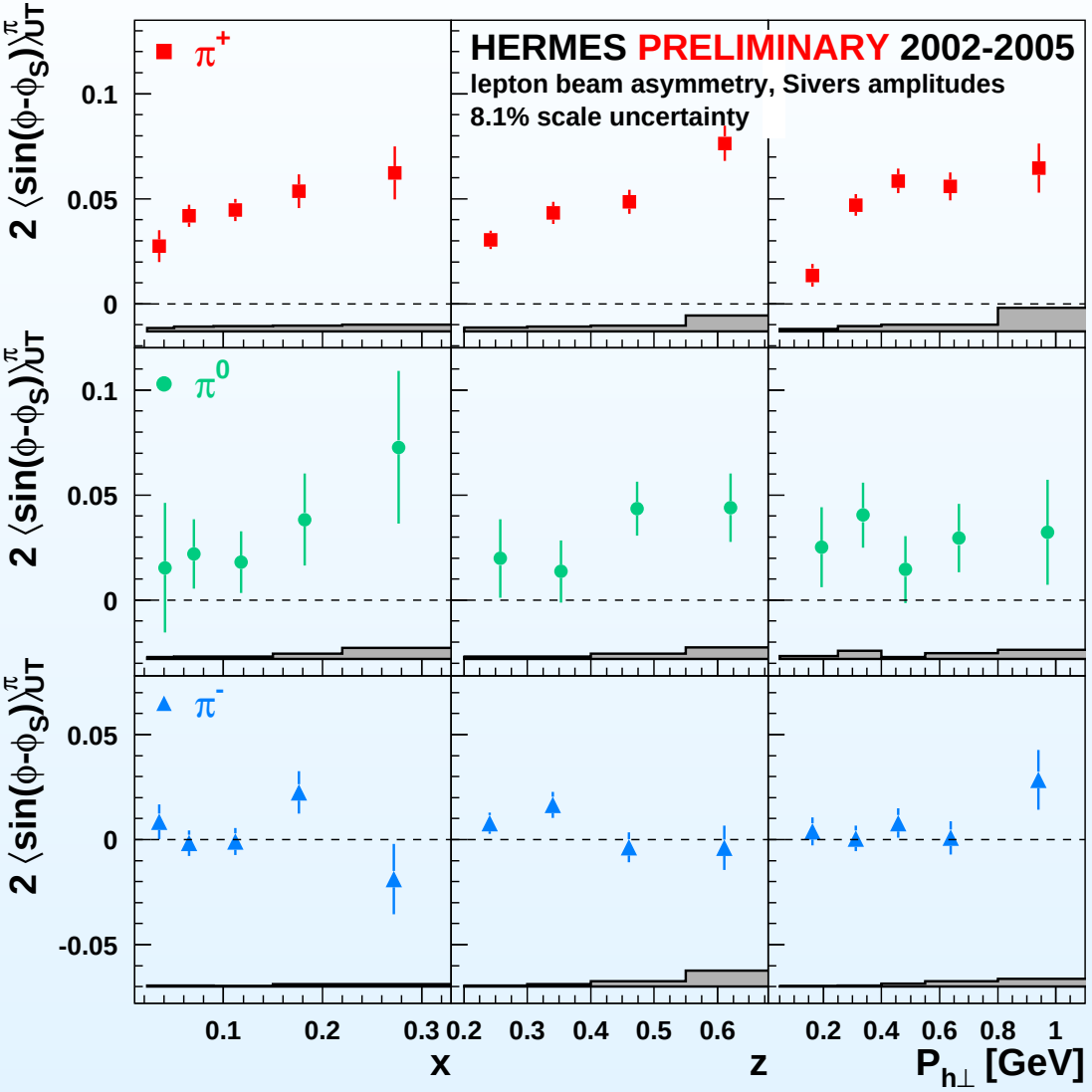


- **final state interactions (naive-T-odd):**

  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:

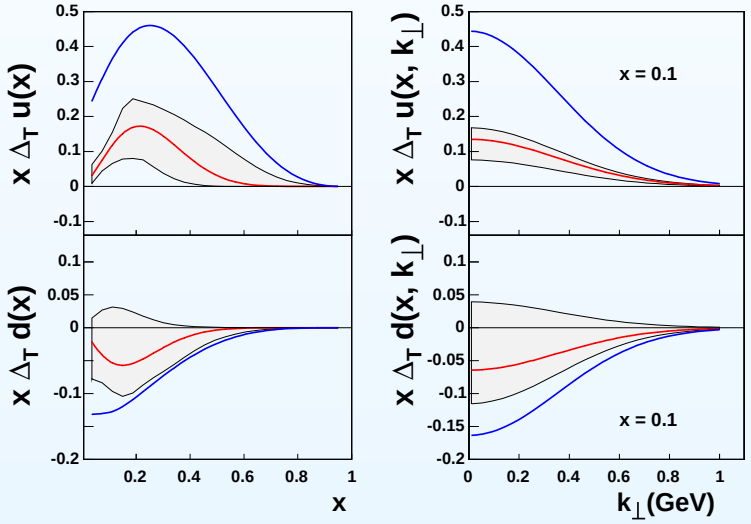
$$f_{1T}^{\perp q}(x) \otimes D_1^q(z).$$

from 2002–2005 data:

- significantly positive for π^+
- implies non-zero L_z^q
- π^- amplitude consistent with zero
- isospin symmetry of π-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 π-mesons
  ➥ enables quantitative extraction of transversity distribution



- significant Sivers amplitudes for π^+ 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