## DIS *2005: Spin physics working group*

# *Transversity measurements at HERMES*

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**Foundations**

- Transversity distribution
- Azimuthal single-spin asymmetries
- Collins moments and Sivers moments

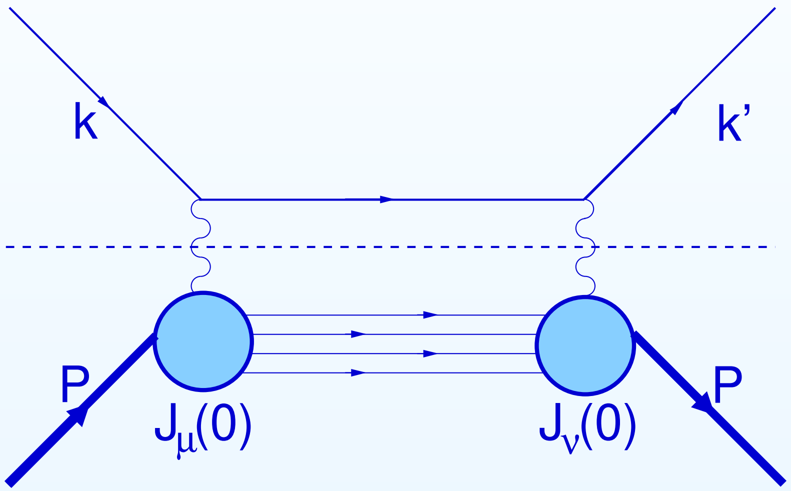
**Extraction**

- Extraction of moments
- 2002–2004 results
- Subleading-twist effects

# Quark-nucleon scattering:

**Electron-hadron scattering:**

leptonic tensor $l^{\mu\nu}$




hadronic tensor $W^{\mu\nu}$

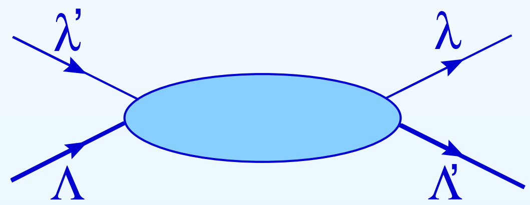
(can be interpreted in quark distribution functions)

**Forward virtual Compton scattering:**

related to $W^{\mu\nu}$ by optical theorem:

$$2\pi W^{\mu\nu} = \mathrm{Im}\, T^{\mu\nu}$$

quark-nucleon forward amplitude $\mathcal{A}$

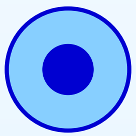
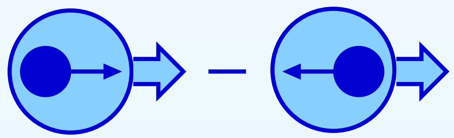
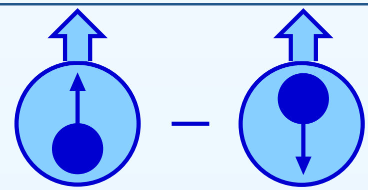



with helicities of quarks ($\lambda^{(\prime)}$) and hadrons ($\Lambda^{(\prime)}$)

Leading twist quark distribution functions can be expressed in terms of quark-nucleon forward amplitudes. Due to helicity conservation ($\Lambda + \lambda = \Lambda' + \lambda'$), parity and time-reversal invariance there are exactly three independent amplitudes:

$$\mathcal{A}_{++,++}, \quad \mathcal{A}_{+-,+-} \quad \text{and} \quad \mathcal{A}_{+-,-+}.$$

# Leading twist quark distributions:

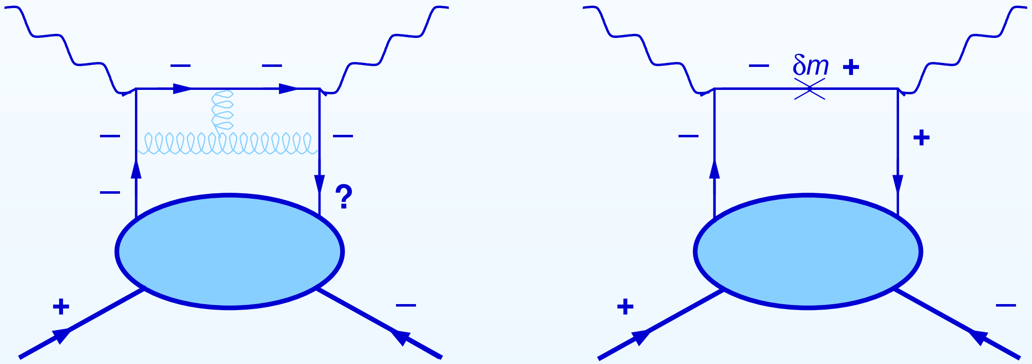
| **momentum distribution** $\boldsymbol{q(x,Q^2)}$ | **helicity distribution** $\boldsymbol{\Delta q(x,Q^2)}$ | ***transversity*** **distribution** $\boldsymbol{\delta q(x,Q^2)}$ |
|---|---|---|
| **forward quark-nucleon amplitudes:** (in helicity basis) | | |
| $\sim \mathrm{Im}\left(A_{++,++} + A_{+-,+-}\right)$ measures spin average | $\sim \mathrm{Im}\left(A_{++,++} - A_{+-,+-}\right)$ measures helicity difference | $\sim \mathrm{Im}\left(A_{+-,-+}\right)$ measures helicity flip |
| **probabilistic interpretation:** | | |
|  (in helicity basis) |  (in helicity basis) |  (in basis of transverse spin eigen states) |

$\longrightarrow$ complete description of quark momentum ($P$) and spin ($S$) at leading twist:

$$\Phi(x) \quad = \quad \frac{1}{2}\left\{\boldsymbol{q}\left(\boldsymbol{x},\boldsymbol{Q^2}\right)\not{P} + \lambda_N \boldsymbol{\Delta q}\left(\boldsymbol{x},\boldsymbol{Q^2}\right)\gamma_5\not{P} + \boldsymbol{\delta q}\left(\boldsymbol{x},\boldsymbol{Q^2}\right)\not{P}\gamma_5\not{S}_\perp\right\}.$$

# Properties of transversity:

- The Difference between distributions $\Delta q\left(x, Q^2\right)$ and $\delta q\left(x, Q^2\right)$ provides measurement of the relativistic nature of the quarks inside the nucleon.
- **Chirality and measurement**: The transversity distribution is chiral-odd,




i.e. cannot be determined in inclusive DIS, another chiral-odd fragmentation (or distribution) function is needed.

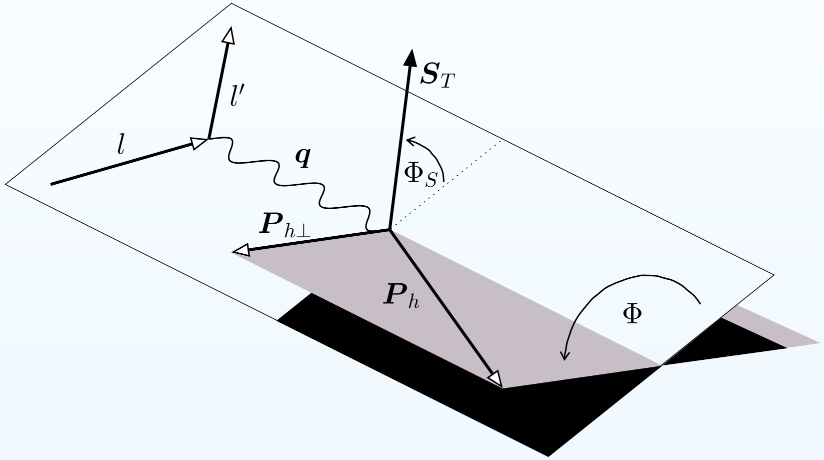
- The transversity distribution can be measured in experiments with two hadrons in the initial state or one hadron both in initial and final state. Thereby at least one hadron has to be transversely polarised.
- At HERMES

$$\delta q\left(x, Q^2\right) \times H_1^{\perp}\left(z,(-z\boldsymbol{k}_T)^2\right)$$

is accessible in azimuthal single-spin asymmetries in semi-inclusive DIS.

# Azimuthal single-spin asymmetries:

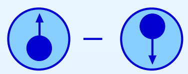
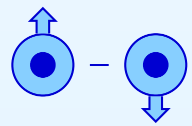
- **Semi-inclusive DIS on a transversely polarised target**:




In addition to the azimuthal angle $\boldsymbol{\Phi}$ the azimuthal angle $\boldsymbol{\Phi_S}$ is observable.

Non-vanishing $\boldsymbol{P_{h\perp}}$ is caused by intrinsic transverse momenta $\boldsymbol{p}_T$ and $\boldsymbol{k}_T$.

- **Generalised distribution and fragmentation functions**:

| **Collins function** $H_1^{\perp}\left(z,(-z\boldsymbol{k}_T)^2\right)$ | **Sivers function** $f_{1T}^{\perp}\left(x,\boldsymbol{p}_T^2\right)$ |
|---|---|
| fragmentation function | distribution function |
|  |  |
| chiral-odd | chiral-even |
| | implies non-vanishing $L_z^q$ |
| naive time reversal odd $\Rightarrow$ | naive time reversal odd $\Rightarrow$ |
| azimuthal single-spin asymmetries | azimuthal single-spin asymmetries |

# Collins and Sivers moments:

- The transverse target cross section contains a convolution integral over intrinsic transverse momenta $\boldsymbol{p}_T$ and $\boldsymbol{k}_T$.
- Assuming a Gaussian dependence one can disentangle the convolution integral.
- The *unweighted* (i.e. no weighting by $\frac{|\boldsymbol{P}_{h\perp}|}{z}$) asymmetry $A^h_{\mathrm{UT}}$ (for each hadron type $h$) becomes:

$$A^h_{\mathrm{UT}} \approx 2\,|\boldsymbol{S}_T|\underset{\substack{\uparrow\\ \textbf{distinctive}}}{\sin(\Phi+\Phi_S)}\,\frac{\overset{\textbf{Collins moment}}{B(y)\sum_q \left(e_q^2\,\boldsymbol{\delta q(x)}\ \boldsymbol{H_1^{\perp(1/2)q}(z)}\right)\Big/\sqrt{\langle p_T^2\rangle+\langle k_T^2\rangle}}}{A(x,y)\sum_q q(x)\ D_1^q(z)}$$

$$-\quad 2\,|\boldsymbol{S}_T|\overset{\substack{\textbf{signature}\\ \downarrow}}{\sin(\Phi-\Phi_S)}\,\frac{\overset{\textbf{Sivers moment}}{\sum_q \left(e_q^2\,\boldsymbol{f_{1T}^{\perp(1/2)q}(x)}\ \boldsymbol{D_1^{\perp q}(z)}\right)\Big/\sqrt{\langle p_T^2\rangle+\langle k_T^2\rangle}}}{\sum_q q(x)\ D_1^q(z)}$$

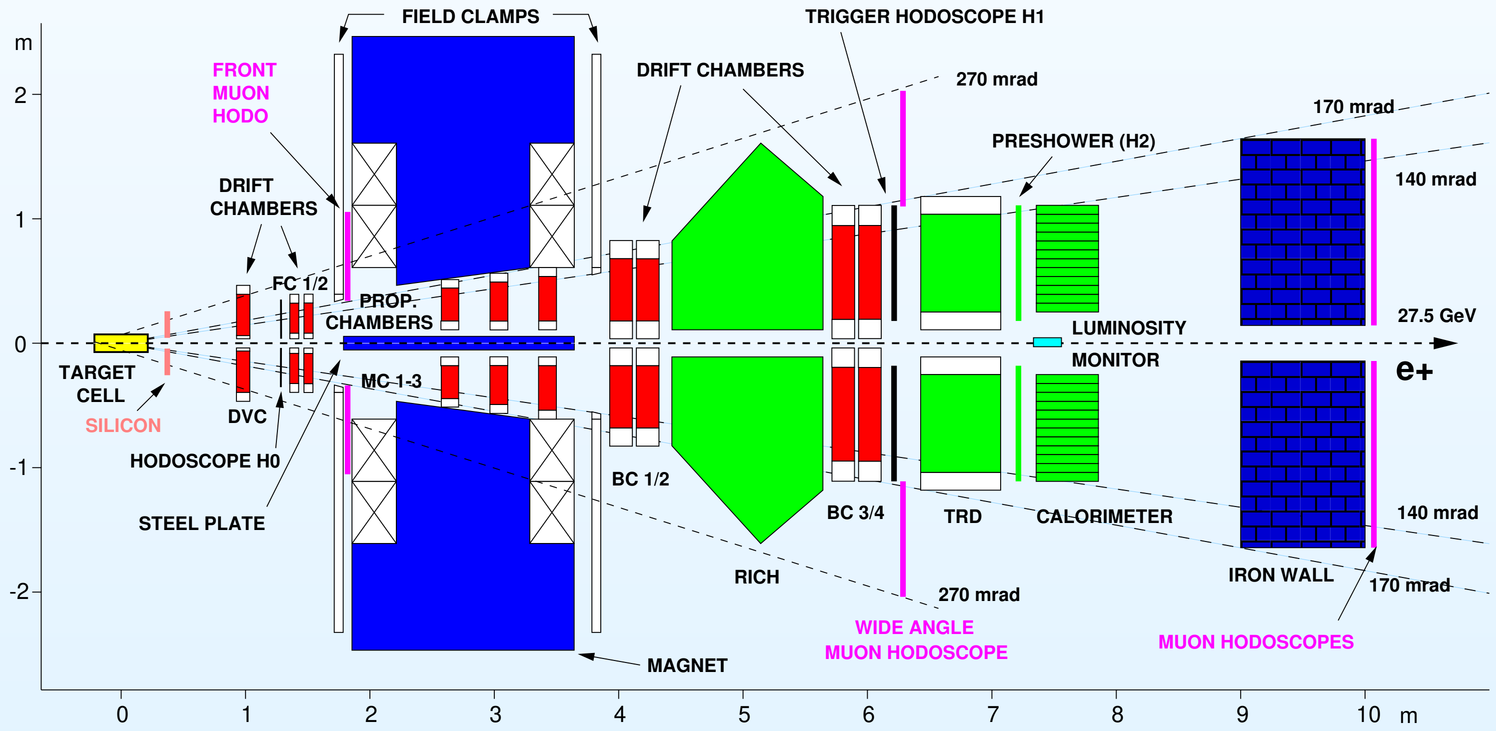
UT means unpolarised beam (U) and transversely polarised target (T).

$\boldsymbol{S}_T$ states target polarisation vector.

# Extraction:

# The HERMES experiment:

- **Deep inelastic scattering** of longitudinally polarised **positrons** (beam energy of $27.6\,\mathtt{GeV}$) on
- a **transversely polarised hydrogen gas target**.
- Forward magnetic spectrometer with precise momentum resolution ($\Delta p/p \leqslant 0.026$) and angle resolution ($\Delta\theta \leqslant 0.6\,\mathtt{mrad}$),




which provides a very clean separation of the scattered lepton track from hadron tracks with an efficiency exceeding 98%.

# Extraction of Collins and Sivers moments:

- Determination of unweighted asymmetries for charged pions:

$$A_{\mathrm{UT}}^{\pi^\pm}(\Phi,\Phi_S) = \frac{1}{\langle P_z \rangle} \cdot \frac{N_{\pi^\pm}^{\Uparrow}(\Phi,\Phi_S) - N_{\pi^\pm}^{\Downarrow}(\Phi,\Phi_S)}{N_{\pi^\pm}^{\Uparrow}(\Phi,\Phi_S) + N_{\pi^\pm}^{\Downarrow}(\Phi,\Phi_S)}$$

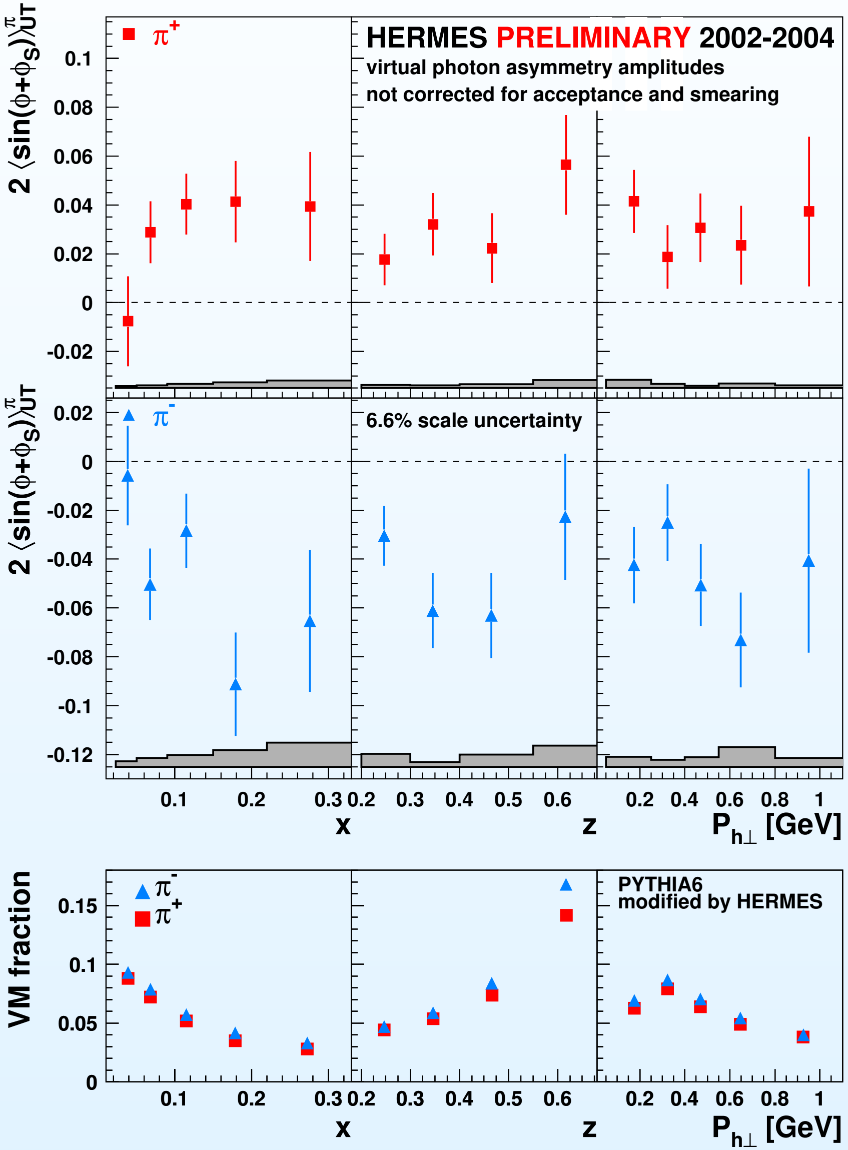
$\langle P_z \rangle = 0.754 \pm 0.050$ (average target polarisation value)

- **Moments** are extracted in the two-dimensional fit:

$$\begin{aligned} A_{\mathrm{UT}}^{\pi^\pm}(\Phi, \Phi_S) \quad = \quad & \overset{\textbf{Sivers moment}}{2 \cdot \langle \sin(\boldsymbol{\Phi} - \boldsymbol{\Phi_S}) \rangle_{\mathrm{UT}}^{\boldsymbol{\pi^\pm}}} \cdot \sin(\Phi - \Phi_S) + \\ & \overset{\textbf{Collins moment}}{2 \cdot \langle \sin(\boldsymbol{\Phi} + \boldsymbol{\Phi_S}) \rangle_{\mathrm{UT}}^{\boldsymbol{\pi^\pm}}} \cdot \frac{B(\langle y \rangle)}{A(\langle x \rangle, \langle y \rangle)} \sin(\Phi + \Phi_S) + \\ & c_3 \cdot \sin(2\Phi - \Phi_S) + c_4 \cdot \sin \Phi_S + c_5 \end{aligned}$$

$A(\langle x \rangle, \langle y \rangle)$, $B(\langle y \rangle)$: kinematic factors; $c_3$, $c_4$, $c_5$: fit parameters

# Unweighted Collins moment:



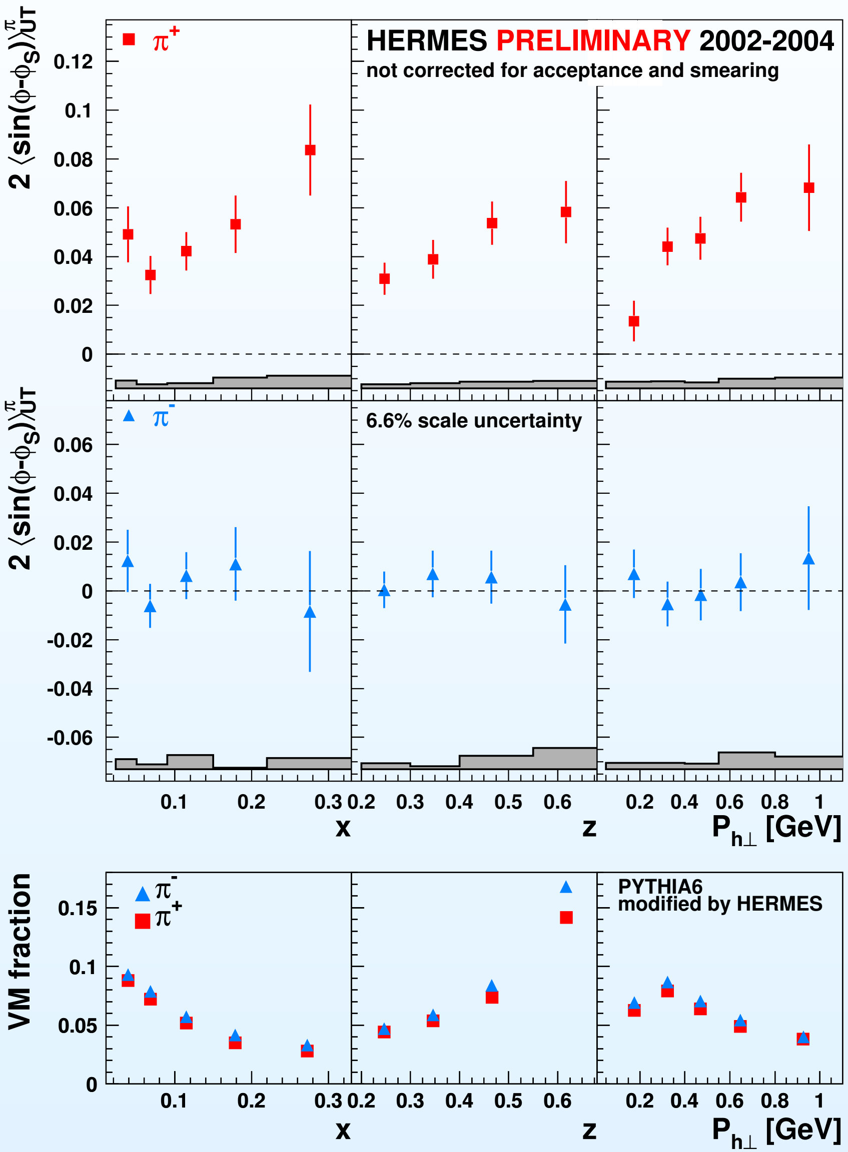

**Results of 2002–2004 data:**

- Result is consistent with published Collins moments.
- Collins moment is positive for $\pi^+$ and negative for $\pi^-$.
- The large negative $\pi^-$ moment is unexpected.
- Additional information on the Collins fragmentation function (from BELLE) is needed in order to extract the transversity distribution.

**Systematic uncertainties:**

- Common scale uncertainty of 6.6% in the moments.
- Background asymmetry of diffractive vector mesons.

# Unweighted Sivers moment:




**Results of 2002–2004 data:**

- Result is consistent with published Sivers moments.
- Sivers moment is significantly positive for $\pi^+$ and implies a non-vanishing orbital angular momentum $L_z^q$.
- Sivers moment for $\pi^-$ is consistent with zero.
- Since spin independent fragmentation function is known, extraction of Sivers function is possible.

**Systematic uncertainties:**

- Common scale uncertainty of 6.6% in the moments.
- Background asymmetry of diffractive vector mesons.

# Subleading-twist effects:

Transverse polarised target:

- **in theory:** polarisation w.r.t. the virtual photon $\longrightarrow A_{\mathrm{UT},\boldsymbol{q}}^{\sin(\Phi\pm\Phi_S)}$
- **in experiment:** polarisation w.r.t. the lepton beam $\longrightarrow A_{\mathrm{UT},\boldsymbol{l}}^{\sin(\Phi\pm\Phi_S)}$

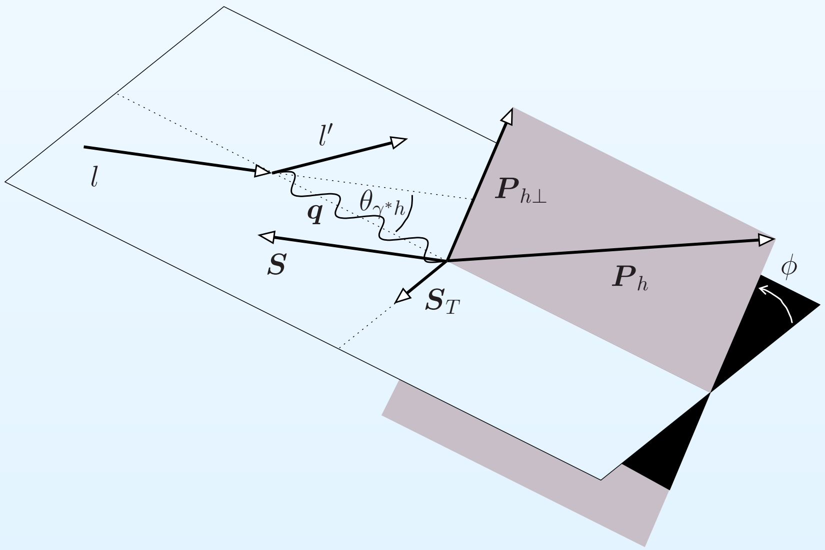
- **Conversion** with subleading-twist term:

$$A_{\mathrm{UT},\boldsymbol{q}}^{\sin(\Phi\pm\Phi_S)} \approx A_{\mathrm{UT},\boldsymbol{l}}^{\sin(\Phi\pm\Phi_S)} - \frac{1}{2}\sin\theta_{\gamma^*} A_{\mathrm{UL},\boldsymbol{l}}^{\sin\Phi}$$

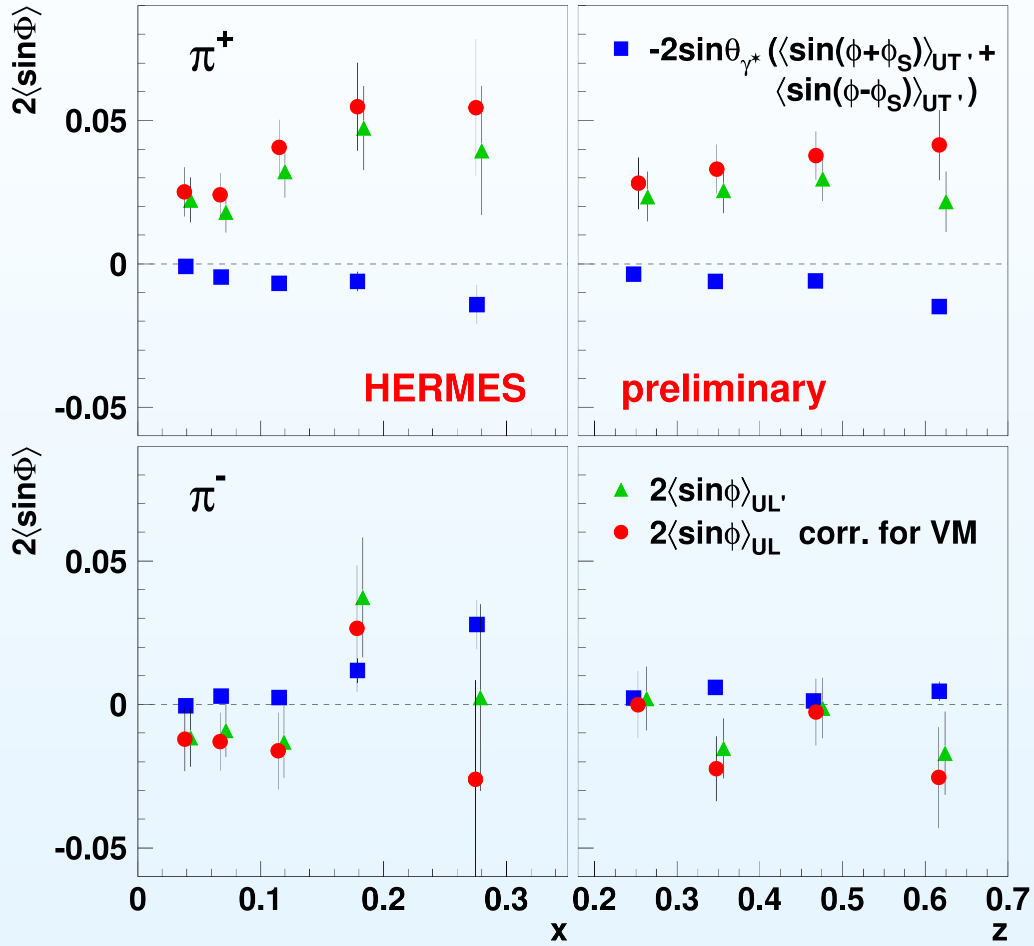
$\theta_{\gamma^*}$ polar angle between the incoming beam direction and the virtual photon direction

- Longitudinal lepton moments $\langle\sin\Phi\rangle_{\mathrm{UL}}^{\boldsymbol{l}}$ (subleading-twist term) were extracted.

Semi-inclusive DIS on a longitudinally polarised target (L):



# Results of $A_{\mathrm{UL},q}^{\sin\Phi}$:




$A_{\mathrm{UL},q}^{\sin\Phi}$ is labelled $\langle \sin\Phi\rangle_{\mathrm{UL}}$.

$A_{\mathrm{UL},l}^{\sin\Phi}$ is labelled $\langle \sin\Phi\rangle'_{\mathrm{UL}}$ .

**Results:**

- $A_{\mathrm{UL},q}^{\sin\Phi}$ is about $2-5\%$ for $\pi^+$
- and approximately zero for $\pi^-$.
- Systematic uncertainty is less than $0.003$.
- Maximum difference $|A_{\mathrm{UT},q} - A_{\mathrm{UT},l}| < 0.004$

# Summary and outlook:

- Evidence for both Collins and Sivers asymmetries
- Non-zero Sivers function for $\pi^+$ implies non-vanishing orbital momentum of quarks inside the nucleon.
- Extraction of virtual photon asymmetries is in progress.
- Extraction of Sivers function is in progress.
- Amount of data will increase due continued data recording in running period 2004–2005.