Signals for transverse-momentum-dependent quark distribution functions observed at the HERMES *experiment*

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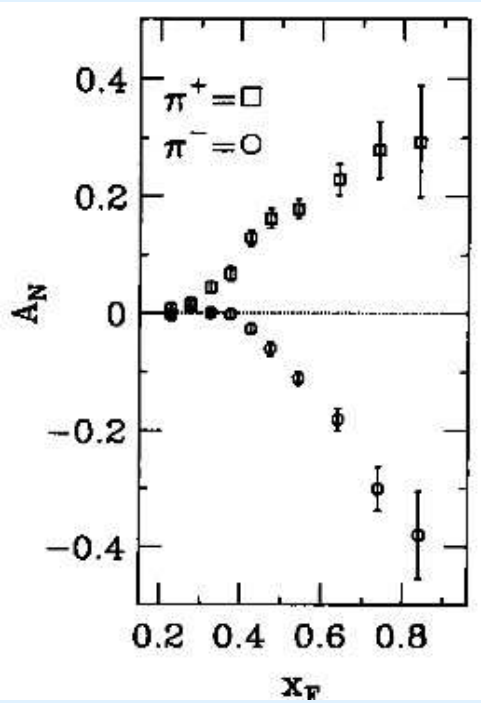
on behalf of the hermes collaboration

Where worlds collide:

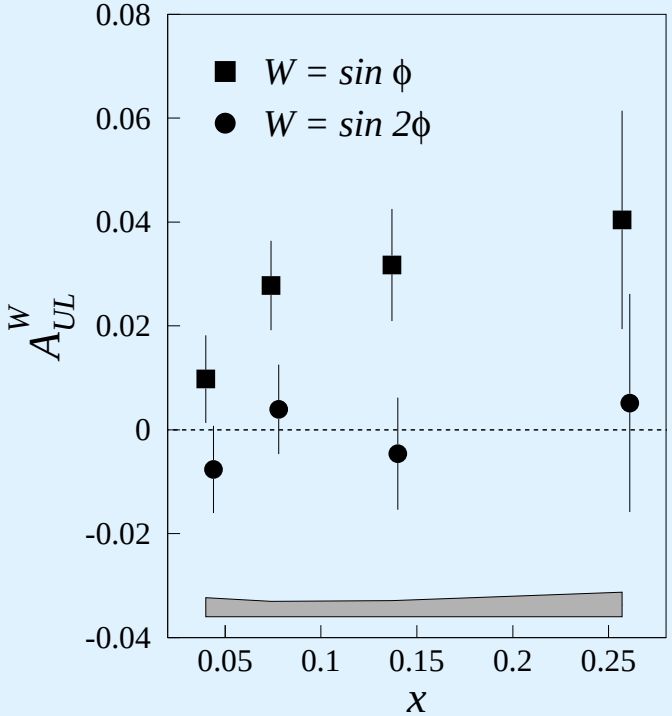
- **Observation of single-spin asymmetries**:

E581/E704 ($p^{\Uparrow}p \to hX$) :



PL**B261**, 201–206, 1991

HERMES ($lp^{\Rightarrow} \to l'hX$) :



PRL**84**, 4047–4051, 2000

- Global analysis of:

transverse-momentum-dependent PDF

Leading-twist representation of the nucleon structure:

- description of the nucleon structure **including** $\boldsymbol{p}_T$:

$$\frac{1}{2}\,\mathrm{Tr}\left[\left(\gamma^+ + \lambda\gamma^+\gamma_5\right)\Phi\right] = \frac{1}{2}\left[f_1^q + S_T^i\epsilon^{ij}p_T^j\frac{1}{M}\,f_{1\mathsf{T}}^{\perp,q} + \lambda\Lambda\,g_1^q + \lambda S_T^i p_T^i\frac{1}{M}\,g_{1\mathsf{T}}^{\perp,q}\right],$$

$$\frac{1}{2}\,\mathrm{Tr}\left[\left(\gamma^+ - s_T^j i\sigma^{+j}\gamma_5\right)\Phi\right] = \frac{1}{2}\left[f_1^q + S_T^i\epsilon^{ij}p_T^j\frac{1}{M}\,f_{1\mathsf{T}}^{\perp,q} + s_T^i\epsilon^{ij}p_T^j\frac{1}{M}\,h_1^{\perp,q} + s_T^i S_T^i\,h_1^q + s_T^i\left(2p_T^i p_T^j - \boldsymbol{p}_T^2\delta^{ij}\right)S_T^j\frac{1}{2M^2}\,h_{1\mathsf{T}}^{\perp,q} + \Lambda s_T^i p_T^i\frac{1}{M}\,h_{1\mathsf{L}}^{\perp,q}\right],$$

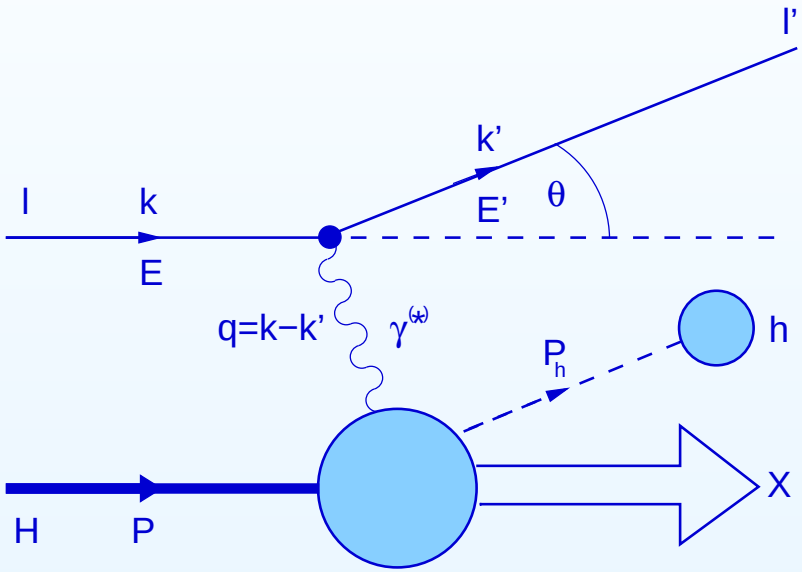
quark λ and nucleon helicity Λ, transverse spins $\boldsymbol{s}_T$ and $\boldsymbol{S}_T$ of quarks and nucleons

- **transverse-momentum-dependent PDF**
  ➥ related to **spin-orbit correlations**
  ➥ constraints on orbital angular momentum (contributions)?

- **naive-T-odd** Sivers $f_{1\mathsf{T}}^{\perp,q}$ and Boer–Mulders $h_1^{\perp,q}$ functions
  ➥ initial- or final-state interactions / **transverse SSA**
  ➥ profound consequences on factorisation and universality

The deep-inelastic scattering process:

Lepton scattering by single-photon exchange:



inclusive DIS : $lH \to l'X,$

semi-inclusive DIS : $lH \to l'h_1 \ldots h_n X$

DIS kinematics:

$$Q^2 = -q^2 \overset{\text{lab}}{=} 4EE' \sin^2\left(\frac{\theta}{2}\right)$$

$$\frac{\lambda}{2\pi} \overset{\text{lab}}{=} \frac{1}{|\boldsymbol{q}|}$$

$$x = \frac{Q^2}{2p \cdot q} \overset{\text{lab}}{=} \frac{Q^2}{2M(E - E')}$$

$$y = \frac{P \cdot q}{P \cdot k} \overset{\text{lab}}{=} \frac{E - E'}{E}$$

$$z = \frac{P \cdot P_h}{P \cdot q} \overset{\text{lab}}{=} \frac{E_h}{\nu}$$

Single-hadron production:

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

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

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

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

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

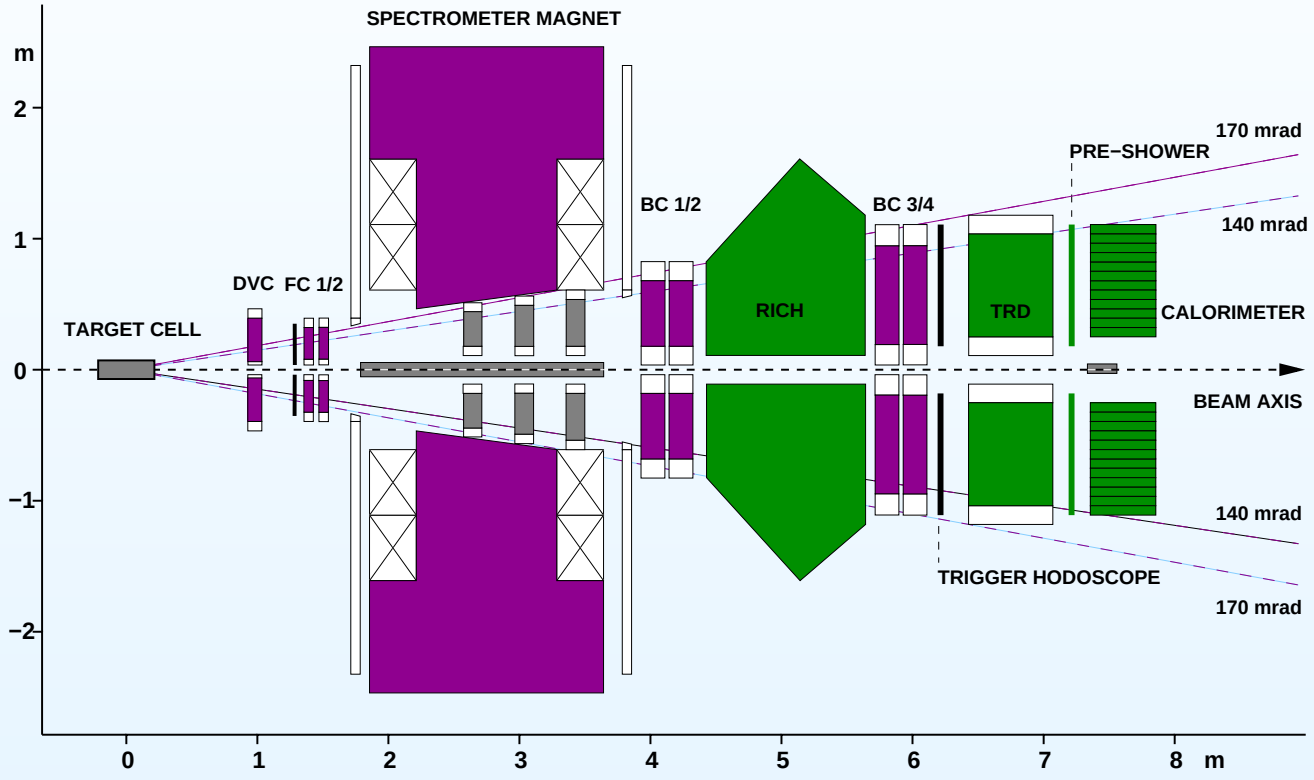
σ_{XY}

Beam Target

Polarization

The HERMES polarised DIS scattering experiment:

- well-suited for **measurements of azimuthal asymmetries**

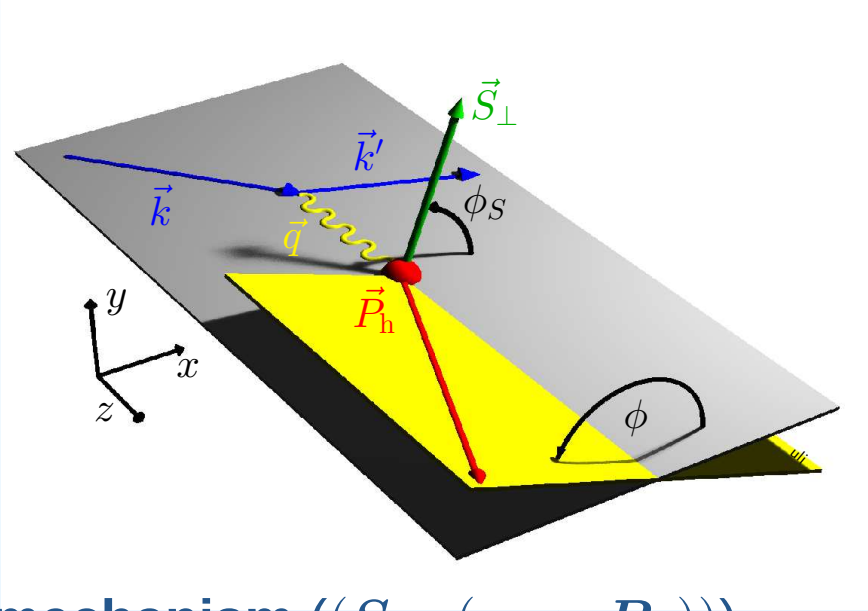


- (un)polarised **gas target** internal to the HERA storage ring
  ➥ background-free measurements from highly polarised nucleons
  ➥ substantial reduction of time-dependent systematics
- very clean lepton-hadron separation and hadron identification

The hunt for transversity

Transversity measurement in single-hadron production:

- observation of **azimuthal asymmetry** $A_{\mathsf{UT}}(\phi,\phi_S)$:

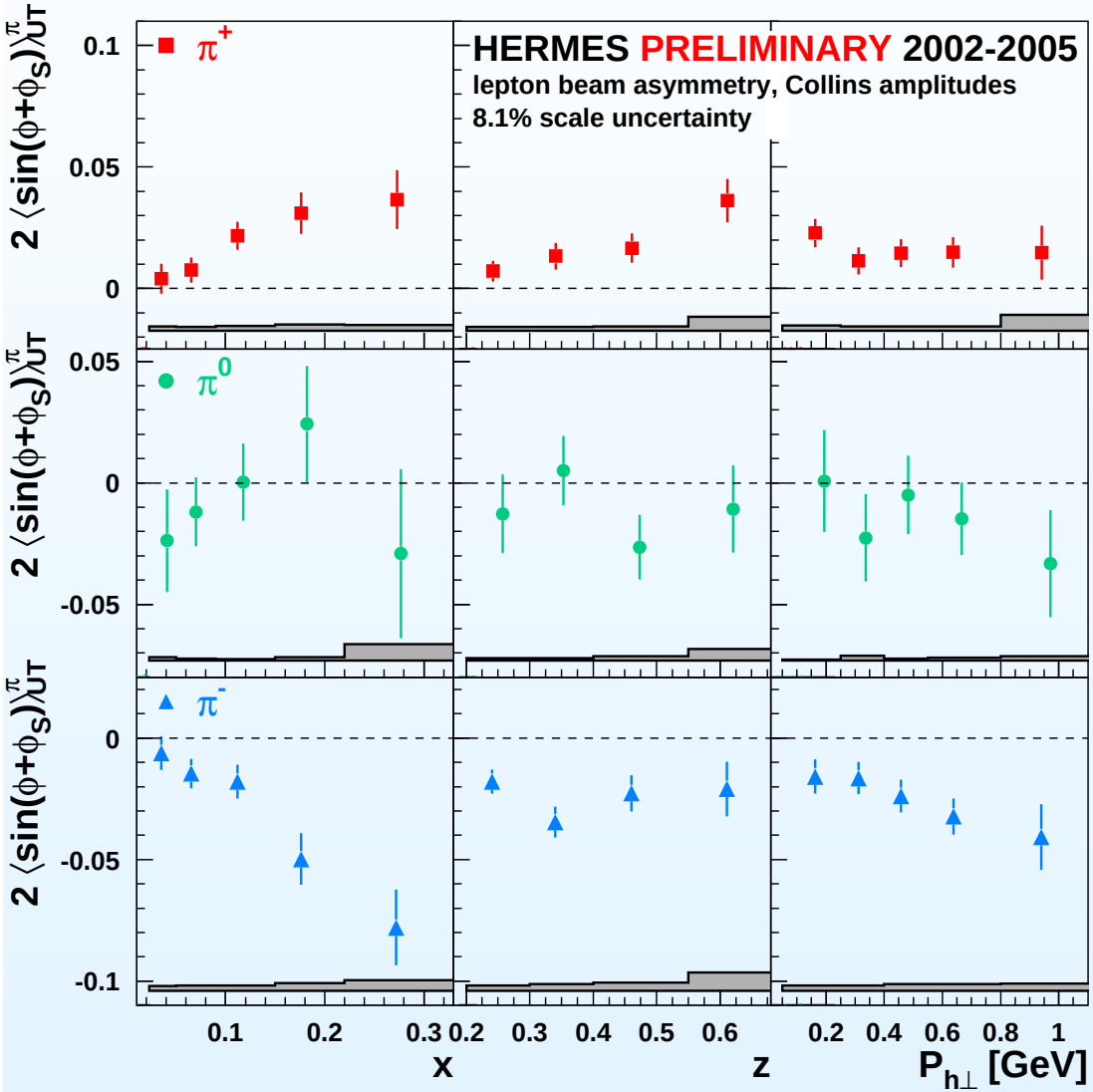


- due to **Collins mechanism** $((S_q \cdot (p_q \times P_h)))$
- **Fourier decomposition of** $\sigma_{\mathsf{U}\perp}$ including:

$$\boxed{2\langle \sin(\phi+\phi_S)\rangle_{\mathsf{UT}} = \frac{\sum_q e_q^2 h_1^q(x,p_T^2) \otimes_{\mathcal{W}} H_1^{\perp,q}(z,K_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,K_T^2)},}$$

$$\sin(\phi-\phi_S),\ \sin(3\phi-\phi_S),\ \sin(\phi_S),\ \sin(2\phi-\phi_S),\ \sin(2\phi+\phi_S).$$

The Collins amplitudes for pions:



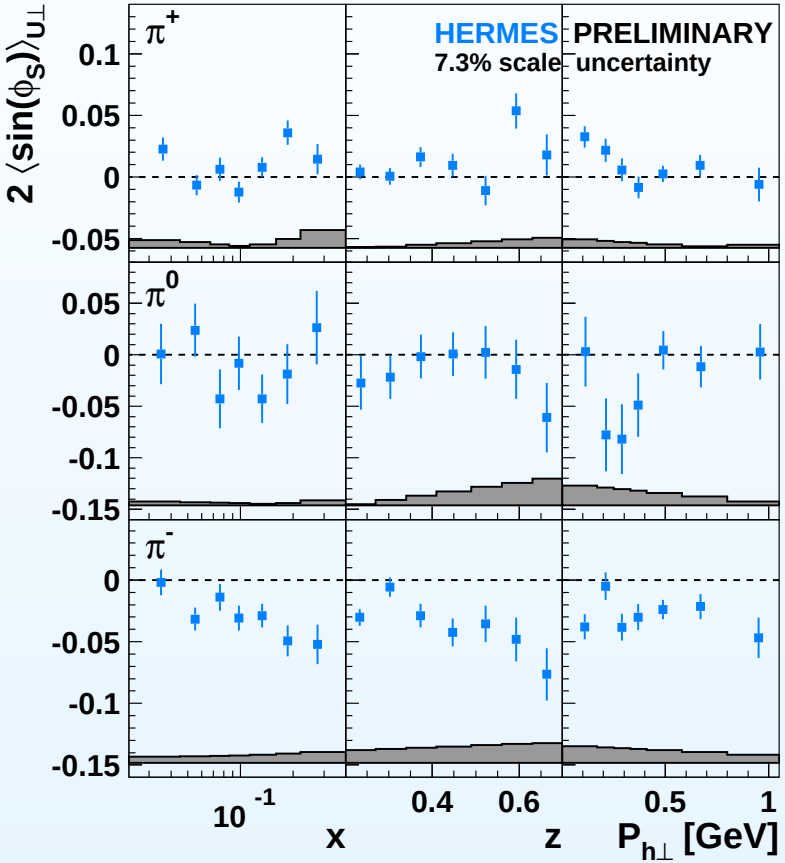
Results of the Collins amplitude:

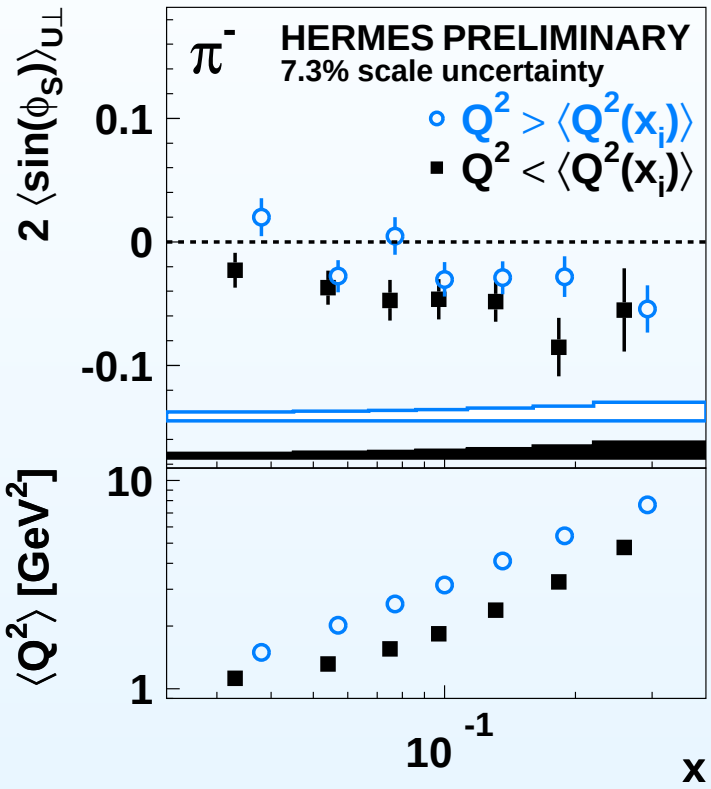
$$h_1^q(x) \otimes H_1^{\perp q}(z)$$

from 2002–2005 data:

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

The $\langle \sin(\phi_S) \rangle_{U\perp}$ Fourier component:



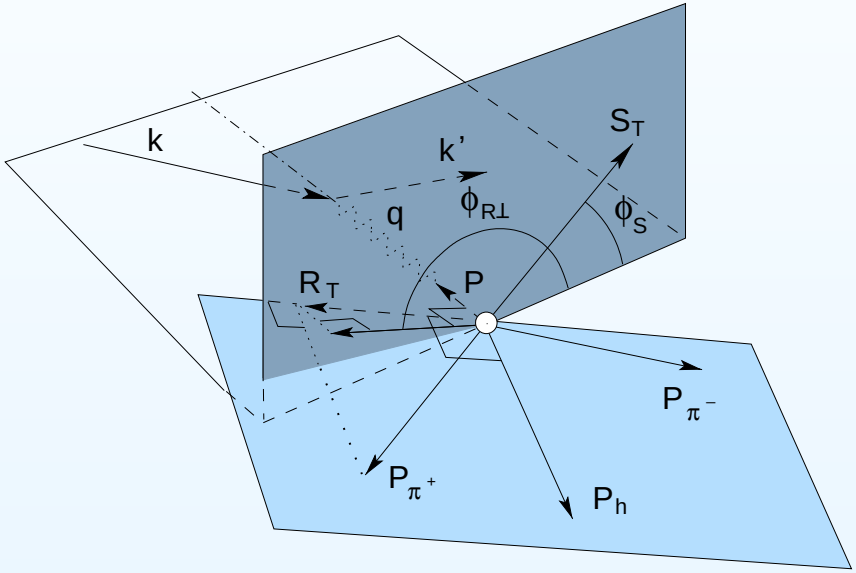


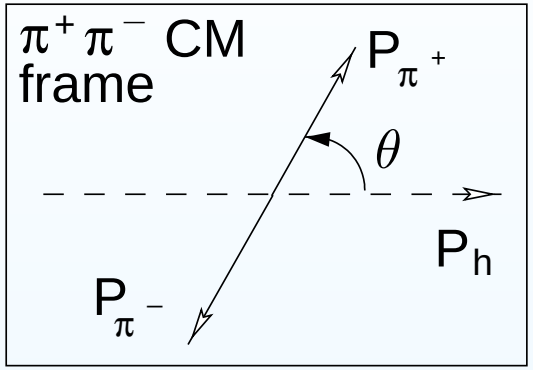
integration over transverse hadron momentum:

$$F_{UT}^{\sin(\phi_S)}(x,Q^2,z) = -x\frac{2M_h}{Q}\sum_q e_q^2\, h_1^q(x)\,\frac{\tilde{H}^q(z)}{z}$$

Transversity measurement in dihadron production:

transverse SSA: $S_q \cdot (p_q \times R)$





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

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

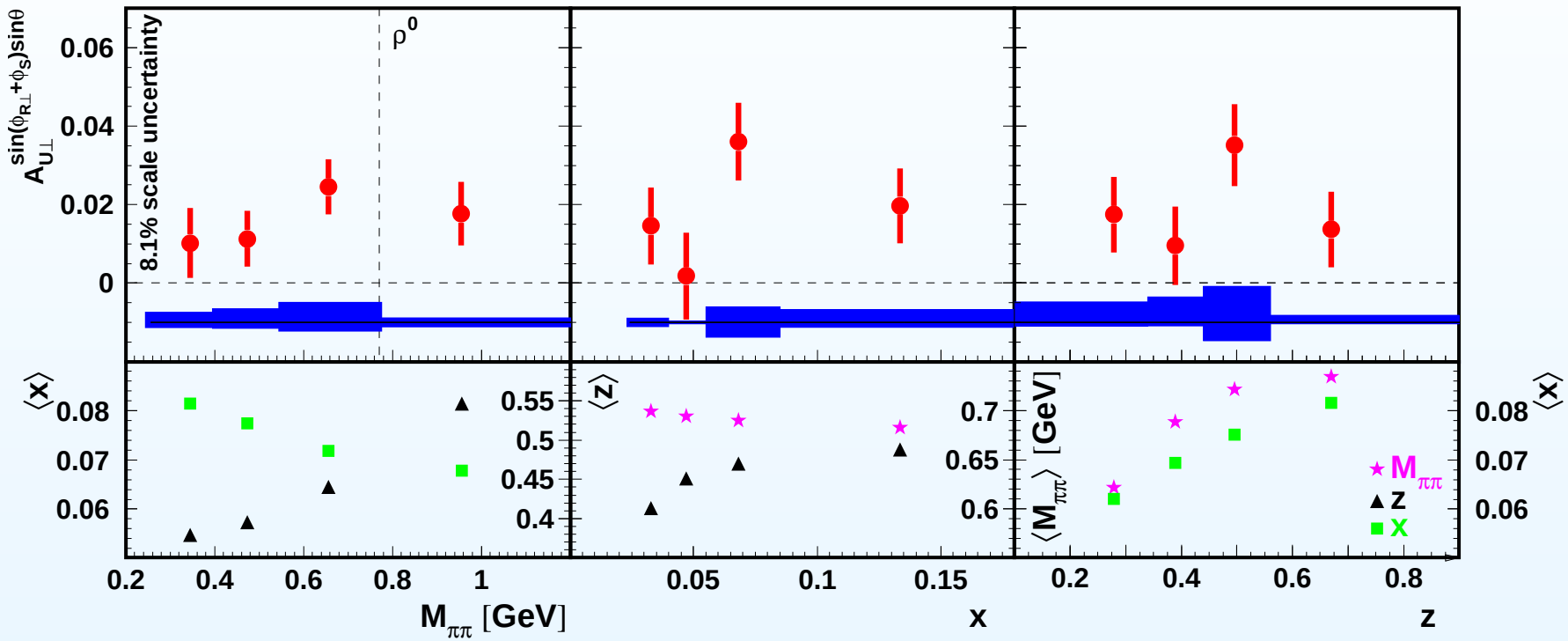
$$R_T \equiv R - (R \cdot \hat{P}_h)\hat{P}_h$$

azimuthal angles ϕ_S and $\phi_{R_\perp}$:

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

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

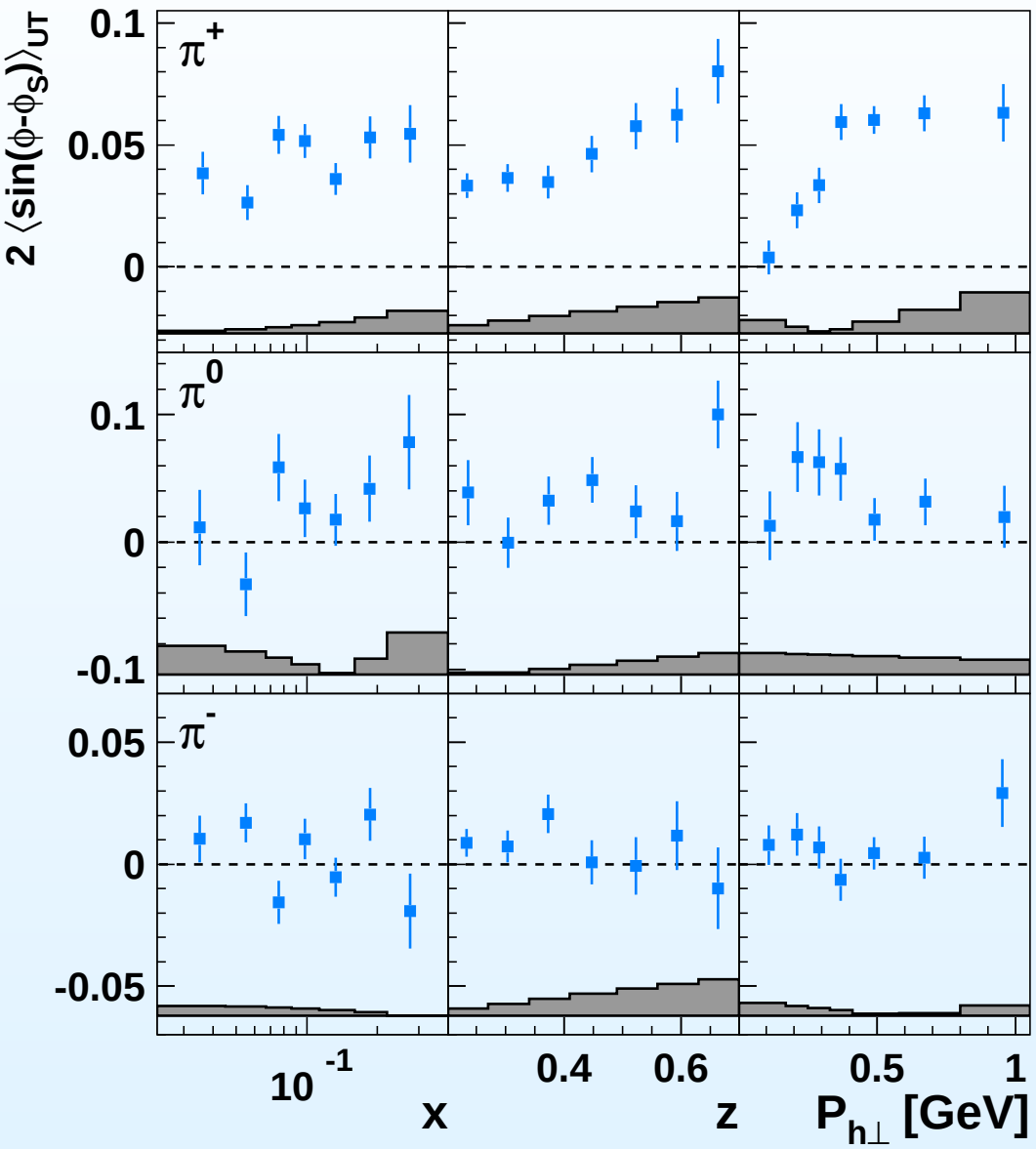
Results on SSA in semi-inclusive $\pi^+\pi^-$production:



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

Evidence for naive-T-odd quark distribution functions

The Sivers amplitudes for π-mesons:



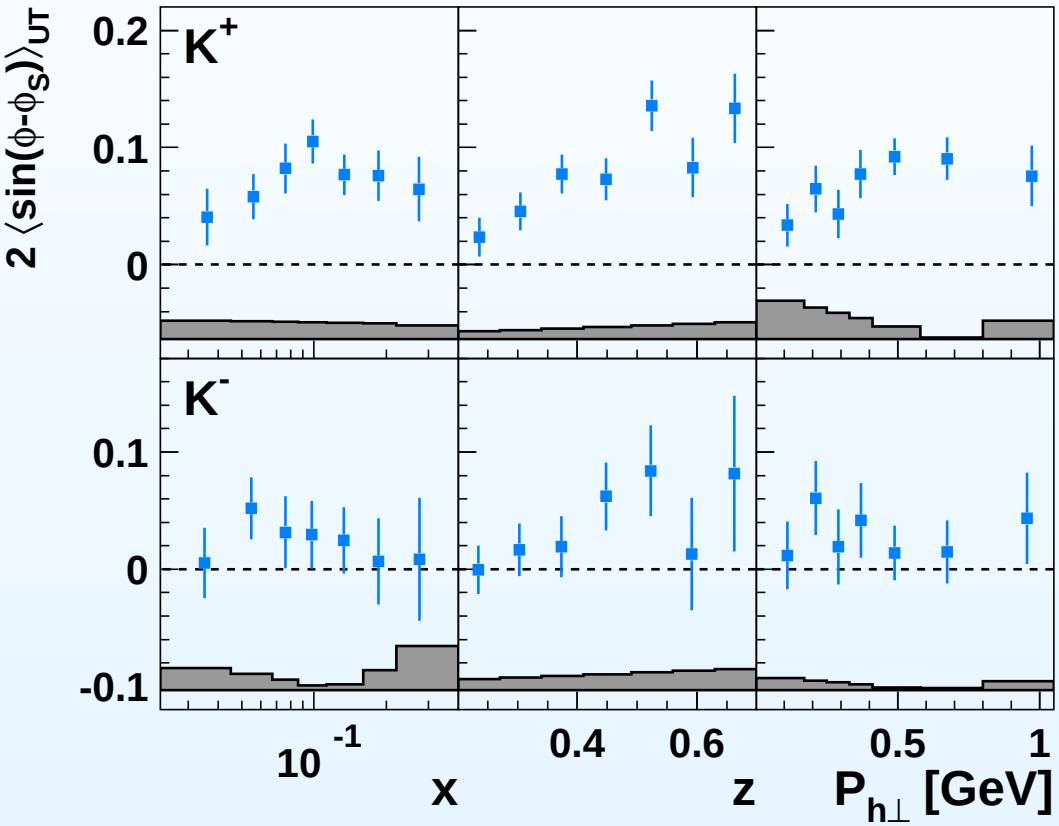
Results for Sivers amplitude:

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

from 2002–2005 data:

- significantly positive for π^+
  ➥ $f_{1T}^{\perp,u} < 0$, $L_z^u > 0$
- significantly positive for π^0
- consistent with zero for π^-
  ➥ $f_{1T}^{\perp,d} > 0$?
- increase with z for $\pi^+$and π^0
- $P_{h\perp} \to 0.0\,\mathrm{GeV}$: linear decrease
- $P_{h\perp} > 0.4\,\mathrm{GeV}$: saturation for π^+
- isospin symmetry fulfilled

The Sivers amplitudes for charged K-mesons:



Results for Sivers amplitude:

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

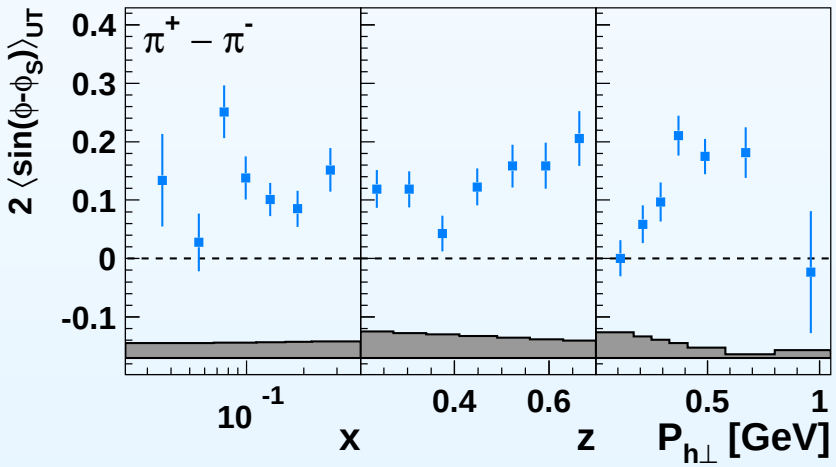
from 2002–2005 data:

- significantly positive for K^+
  ➥ $f_{1T}^{\perp,u} < 0$, $L_z^u > 0$
- significantly positive for K^-
- increase with z
- $P_{h\perp} \to 0.0$ GeV: linear decrease
- $P_{h\perp} > 0.4$ GeV: saturation for K^+

Pion-difference Sivers amplitudes:

- suppress ρ^0 contribution by extraction of pion-difference SSA:

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{|\boldsymbol{S}_T|}\frac{(\sigma_{U\Uparrow}^{\pi^+}-\sigma_{U\Uparrow}^{\pi^-})-(\sigma_{U\Downarrow}^{\pi^+}-\sigma_{U\Downarrow}^{\pi^-})}{(\sigma_{U\Uparrow}^{\pi^+}-\sigma_{U\Uparrow}^{\pi^-})+(\sigma_{U\Downarrow}^{\pi^+}-\sigma_{U\Downarrow}^{\pi^-})}$$



- significantly positive
  ➥ $f_{1T}^{\perp,u} < 0$, $L_z^u > 0$
- increase with z
- linear decrease for $P_{h\perp} \to 0.0\,\mathrm{GeV}$
- saturation for $P_{h\perp} > 0.4\,\mathrm{GeV}$

- possible interpretation in terms of valence-quark distributions:

$$A_{\mathrm{UT}}^{\pi^+-\pi^-} = -\frac{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

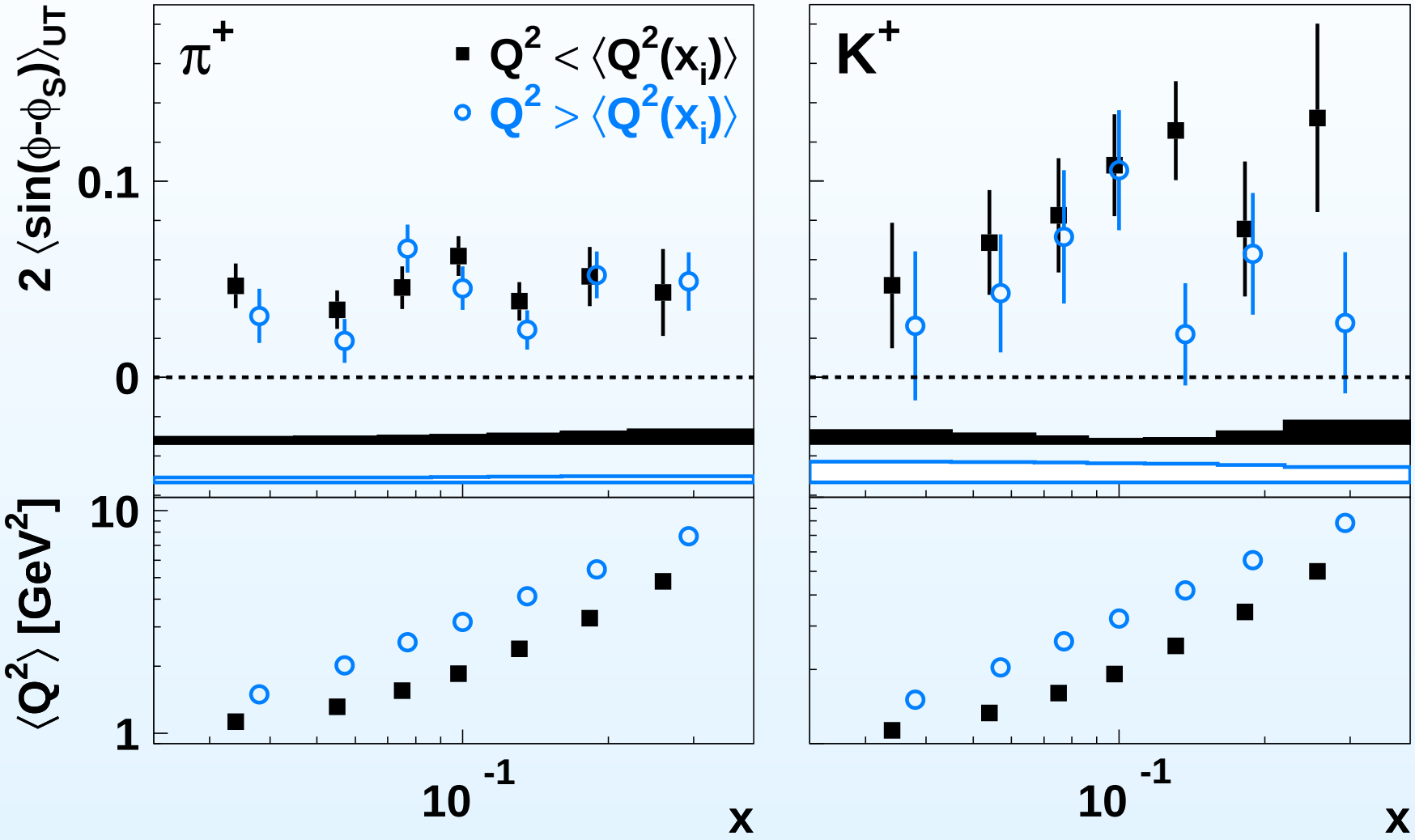
The role of higher twist terms:

- **Sivers amplitude:**

$$2\,\langle \sin(\phi-\phi_S)\rangle_{\mathsf{UT}} \propto F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon\, F_{UT,L}^{\sin(\phi-\phi_S)}$$

- $F_{UT,T}^{\sin(\phi-\phi_S)} = -\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M} f_{1T}^{\perp} D_1\right]$
- $F_{UT,L}^{\sin(\phi-\phi_S)} = 0$ (leading twist and subleading twist accuracy)
  - $\frac{\boldsymbol{P}_{h\perp}^2}{z^2 Q^2}$-suppressed compared to $F_{UT,T}$
  - can be generated by α_s-corrections at high transverse momentum

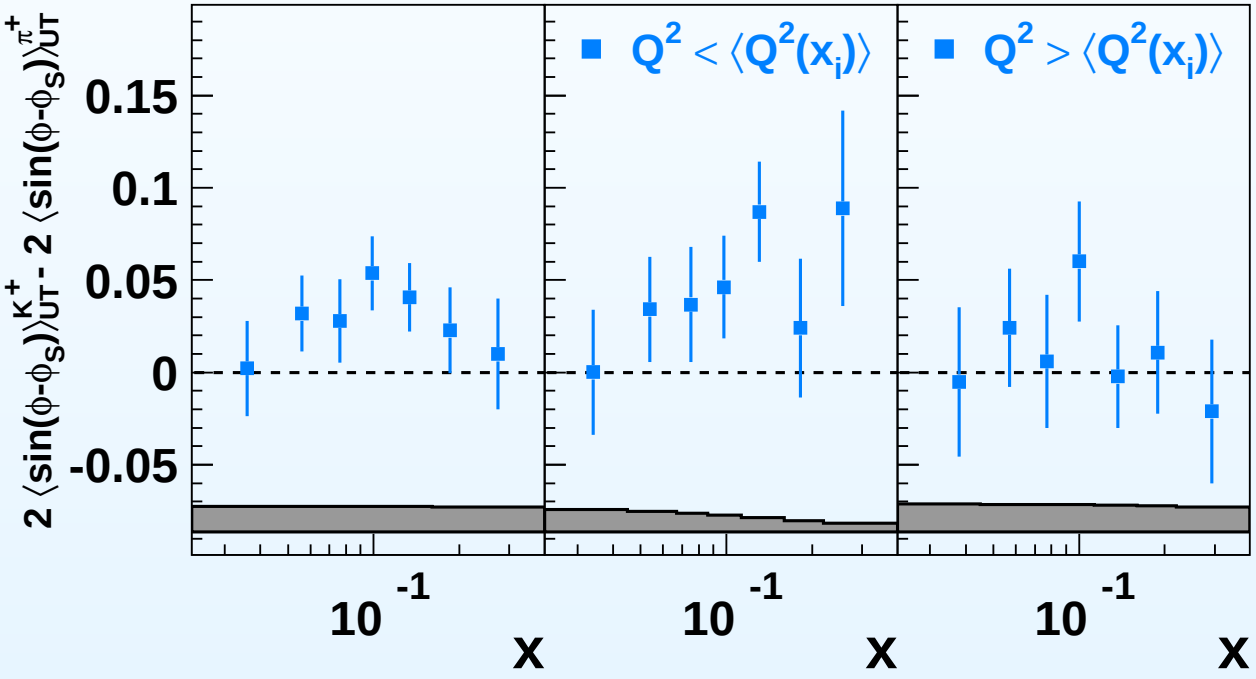
Examination of other $1/Q^2$-suppressed contributions:



hint of Q^2-dependence for K^+amplitudes

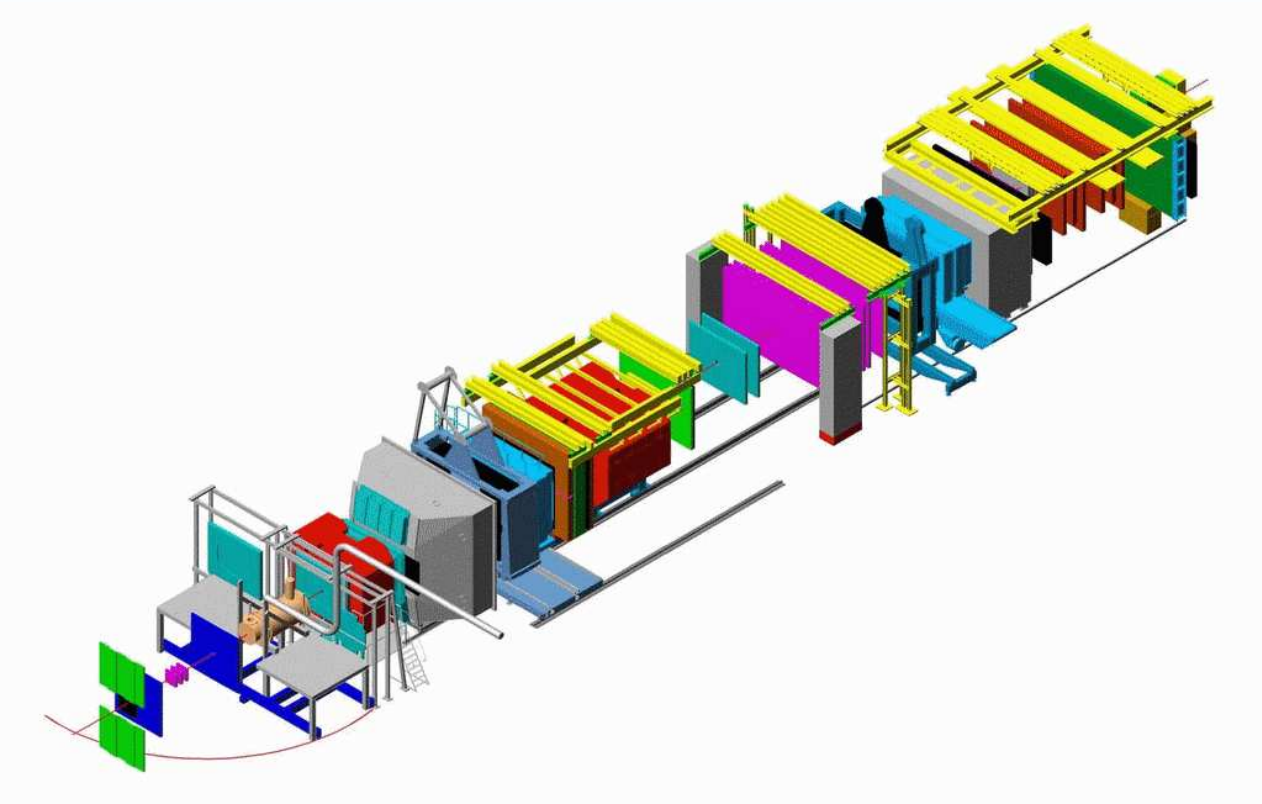
Sivers amplitudes for K^+ and π^+:

- **u-quark dominance:** $2\langle \sin(\phi - \phi_S)\rangle_{\mathrm{UT}}^{\pi^+} \sim 2\langle \sin(\phi - \phi_S)\rangle_{\mathrm{UT}}^{K^+}$
- **difference in K^+ and π^+ Sivers amplitudes:**



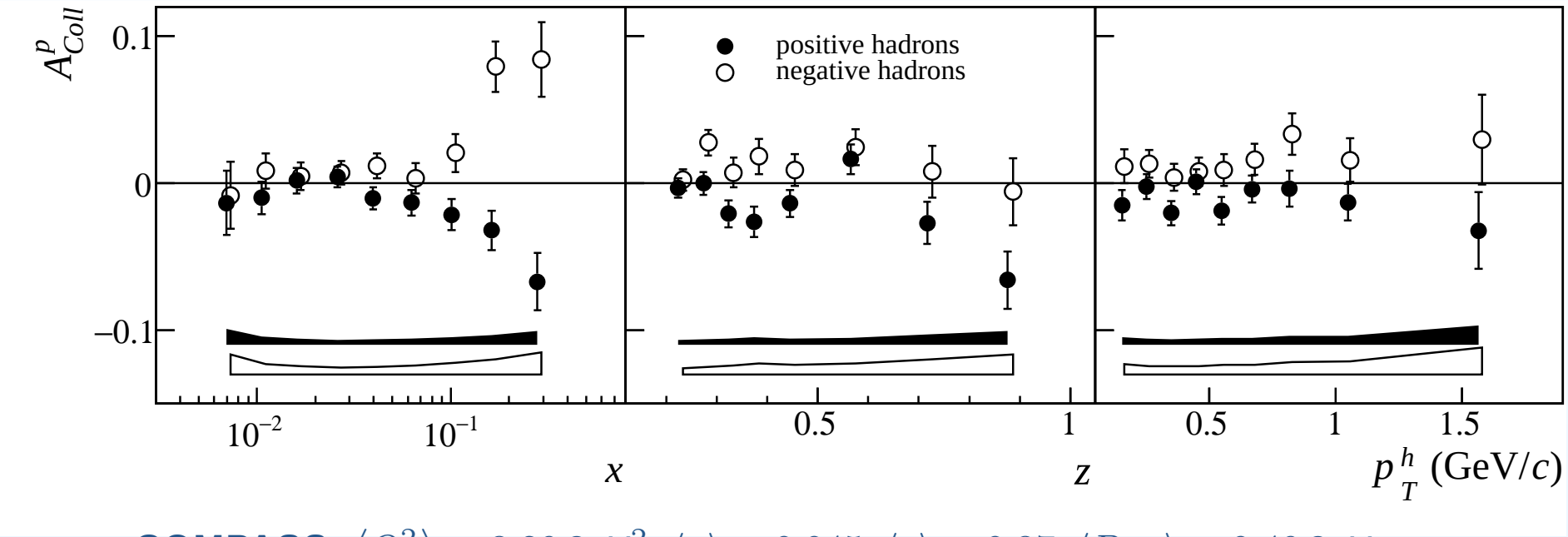
- significant role of other quark flavours?
- higher twist effects in kaon-production?

The COMPASS results:



- polarised ammonia (NH_3) solid state target:
  - three target cells; $1.2\,\mathrm{m}$
  - possible nuclear effects (e.g. $P_{h\perp}$ broadening)
  - dilution factor of 0.15

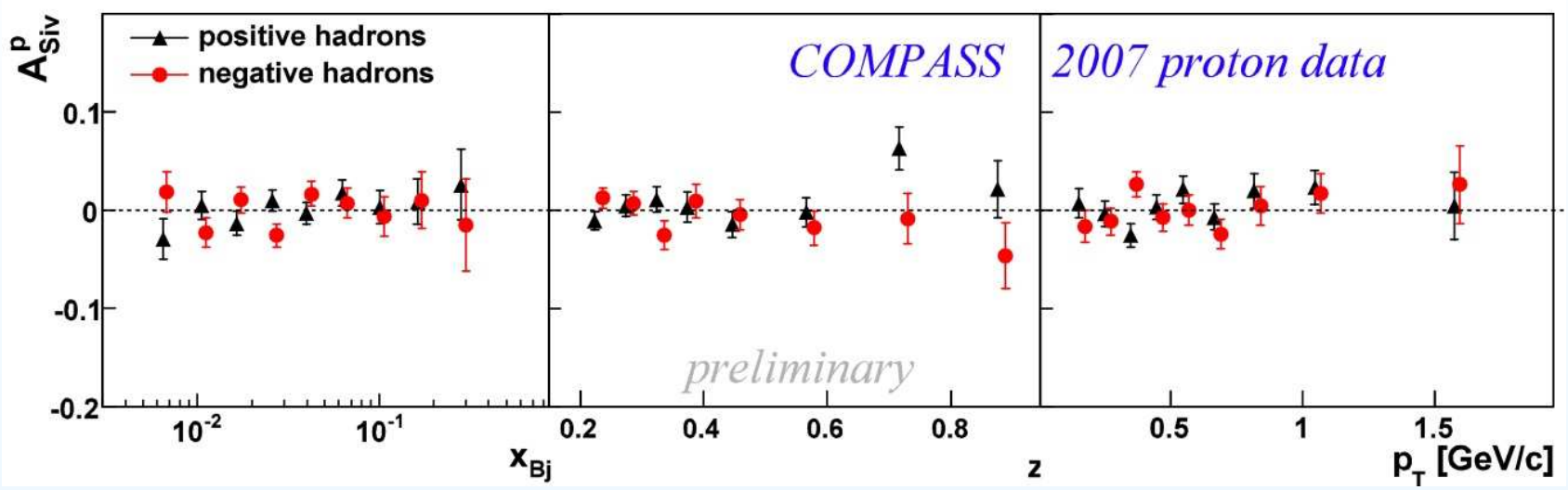
COMPASS measurement of Collins SSA on proton:

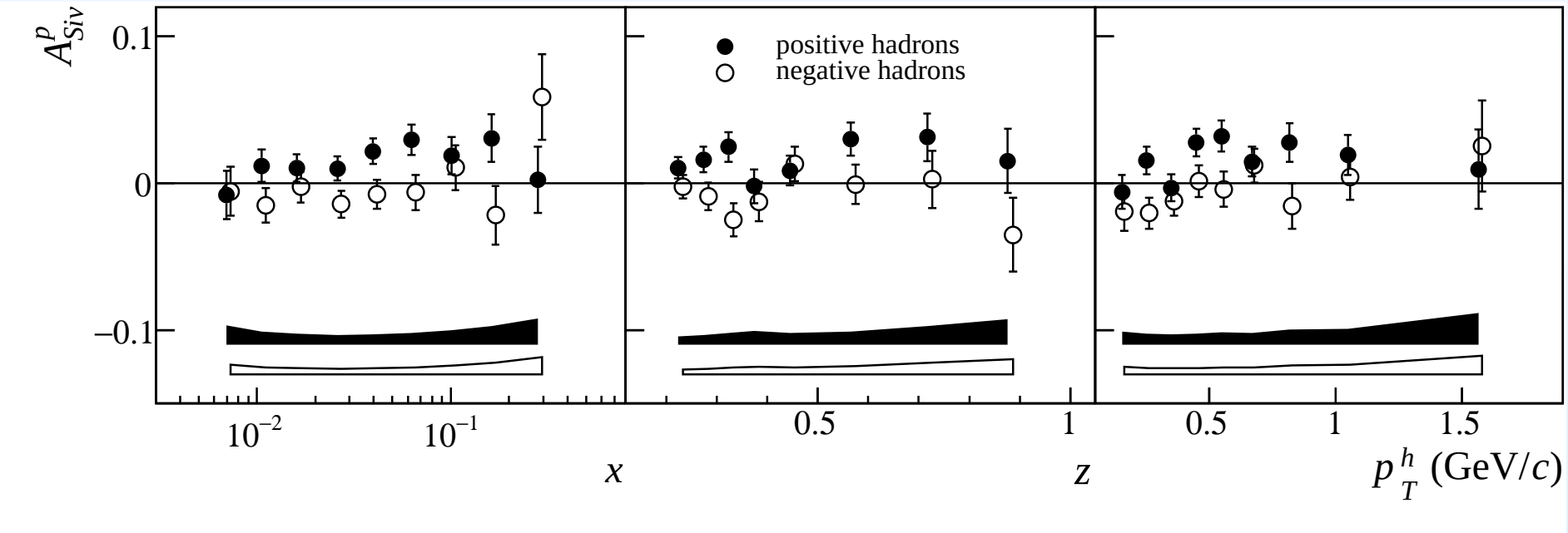


COMPASS: $\langle Q^2 \rangle = 3.29\,\mathrm{GeV}^2$, $\langle x \rangle = 0.045$, $\langle z \rangle = 0.37$, $\langle P_{h\perp} \rangle = 0.49\,\mathrm{GeV}$

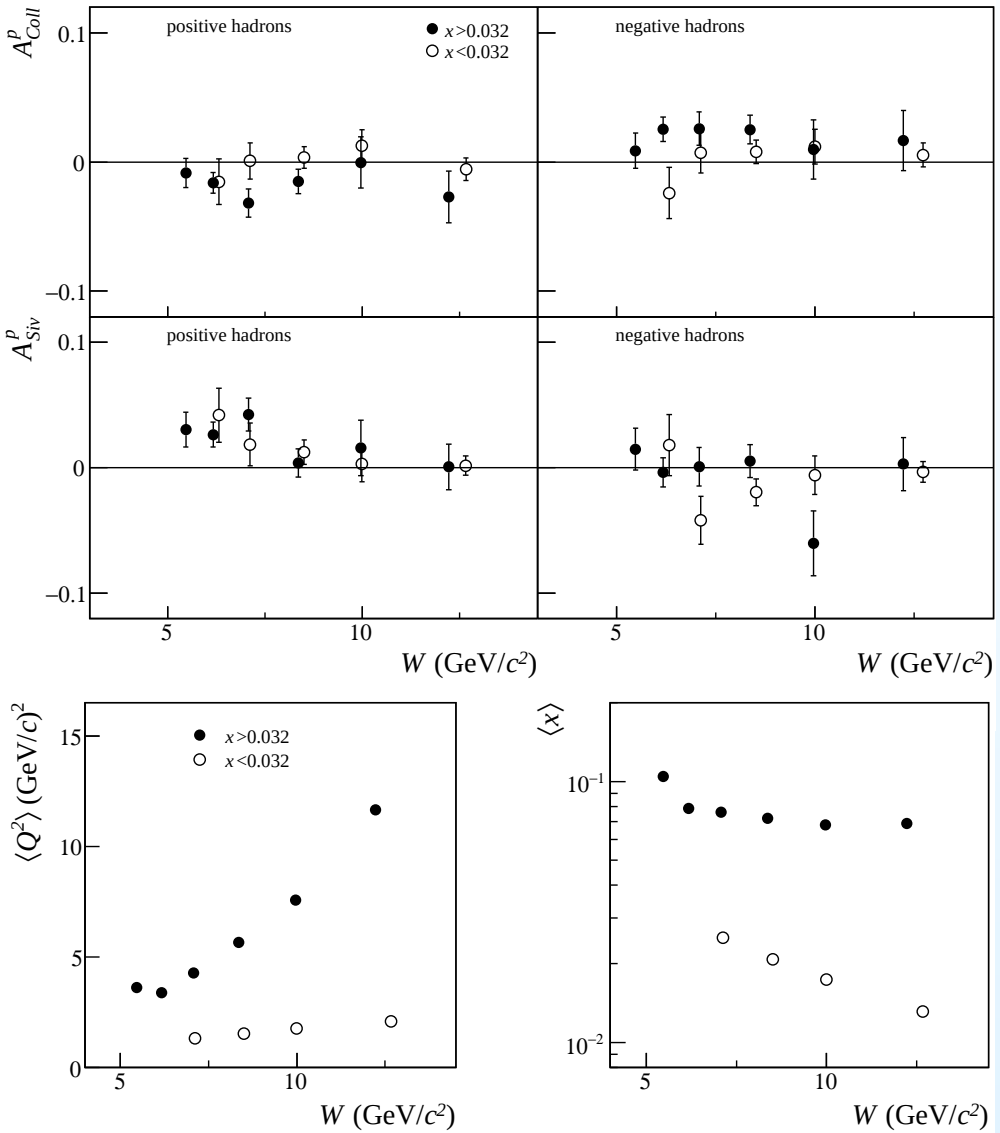
HERMES: $\langle Q^2 \rangle = 2.4o\,\mathrm{GeV}^2$, $\langle x \rangle = 0.094$, $\langle z \rangle = 0.36$, $\langle P_{h\perp} \rangle = 0.41\,\mathrm{GeV}$

COMPASS measurement of Sivers SSA on proton:

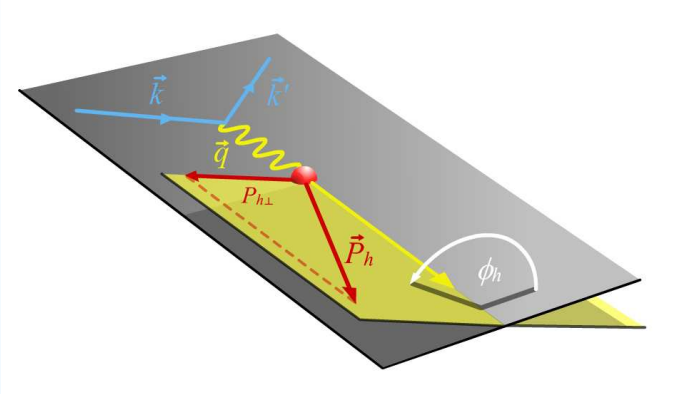




W^2-dependence of COMPASS SSA measurement:



Signals for unmeasured Boer–Mulders function $h_1^\perp$:



Azimuthal modulations of σ_{UU}:

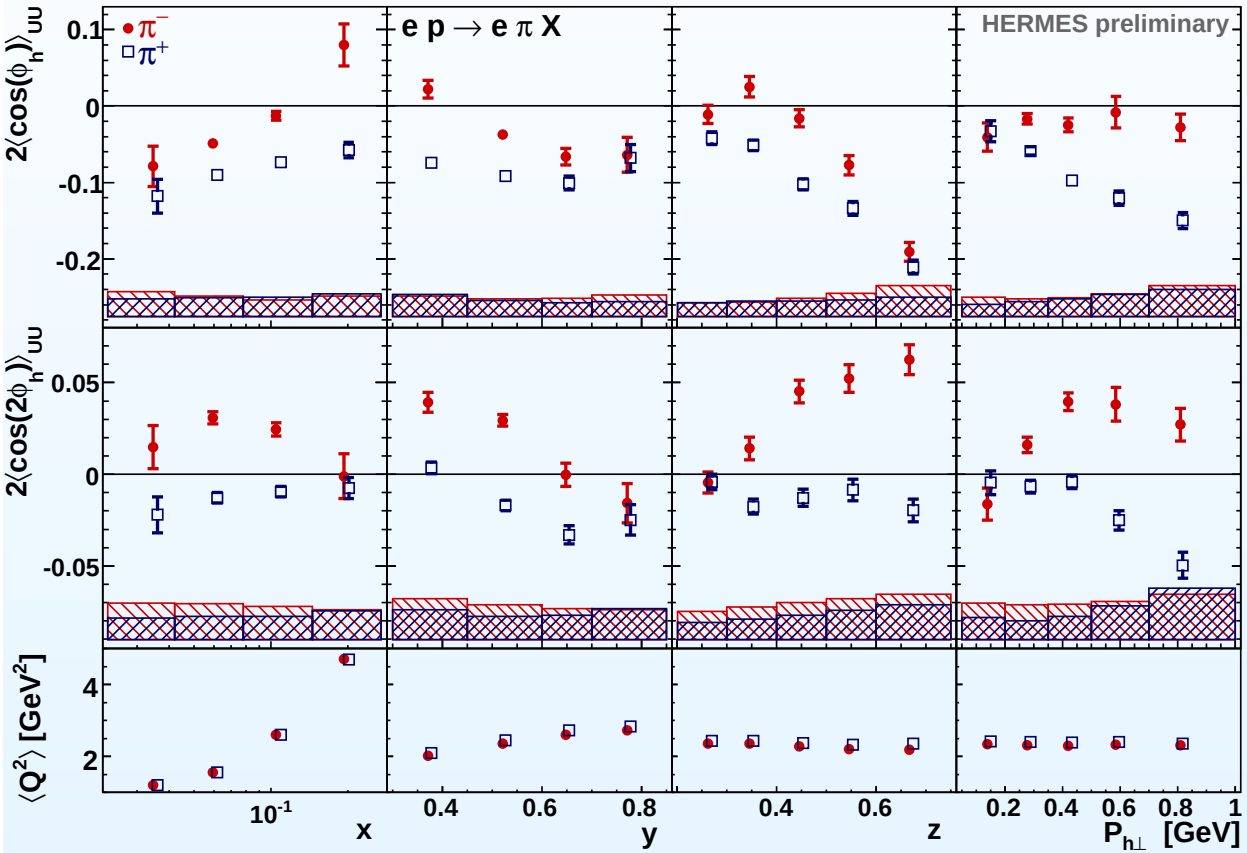
- leading-twist $2\,\langle\cos(2\phi)\rangle_{\mathrm{UU}}$
  - sensitive to **Boer–Mulders effect** ($h_1^\perp \otimes H_1^\perp$)
- subleading-twist $2\,\langle\cos(\phi)\rangle_{\mathrm{UU}}$
  - sensitive to **Cahn effect** ($f_1 \otimes D_1$) and ($h_1^\perp \otimes H_1^\perp$)

Fully differential analysis (x,y,z,$P_{h\perp}$,ϕ)

➥ correction for finite acceptance, QED radiation, detector smearing

hydrogen (2000, 2006) and deuterium (2000, 2005) data

Results for $2\langle\cos(2\phi)\rangle_{UU}$ and $2\langle\cos(\phi)\rangle_{UU}$:



$2\langle\cos(\phi)\rangle_{UU}$:

- negative for π^+ and π^-

$2\langle\cos(2\phi)\rangle_{UU}$:

- positive for π^-
- slightly negative for π^+
- **evidence for Boer–Mulders TMD**

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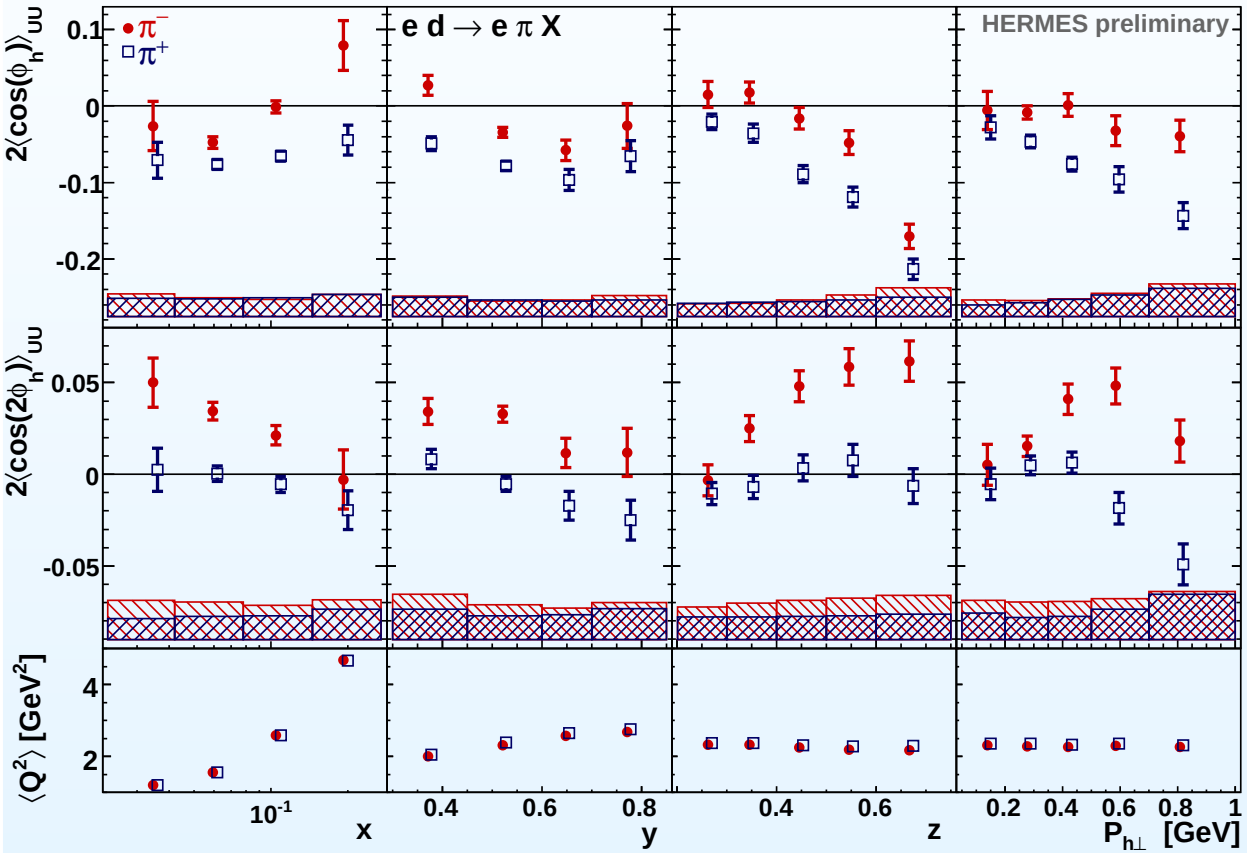

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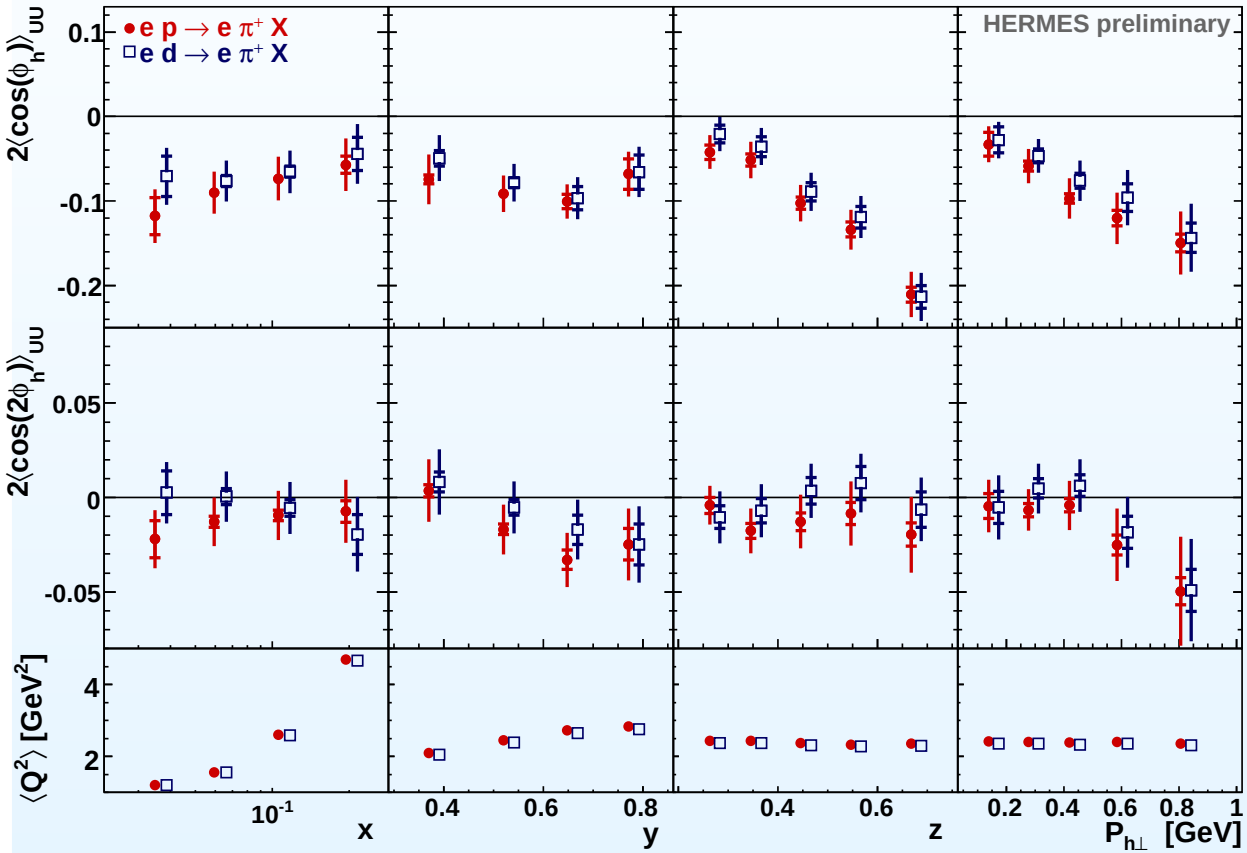

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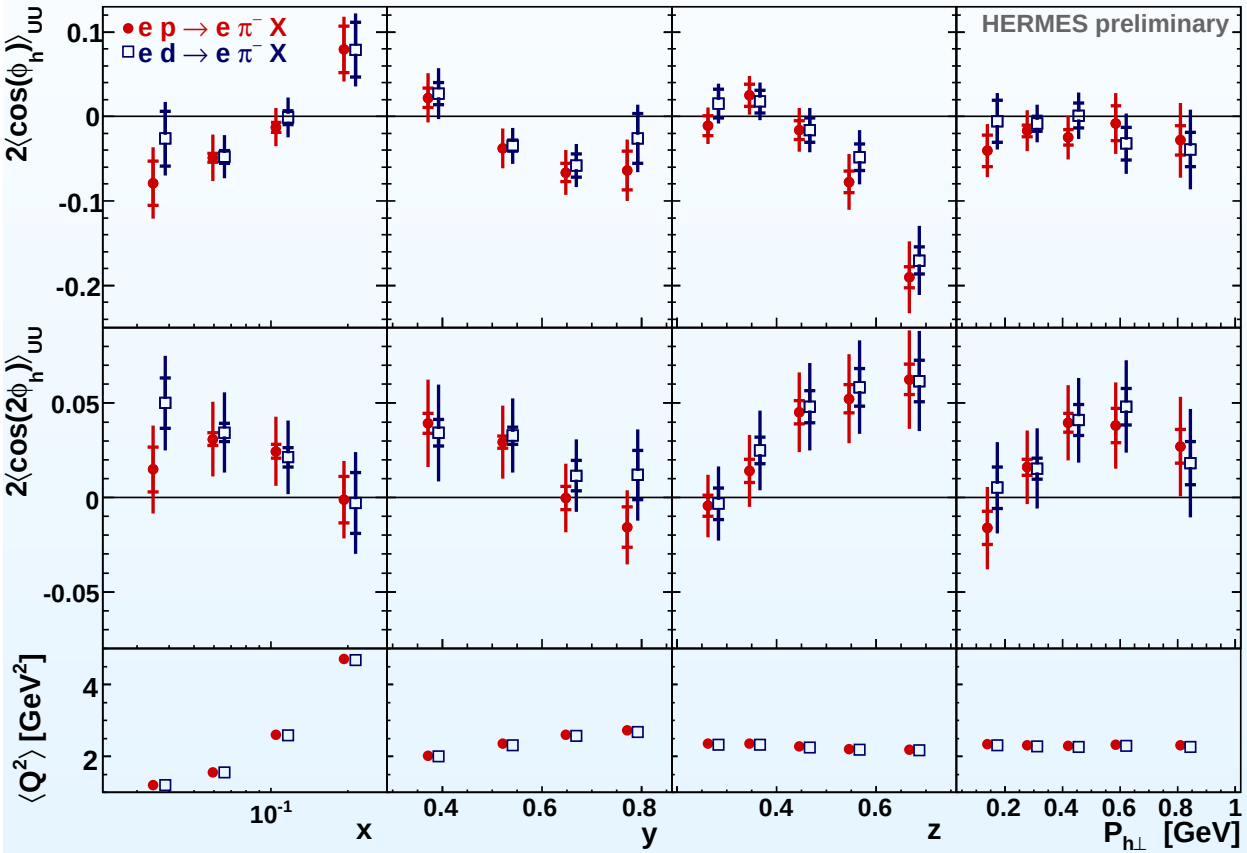
Cahn and Boer–Mulders effect similar for p and d

Results for $2\langle\cos(2\phi)\rangle_{UU}$ and $2\langle\cos(\phi)\rangle_{UU}$:



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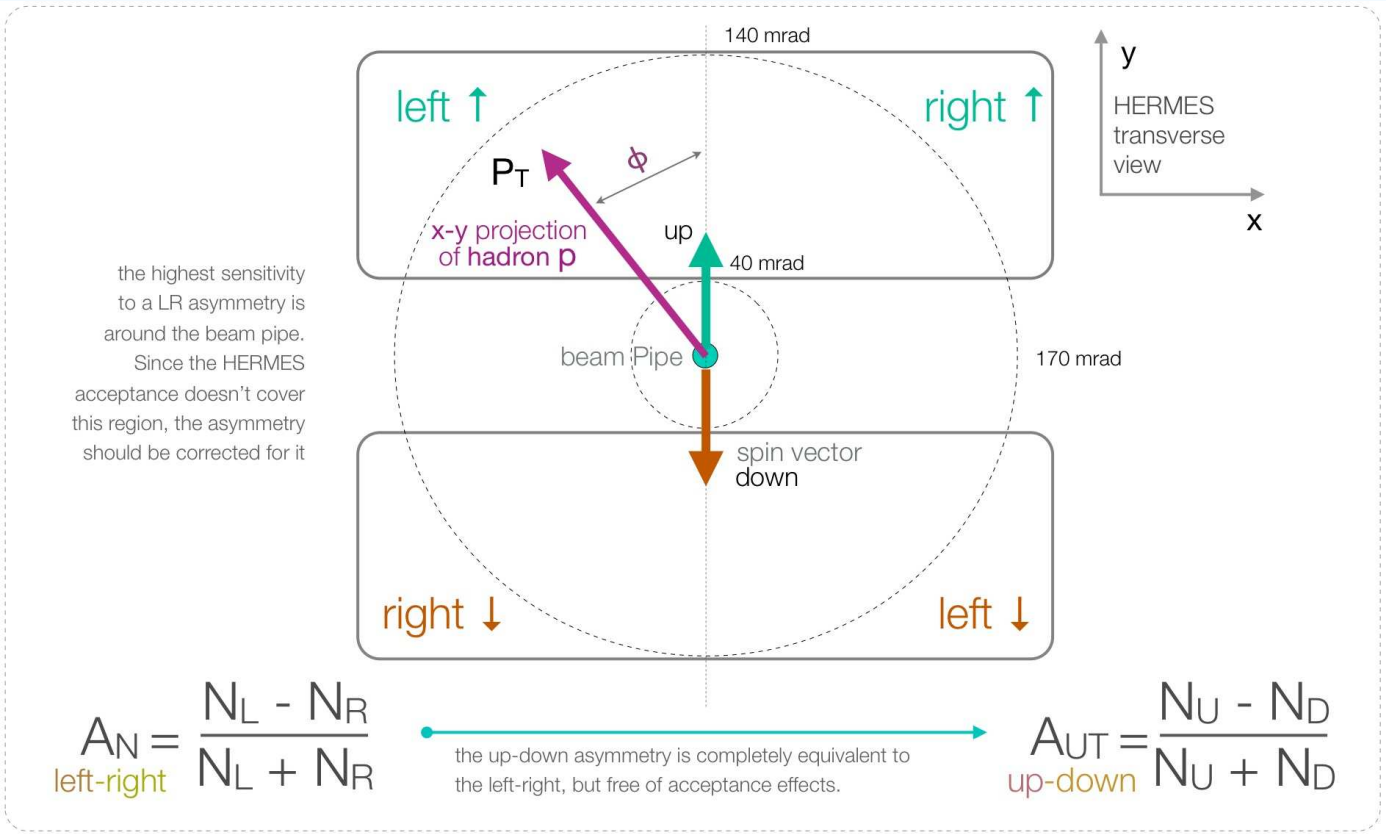
Cahn and Boer–Mulders effect similar for p and d

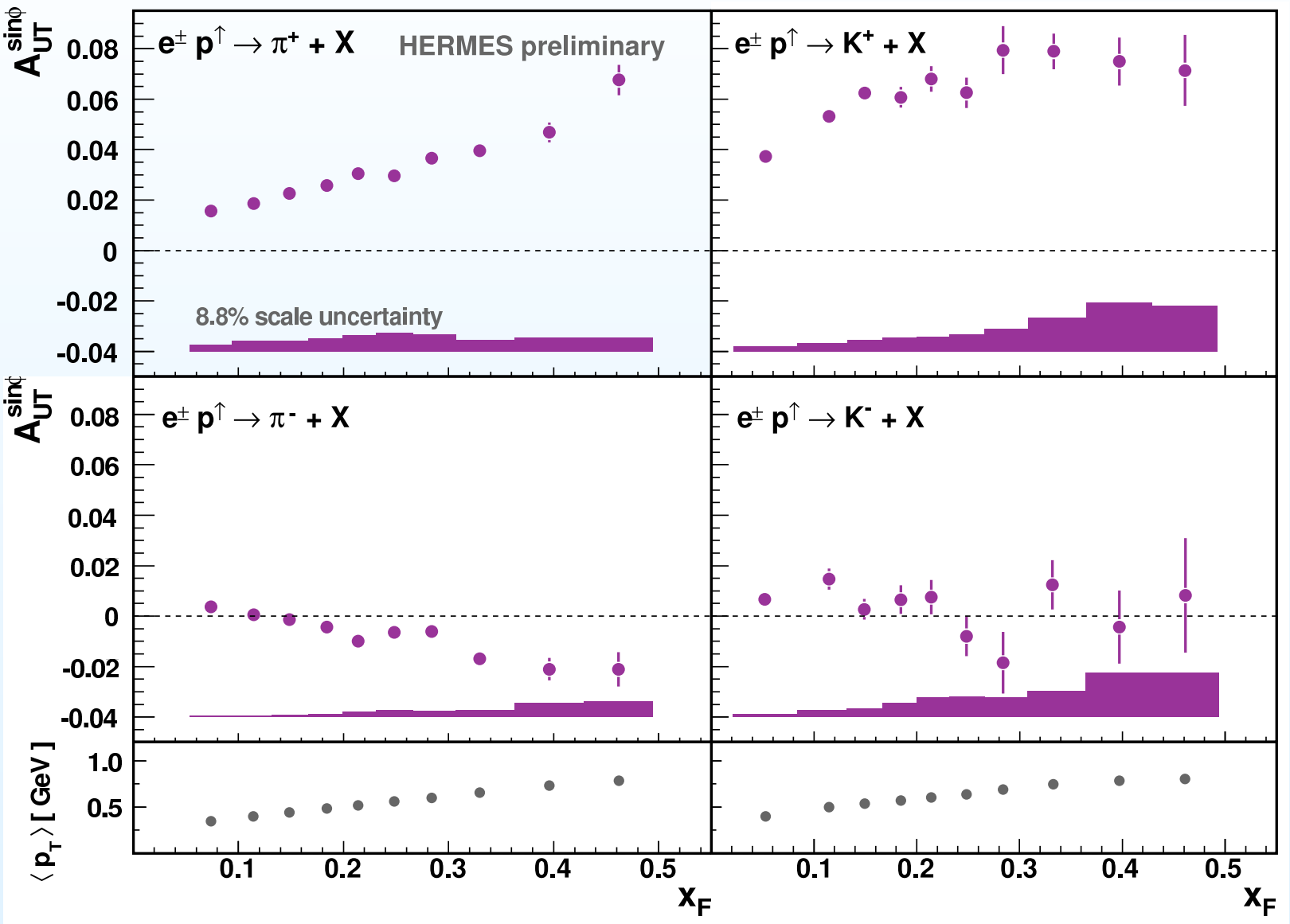
A_N in inclusive hadron production

Reconstruction of the analysing power A_N:

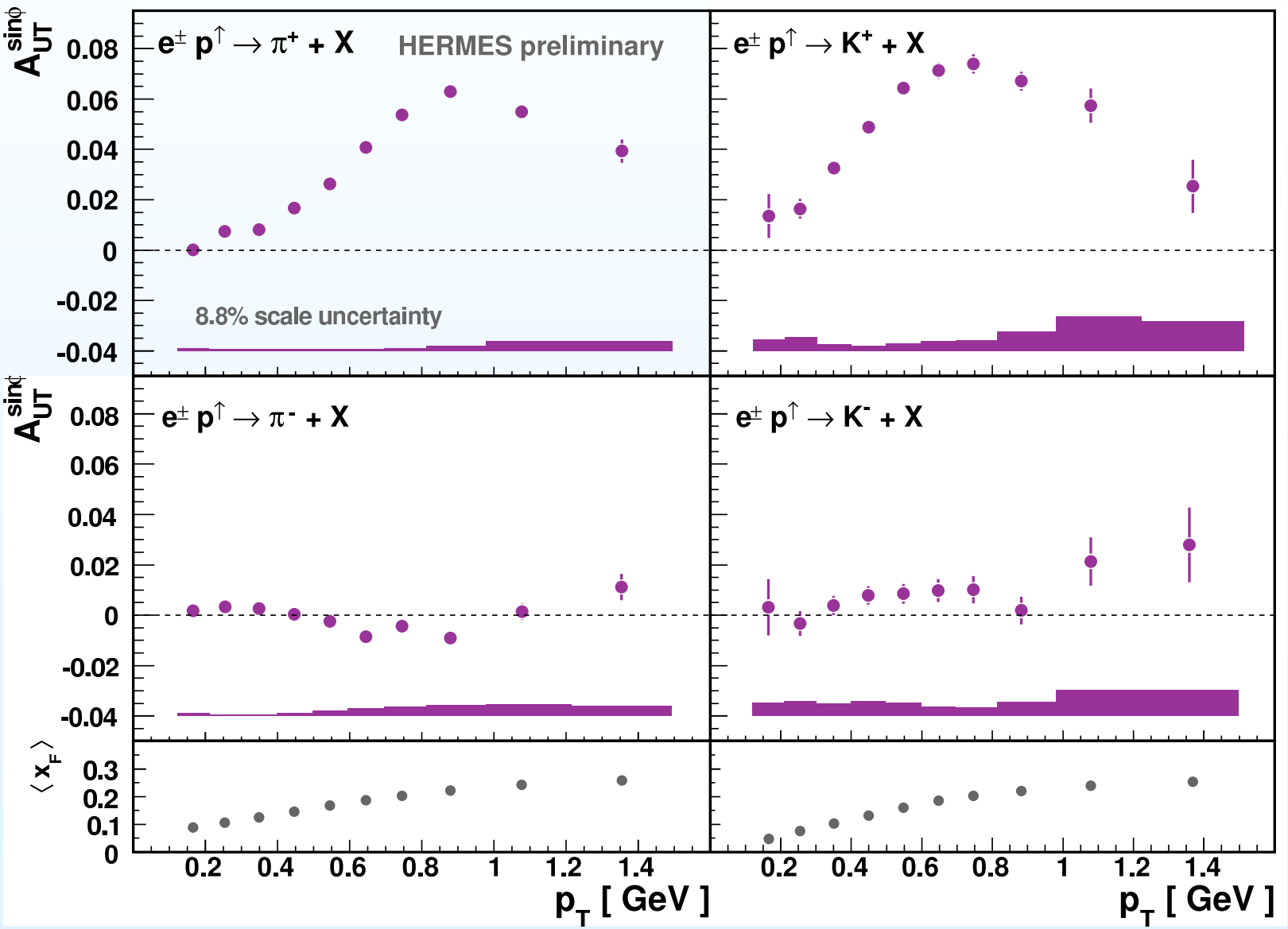
- study of **inclusive hadron production** ($lp^{\Uparrow} \to hX$)
- signal dominated by **quasi-real photoproduction**
- sensitive to **Sivers effect**, Collins effect dynamically suppressed



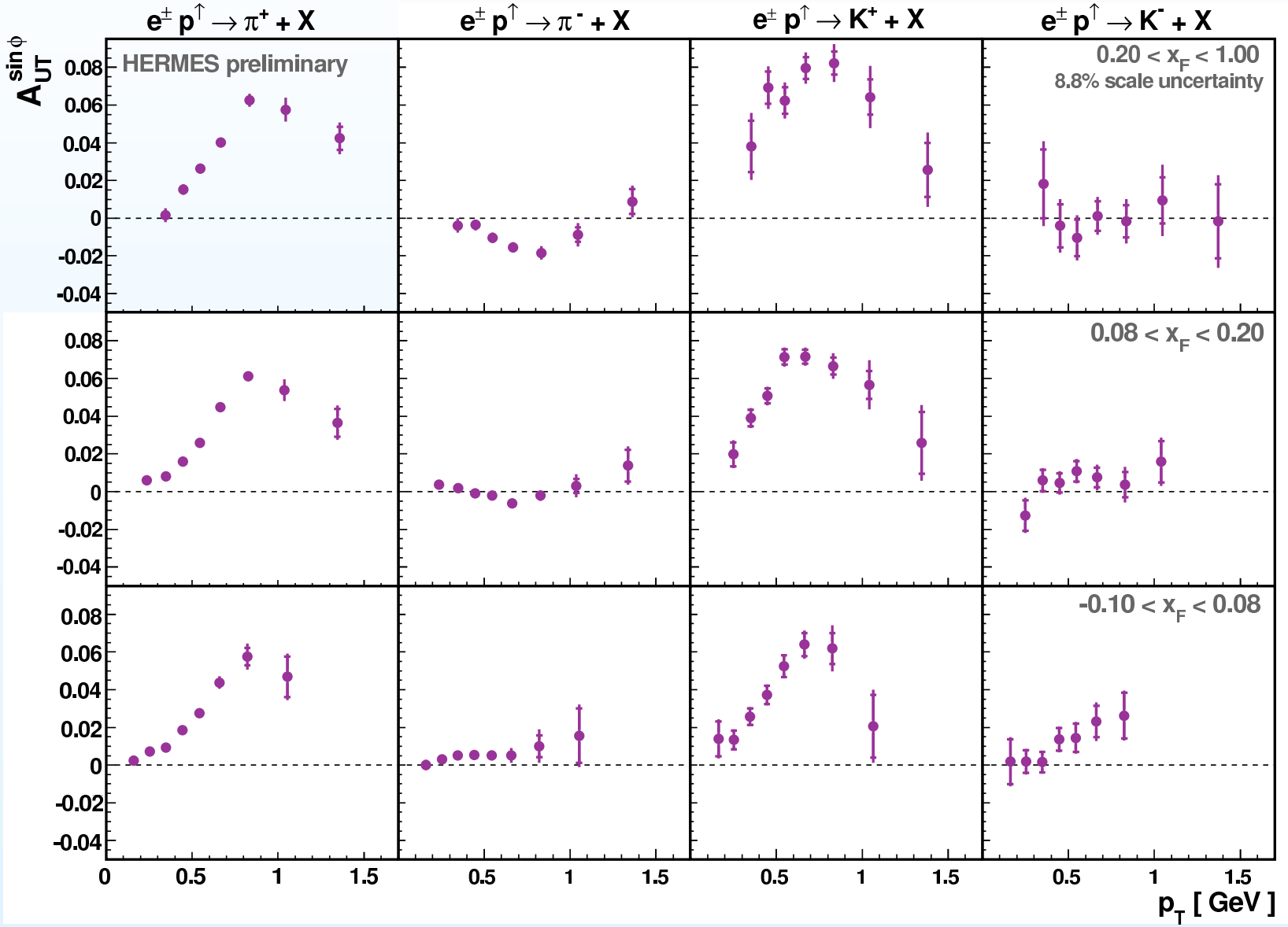
A_N much smaller than in hadron collisions:



(Hadronic) Scale dependence of A_N:



Sign change for $x_F \approx 0$:



Pioneering HERMES results:

- (most) precise analysis of SSA in semi-inclusive DIS
- investigation of σ_{UU}, σ_{UT} (σ_{UL}, σ_{LU}, σ_{LT})
- significant Collins amplitudes for π-mesons
  ➥ enables quantitative extraction of transversity distribution
  ➥ final Collins amplitudes will be published very soon
- first evidence for a naive-T-odd dihadron fragmentation function
  ➥ provides alternative probe for transversity distribution
- significant Sivers amplitudes for π^+, π^0, $K^+$and K^-
  ➥ clear (and first) evidence of naive-T-odd Sivers function
  ➥ enables quantitative extraction of the Sivers function
  ➥ test of universality ($f_{1T}^{\perp,u} < 0$), constraints on L_z^u
- significant $2\langle\cos(\phi)\rangle_{\mathrm{UU}}$ and $2\langle\cos(2\phi)\rangle_{\mathrm{UU}}$ amplitudes for $\pi^{\pm}$
  ➥ sensitivity to Boer-Mulders function
- analysis of A_N in inclusive hadron prodction
  ➥ test of TMD factorisation?

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

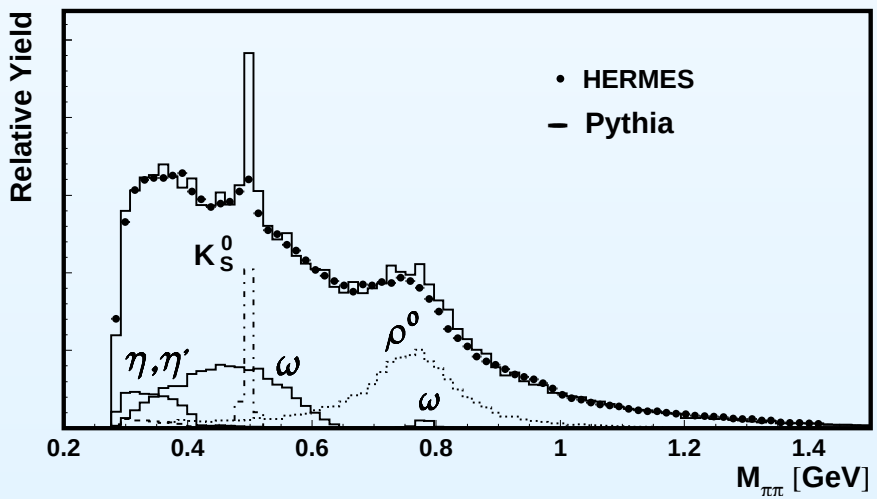
- **Fourier and Legendre expansion:**

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

- focus on **sp- and pp-interference** ($M_{\pi\pi} < 1.5$ 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