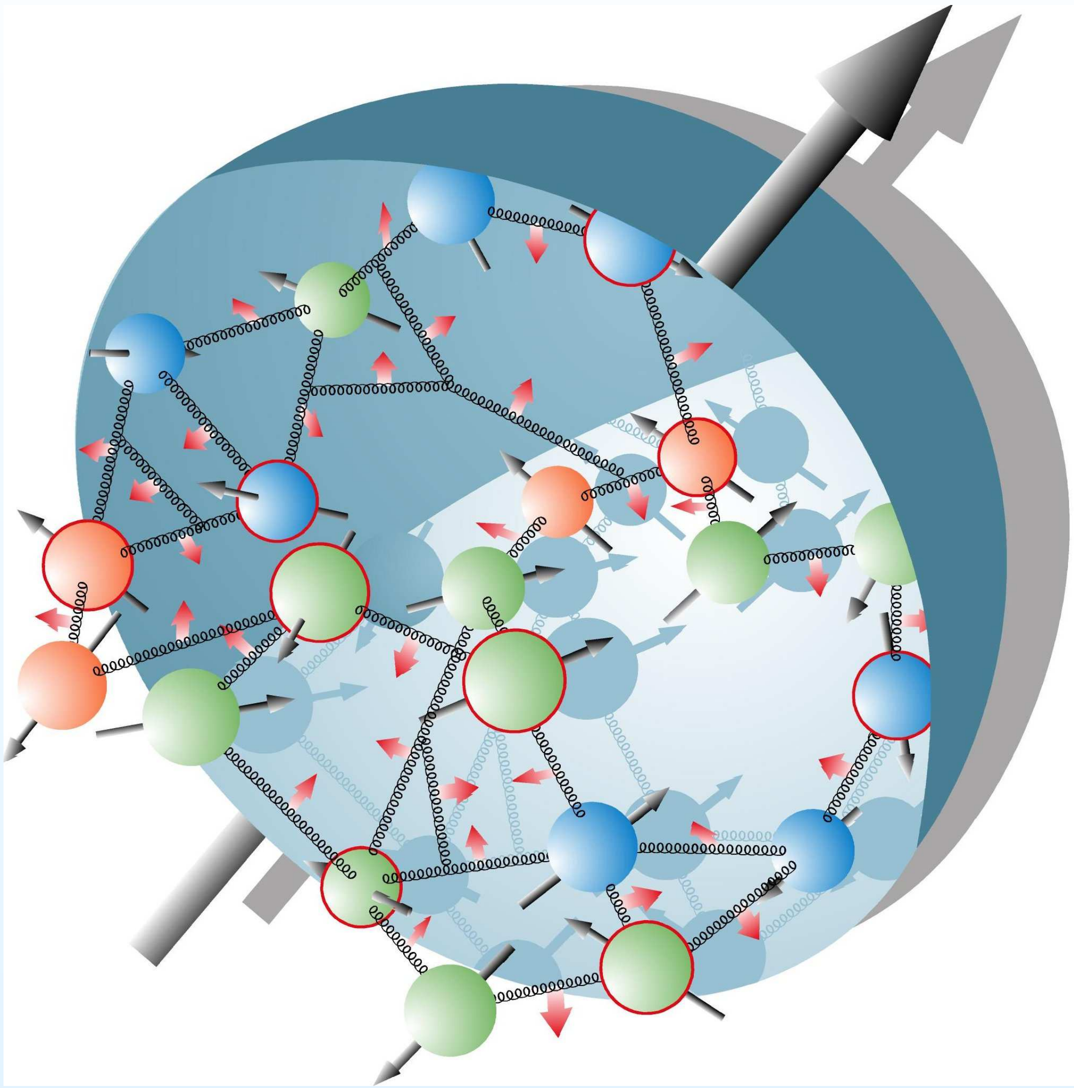
Signals for transverse-momentum-dependent distribution and fragmentation functions observed at the HERMES *experiment*

Markus Diefenthaler

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

on behalf of the hermes collaboration

The spin structure of the nucleon:

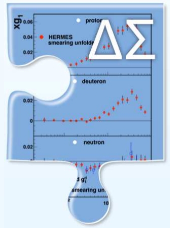


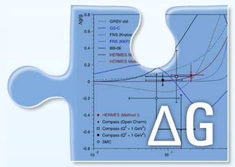
The HERMES legacy:

Longitudinal spin phenomena (1995–2000):

- angular momentum sum rule:

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

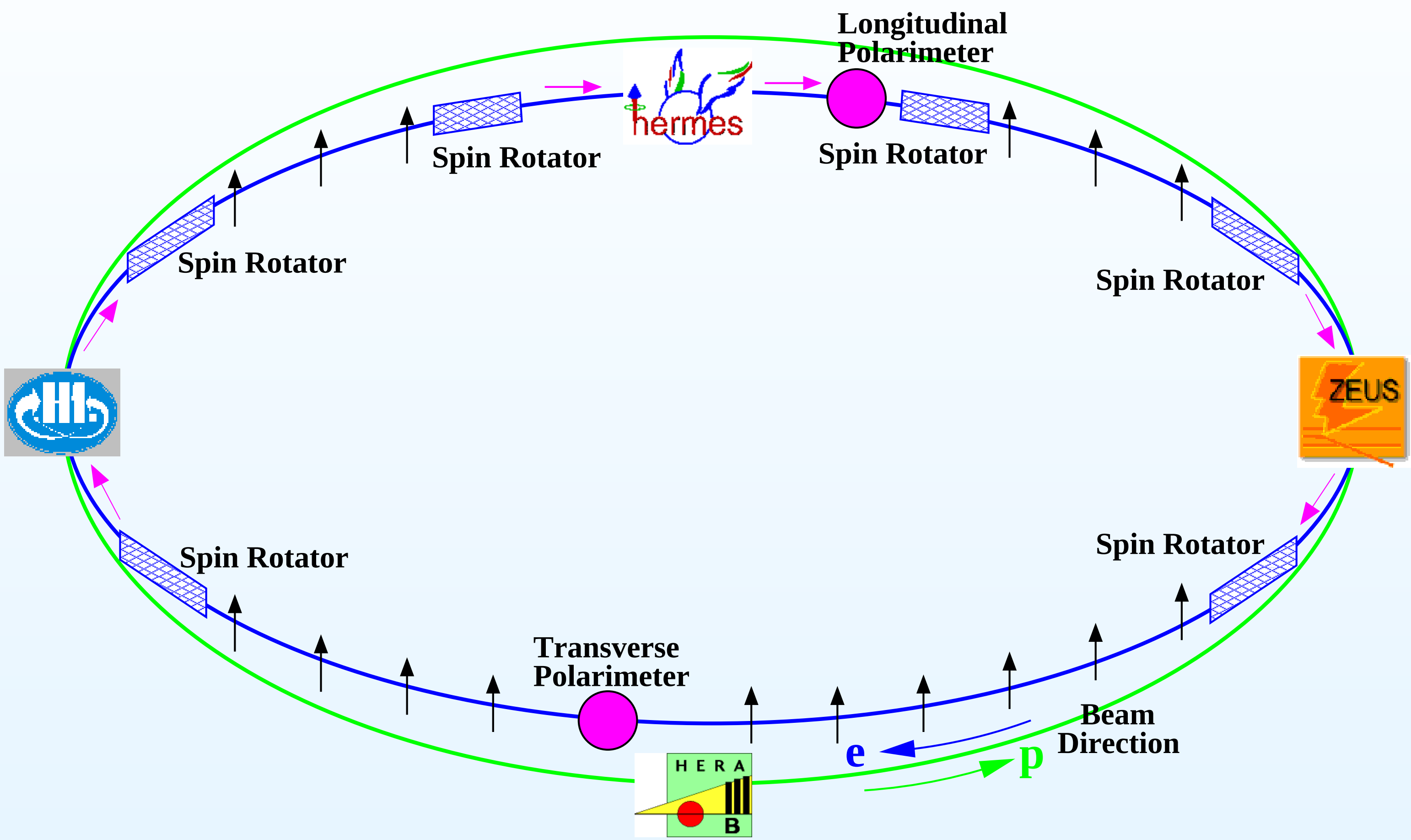




Transverse spin phenomena (2002–2005):

- investigation of σ_{UU}, σ_{UL}, σ_{UT}, σ_{LU}
- transversity measurements
- spin-orbit correlations via TMD measurements
  - ➥ Sivers function $f_{1T}^{\perp,q}$
  - ➥ Boer-Mulders function $h_1^{\perp,q}$
  - ➥ pretzelosity $h_{1T}^{\perp,q}$

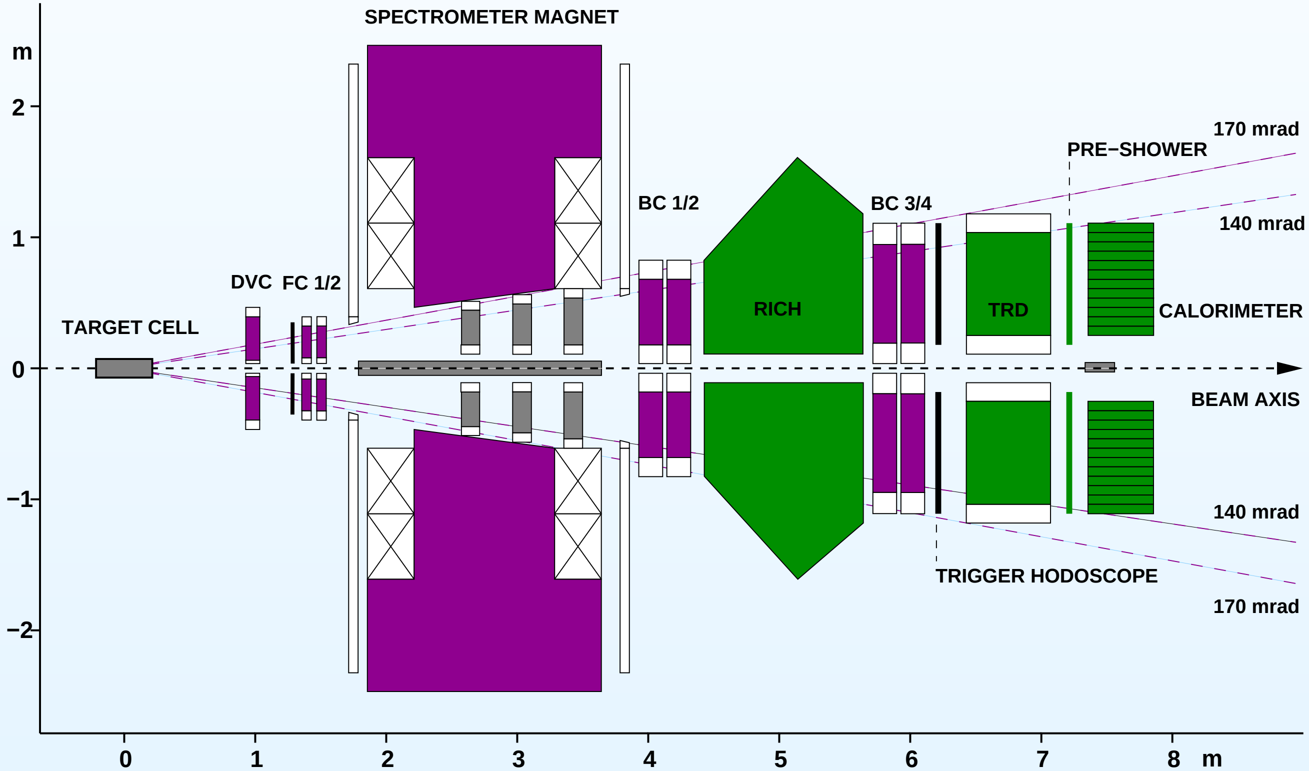
The HERMES polarised scattering experiment:



- longitudinally polarised e^+ and e^- beam of HERA
- $\sqrt{s} \approx 7\,\mathrm{GeV}$

The HERMES polarised scattering experiment:

- (un)polarised **gas target** internal to the HERA storage ring
- background-free measurements from highly polarised nucleons



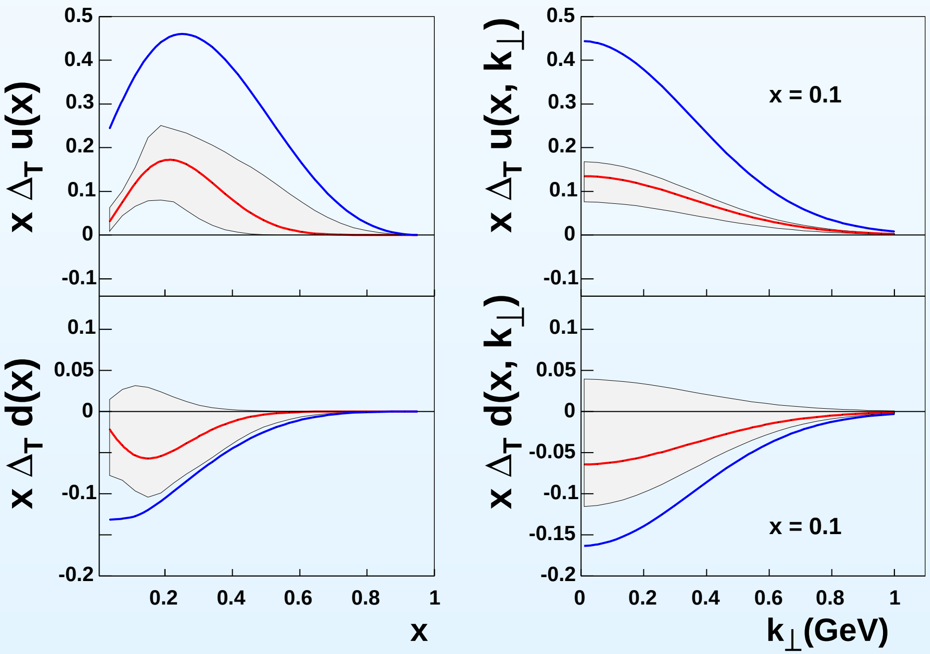
- very clean lepton-hadron separation and hadron identification
- well-suited for **measurements of azimuthal asymmetries**

The hunt for the chiral-odd transversity distribution:

- complete description of quark momentum and spin:

$$\Phi(x) \quad = \quad \frac{1}{2}\left\{ \boldsymbol{f_1^q(x)} \not{P} + \lambda_N \boldsymbol{g_1^q(x)} \gamma_5 \not{P} + \boldsymbol{h_1^q(x)} \not{P} \gamma_5 \not{S}_\perp \right\}$$

- extraction by Anselmino et al., **Phys.Rev.D75:054032,2007**:

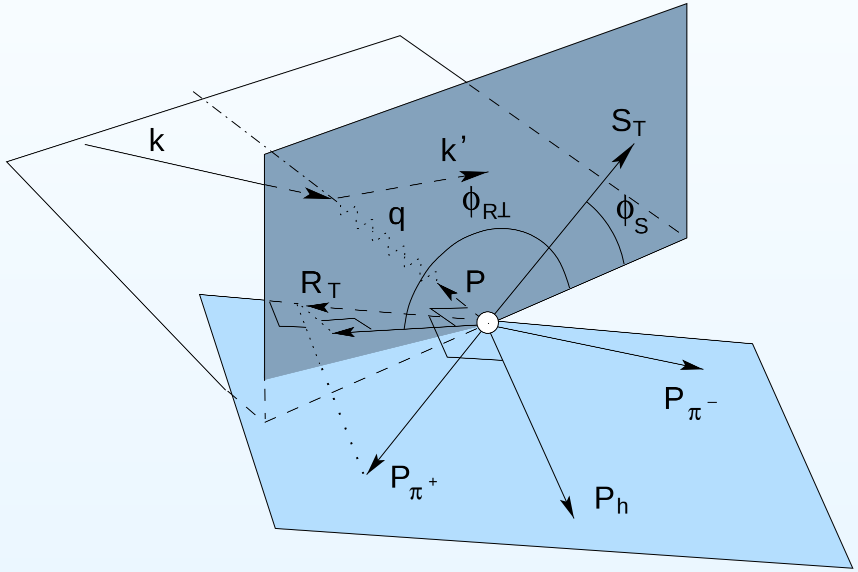


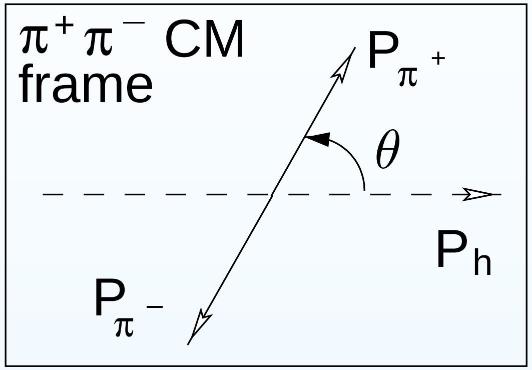
using **data from**:

- **HERMES**
- **COMPASS**
- **BELLE**

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

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





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

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

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

azimuthal angles ϕ_S **and** $\phi_{\boldsymbol{R}_\perp}$**:**

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

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

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

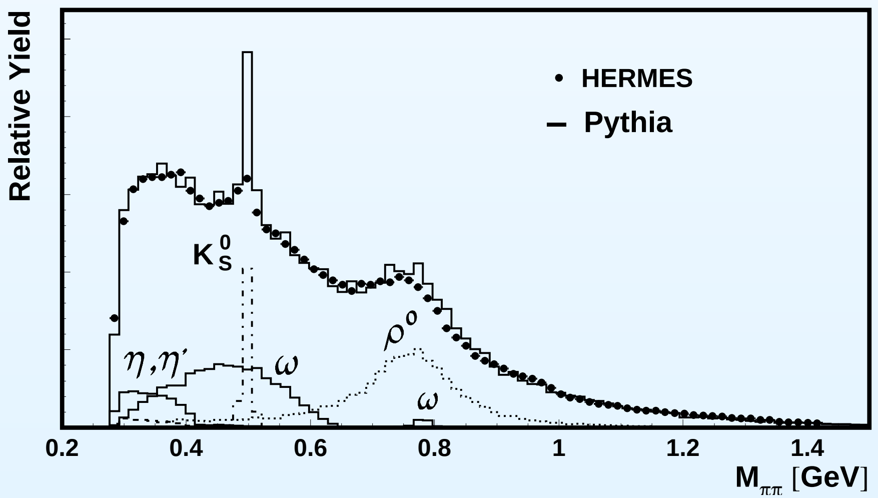
- **Fourier and Legendre expansion:**

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

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

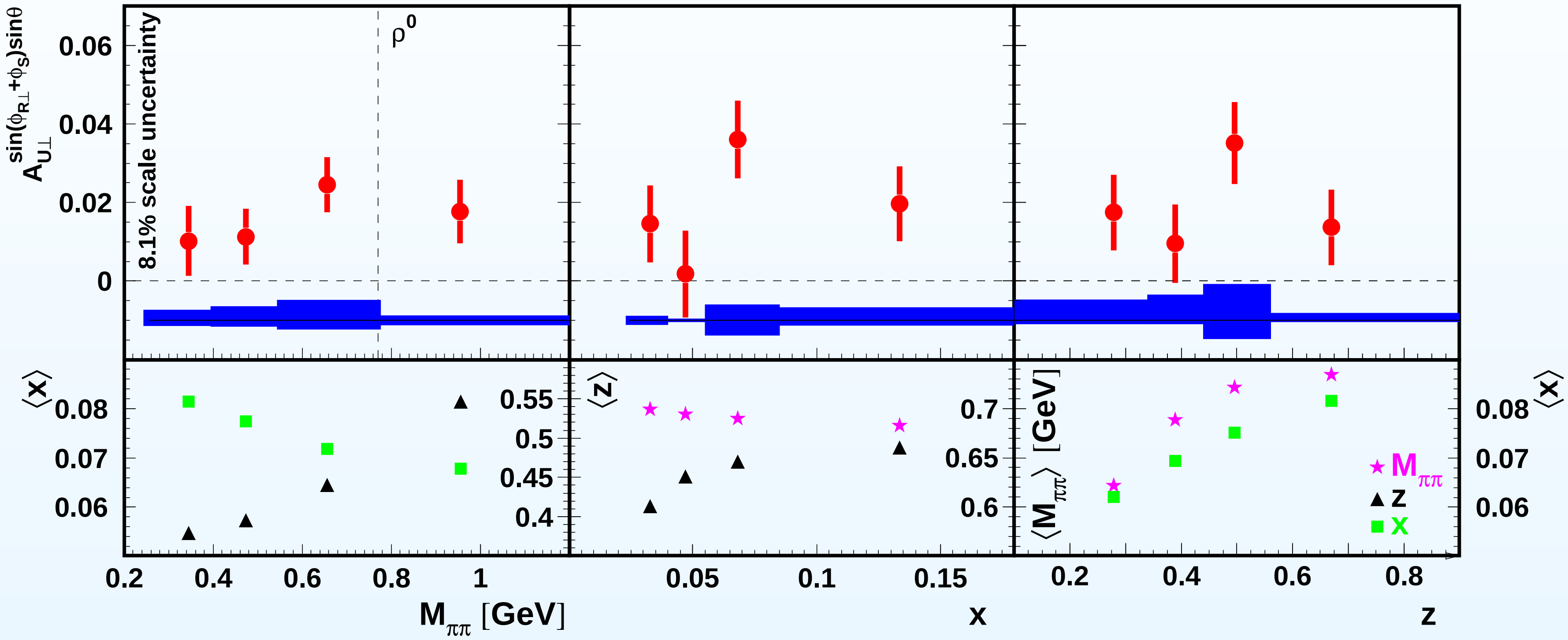
➥ $D_{1,q} \simeq D_{1,q} + D_{1,q}^{sp}\cos\theta + D_{1,q}^{pp}\frac{1}{4}(3\cos^2\theta - 1)$

➥ $H_{1,q}^{\sphericalangle} \simeq H_{1,q}^{\sphericalangle,sp} + H_{1,q}^{\sphericalangle,pp}\cos\theta$



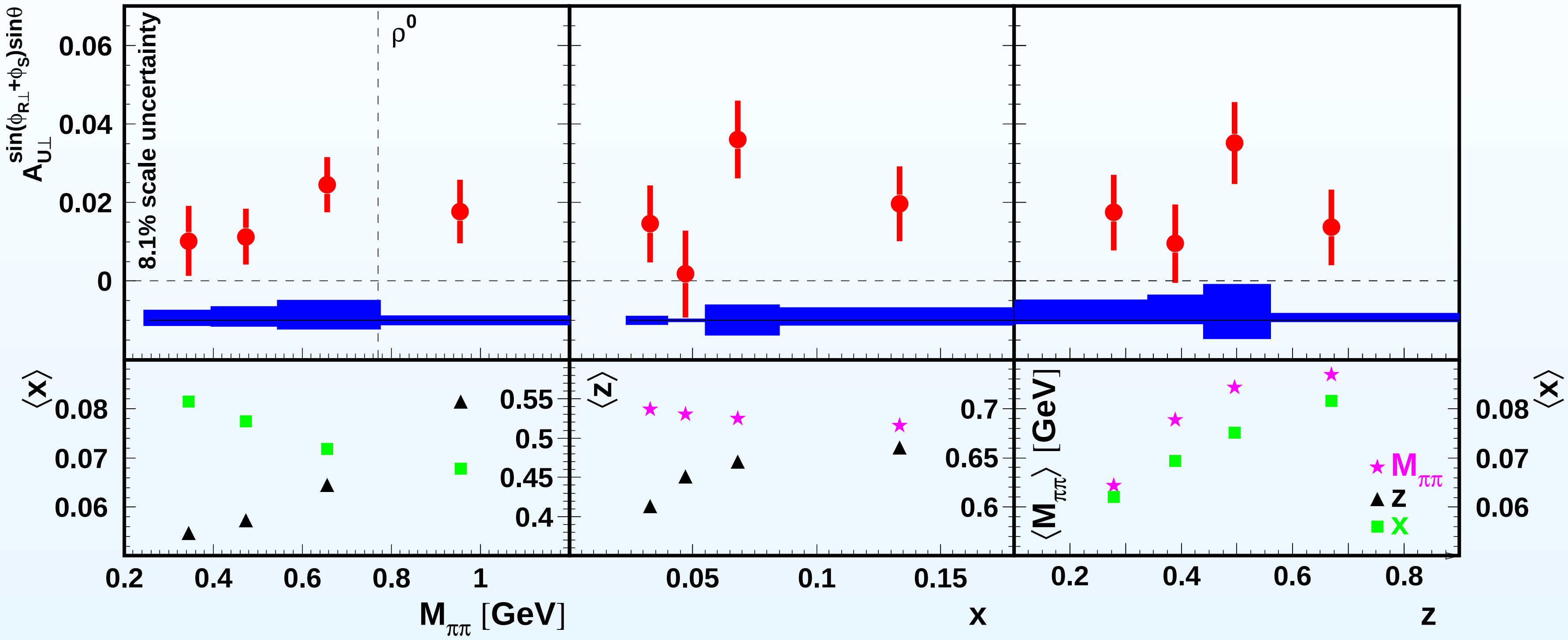
- symmetrisation around $\theta = \pi/2$ ➥ $D_{1,q}^{sp}$ and $H_{1,q}^{\sphericalangle,pp}$ drop out

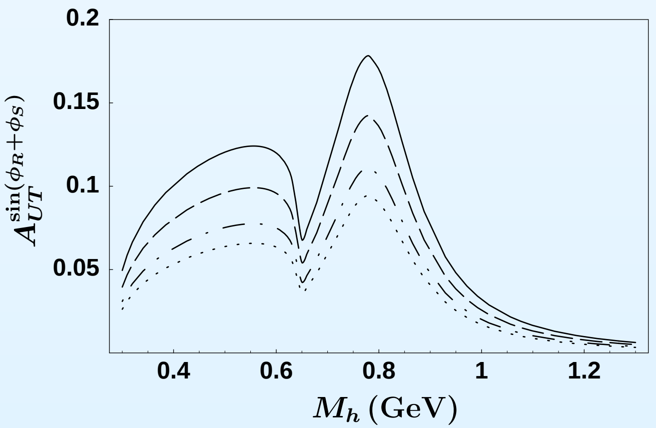
Results on SSA in semi-inclusive $\pi^+\pi^-$ production:



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

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

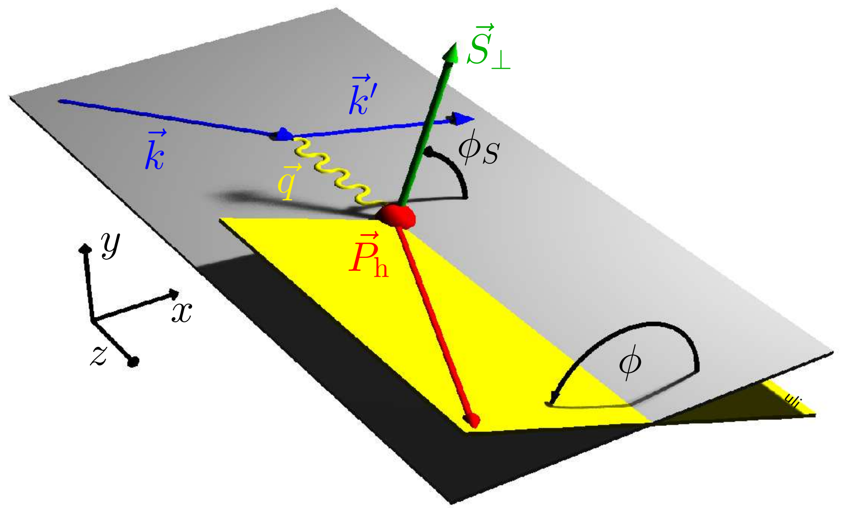




Bacchetta, Radici
(**Phys.Rev.D74:114007,2006**)

Transversity measurement in single-hadron production:

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

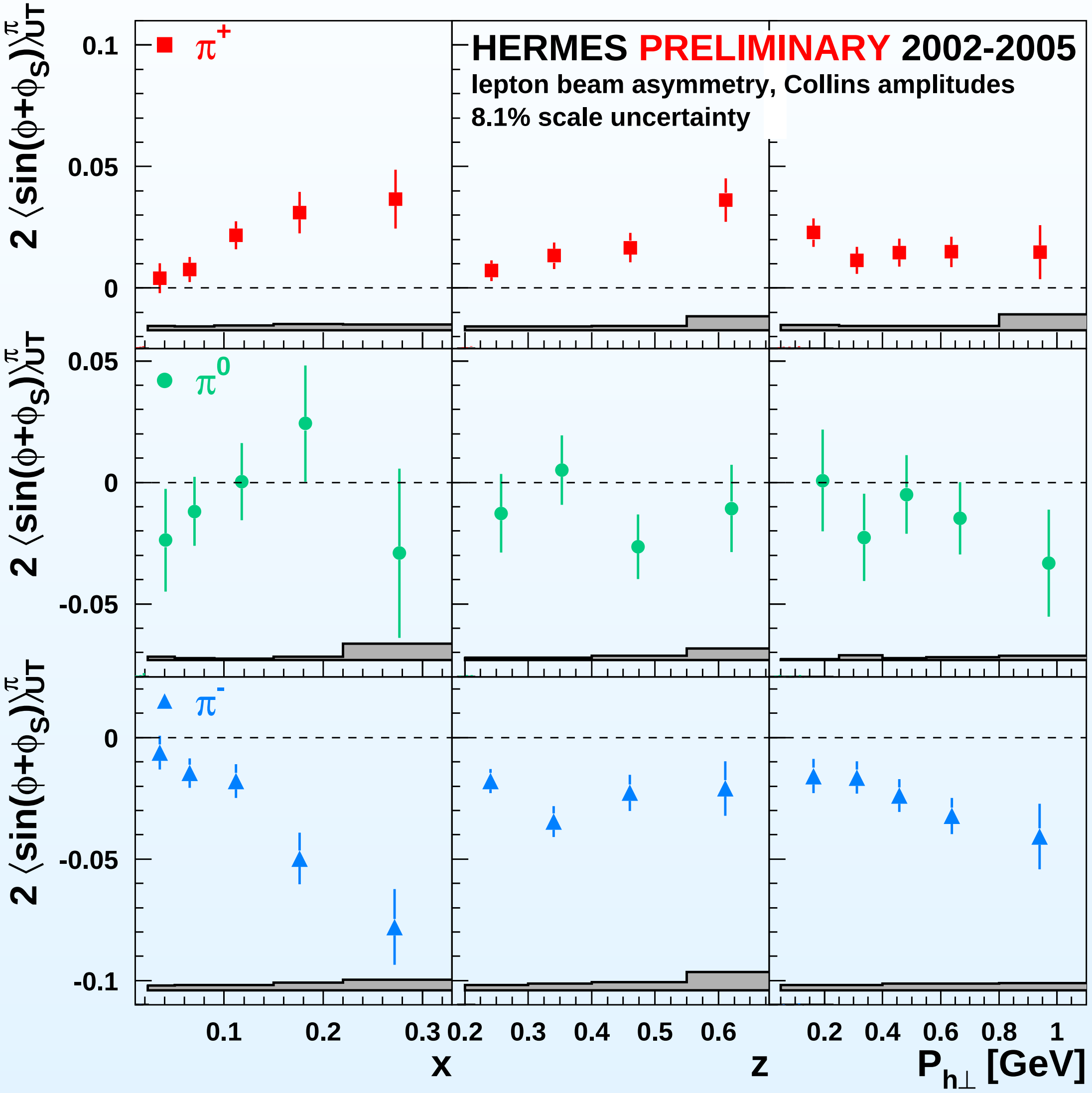


- due to **Collins mechanism** $((S_q \cdot (p_q \times P_h)))$
- **Fourier decomposition of** $\sigma_{U\perp}$ including:

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

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

The Collins amplitudes for pions:



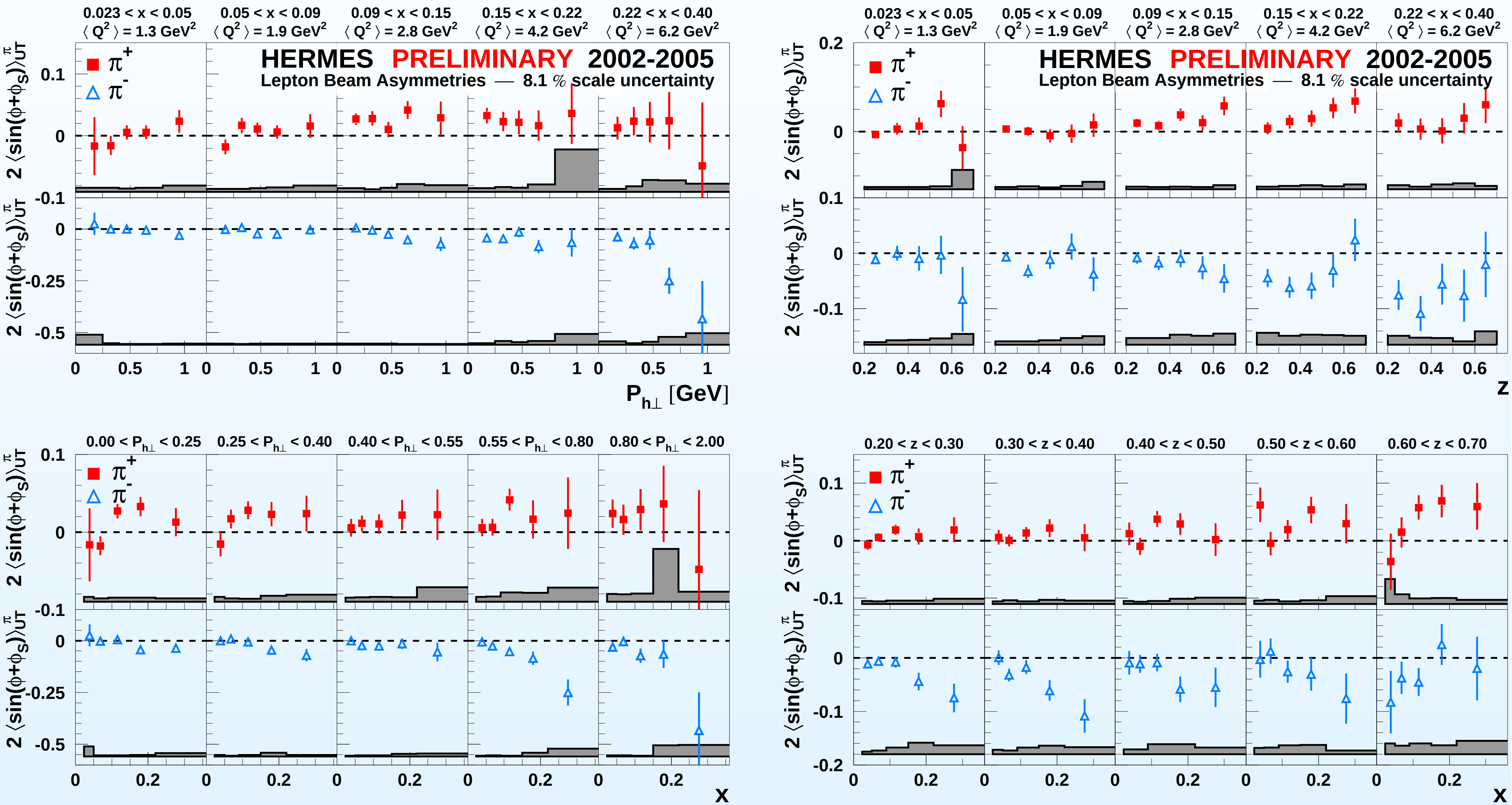
Results of the Collins amplitude:

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

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 kinematic dependence of the Collins amplitudes:

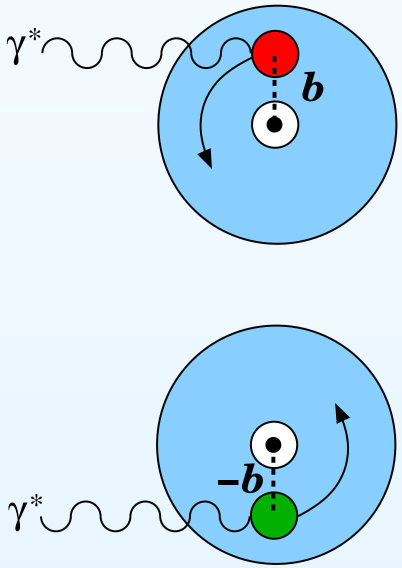


Evidence for naive-T-odd distribution functions:

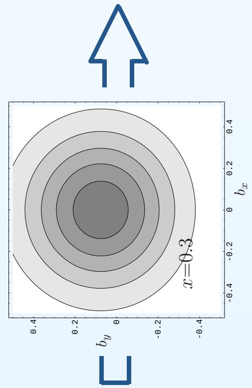
- **naive time reversal odd** (naive-T-odd) **functions**
- involve interference of amplitudes with different helicities
  ➥ suppressed in perturbative QCD
  ➥ assigned to distribution and fragmentation functions
- **associated with spin/orbit effects ($\boldsymbol{S} \cdot (\boldsymbol{P_1} \times \boldsymbol{P_2})$)**
- observation of the naive-T-odd **Sivers function** $f_{1T}^{\perp}$
- observation of the naive-T-odd **Boer-Mulders function** $h_1^{\perp}$

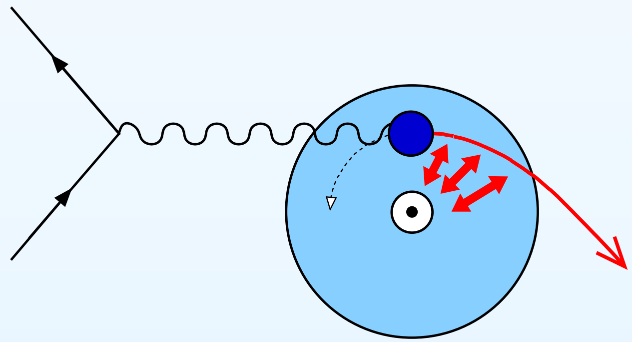
The Sivers mechanism:

- 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**))



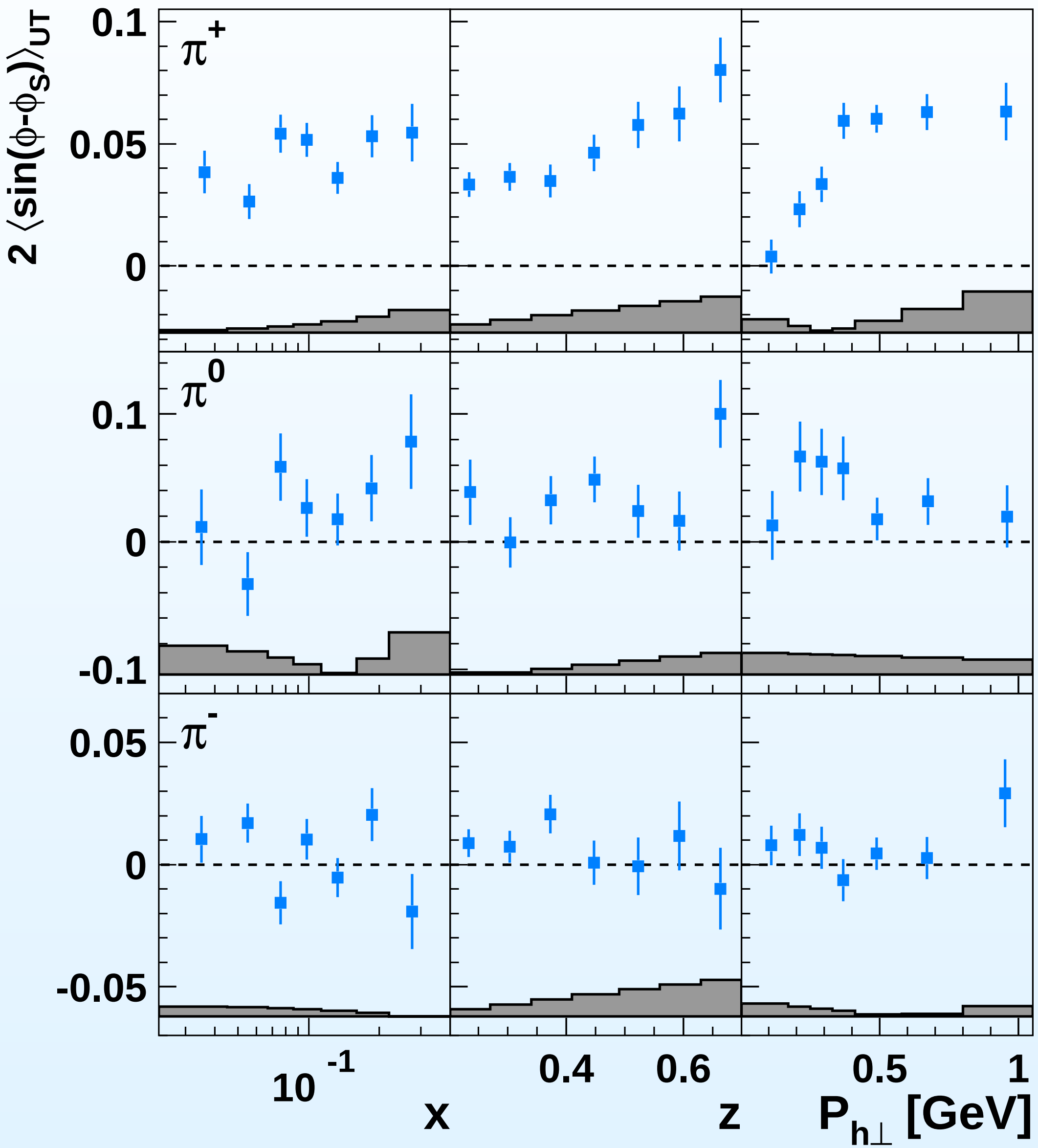
$u_X\,(x,\boldsymbol{b}_\perp)$:





- **SSA** due to **Sivers mechanism** $(\boldsymbol{S_q} \cdot (\boldsymbol{P} \times \boldsymbol{p_q}))$

The Sivers amplitudes for π-mesons:



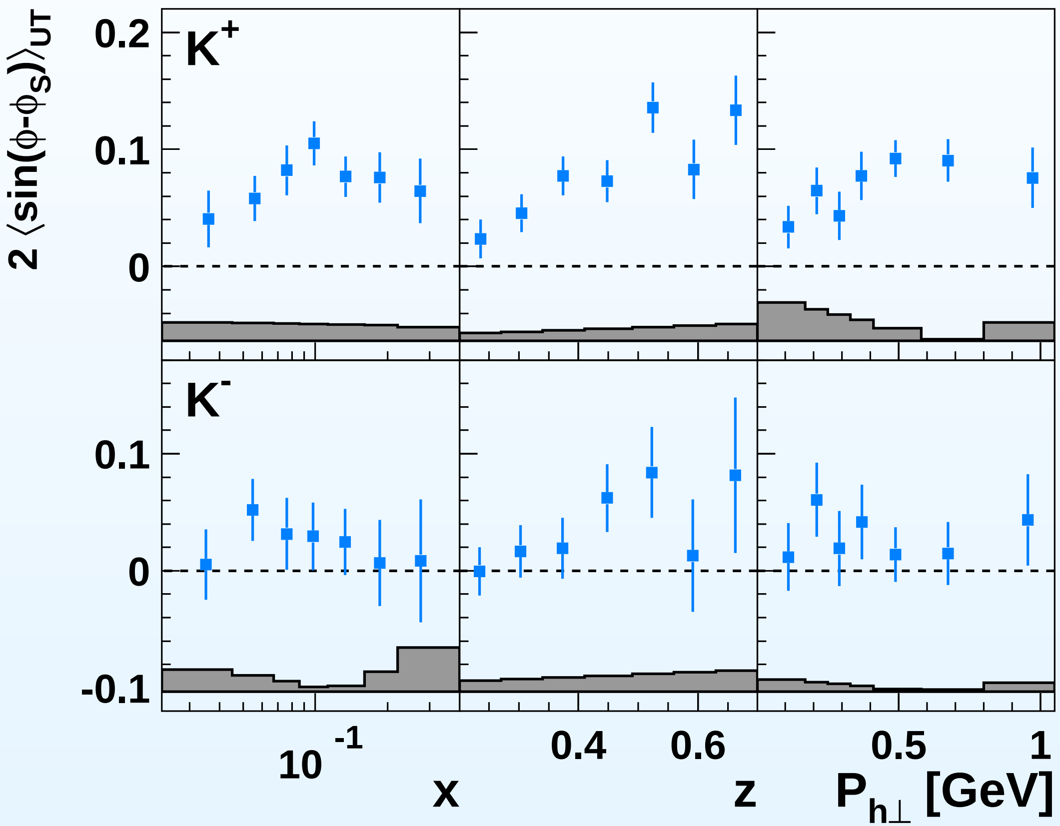
Results for Sivers amplitude:

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

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
- $P_{h\perp} > 0.4$ GeV: saturation for π^+
- $P_{h\perp} \to 0.0$ GeV: linear decrease
- isospin symmetry fulfilled

The Sivers amplitudes for charged K-mesons:



Results for Sivers amplitude:

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

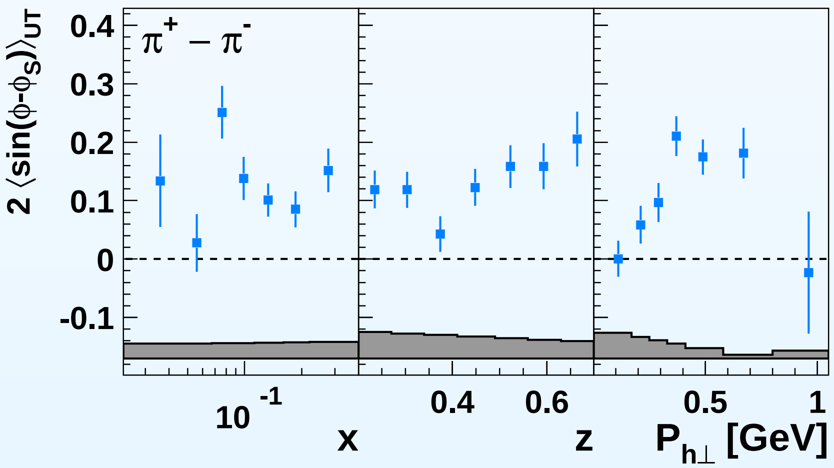
from 2002–2005 data:

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

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
- saturation for $P_{h\perp} > 0.4$ GeV
- linear decrease for $P_{h\perp} \to 0.0$ GeV

- possible interpretation in terms of valence-quark distributions:

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

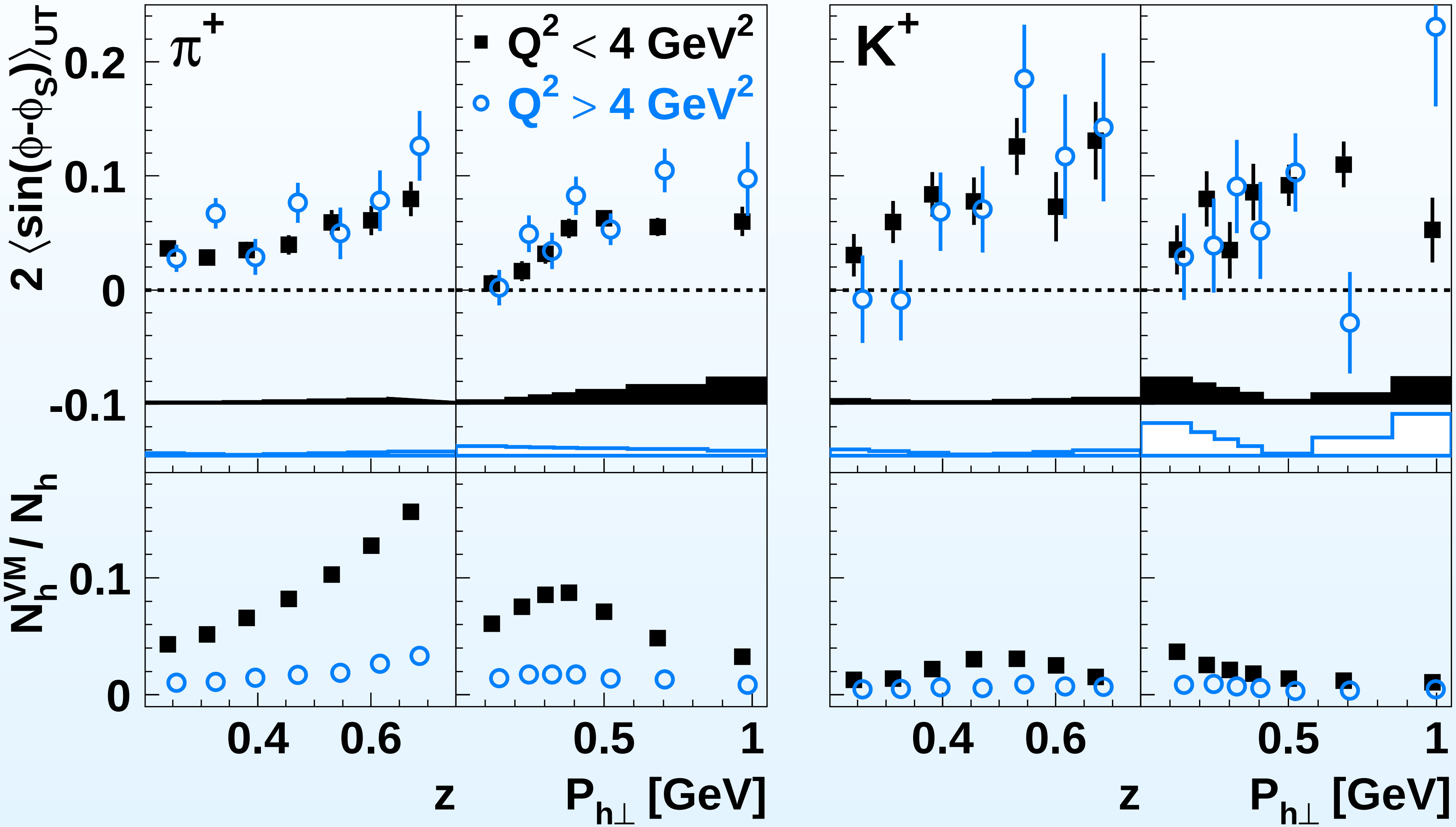
The role of higher twist terms:

- **Sivers amplitude:**

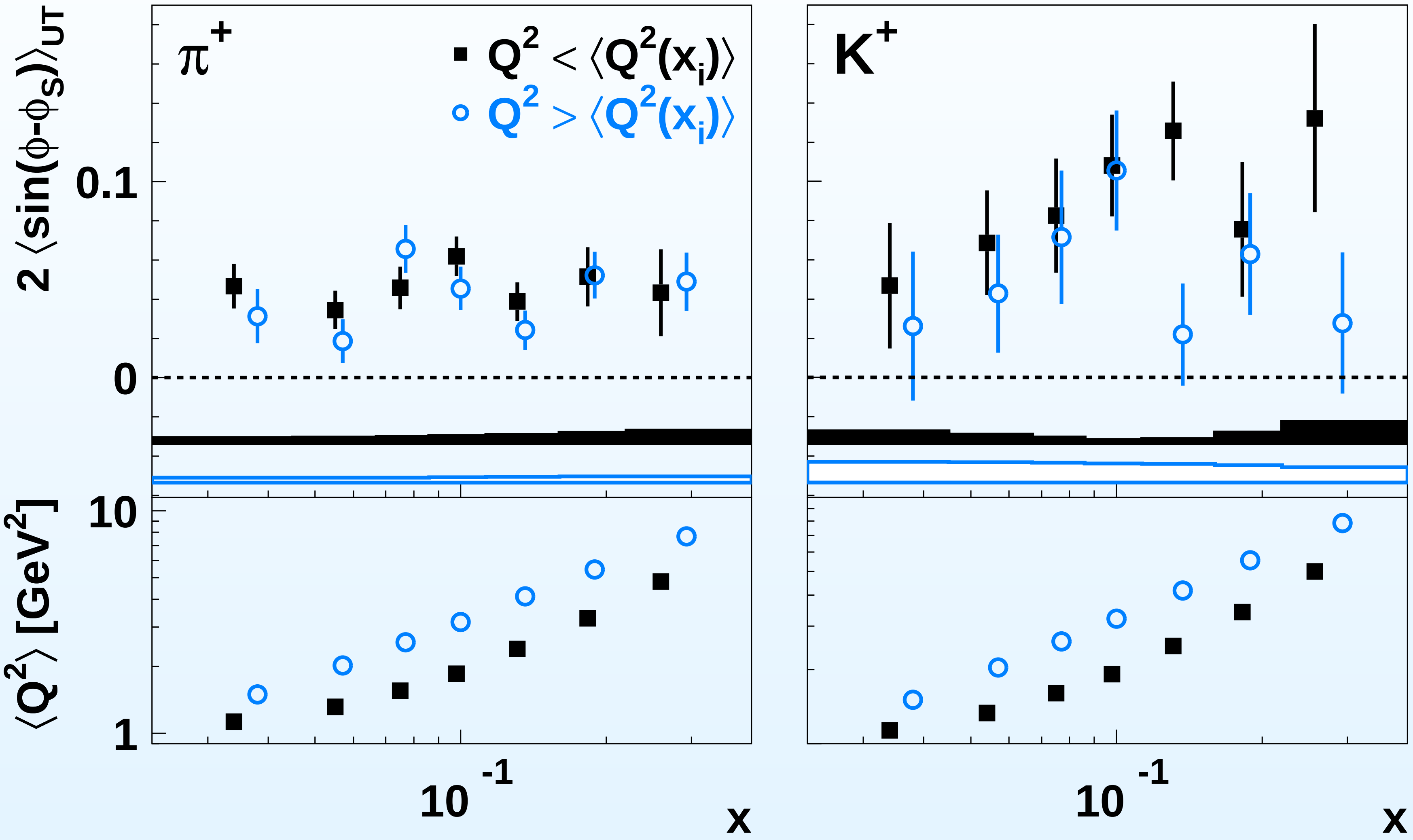
$$2\,\langle\sin(\phi-\phi_S)\rangle_{\mathsf{UT}} \propto F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon\, F_{UT,L}^{\sin(\phi-\phi_S)}$$

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

Examination of vector-meson contribution:



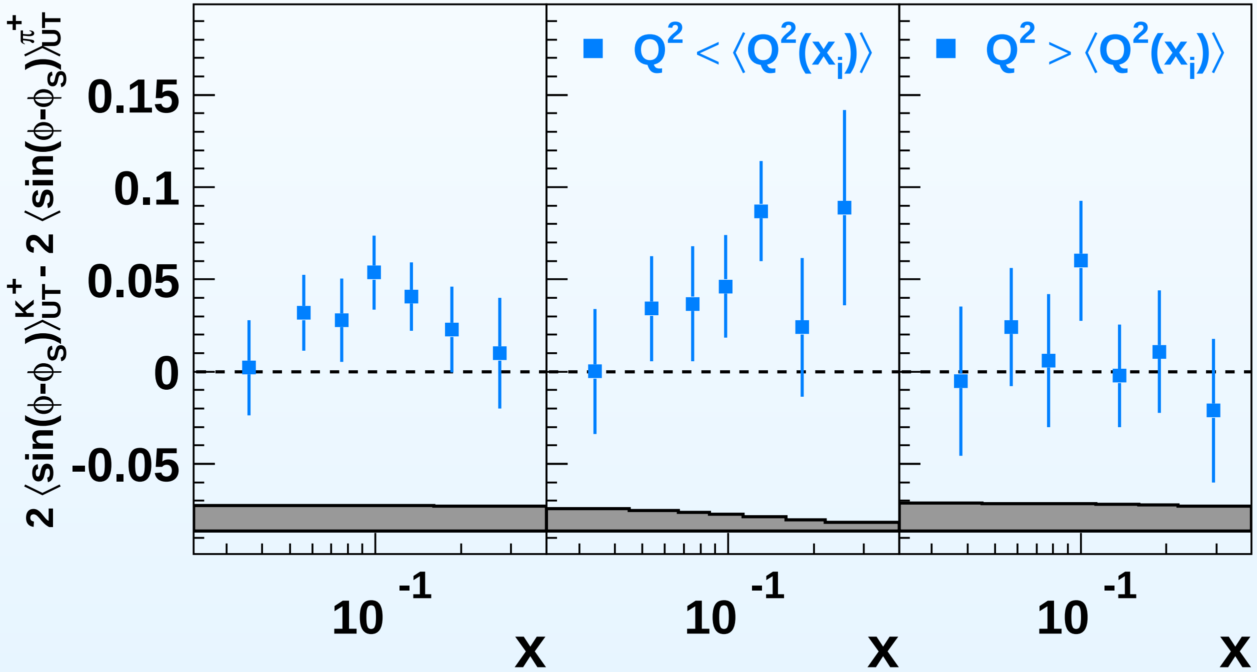
Examination of other $1/Q^2$-suppressed contributions:



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

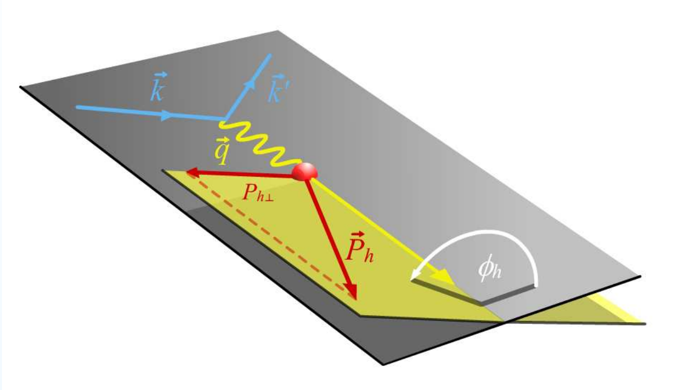
Sivers amplitudes for K^+ and π^+:

- **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?

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



Azimuthal modulations of σ_{UU}:

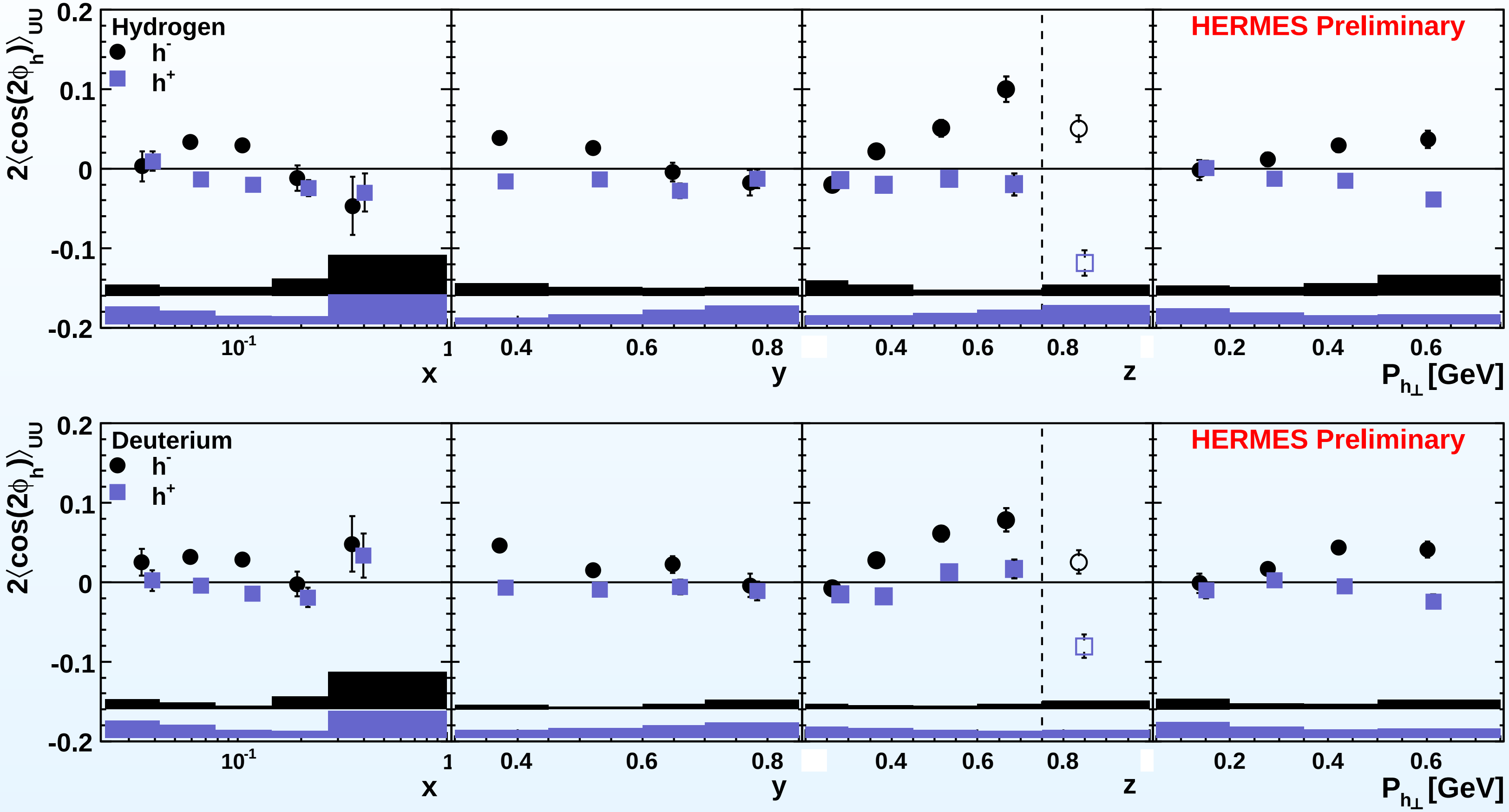
- leading-twist $2\langle\cos(2\phi)\rangle_{UU}$
  - sensitive to **Boer-Mulders function** ($h_1^\perp \otimes H_1^\perp$)
- subleading-twist $2\langle\cos(\phi)\rangle_{UU}$
  - sensitive to **Cahn effect** ($f_1 \otimes D_1$) and $h_1^\perp \otimes H_1^\perp$

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

➥ correction for finite acceptance, QED radiation, detector smearing

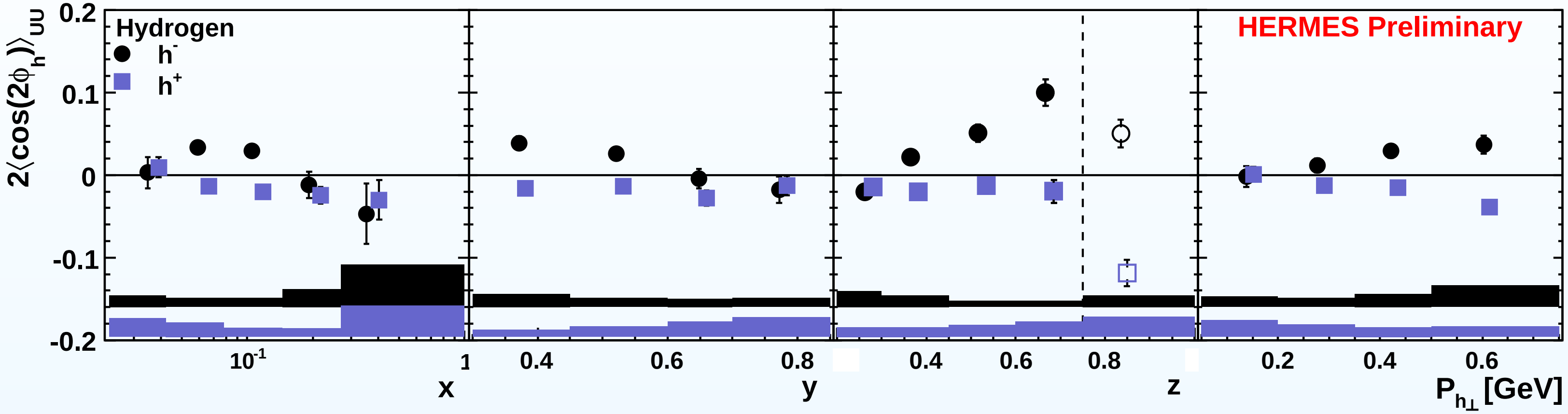
hydrogen (2000, 2006) and deuterium (2000, 2005) data

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

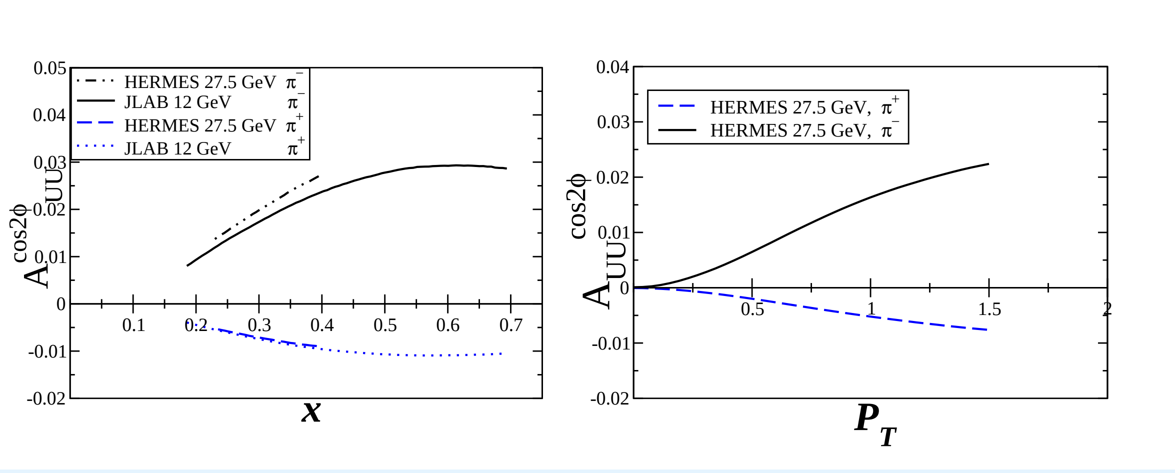


- significantly positive for h^-
- slightly negative for h^+
- $h_1^{\perp,u} = h_1^{\perp,d}$ or $h_1^{\perp,u} = -h_1^{\perp,d}$

Clear signal for Boer-Mulders function?:



model by Gamberg, Goldstein, Schlegel, **Phys.Rev.D77:094016,2007**



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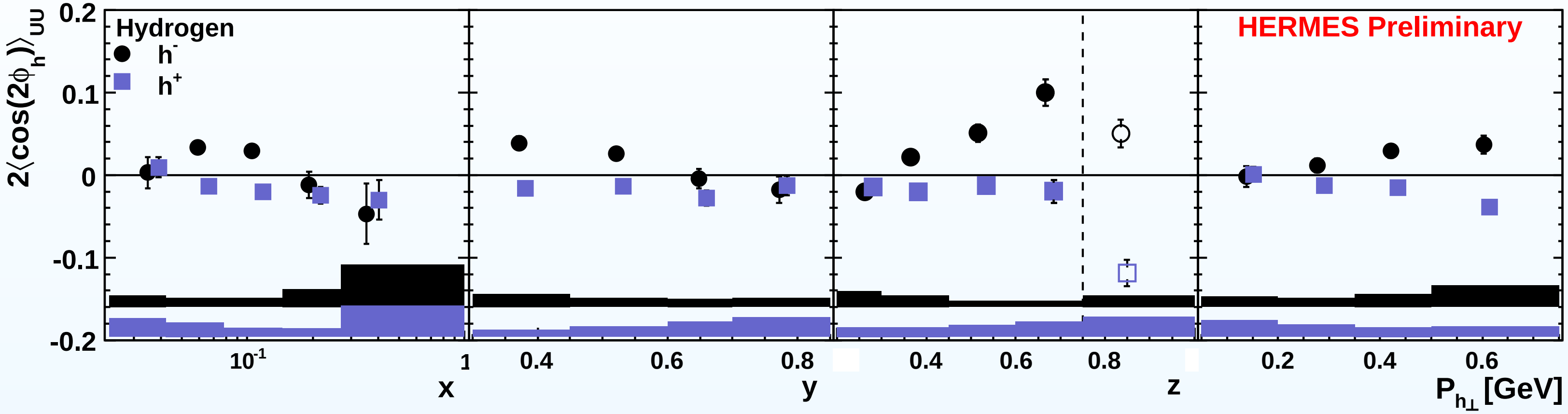
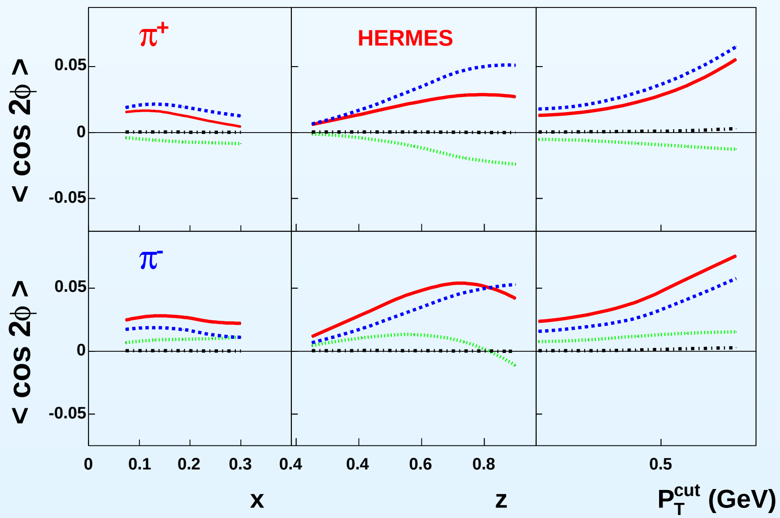
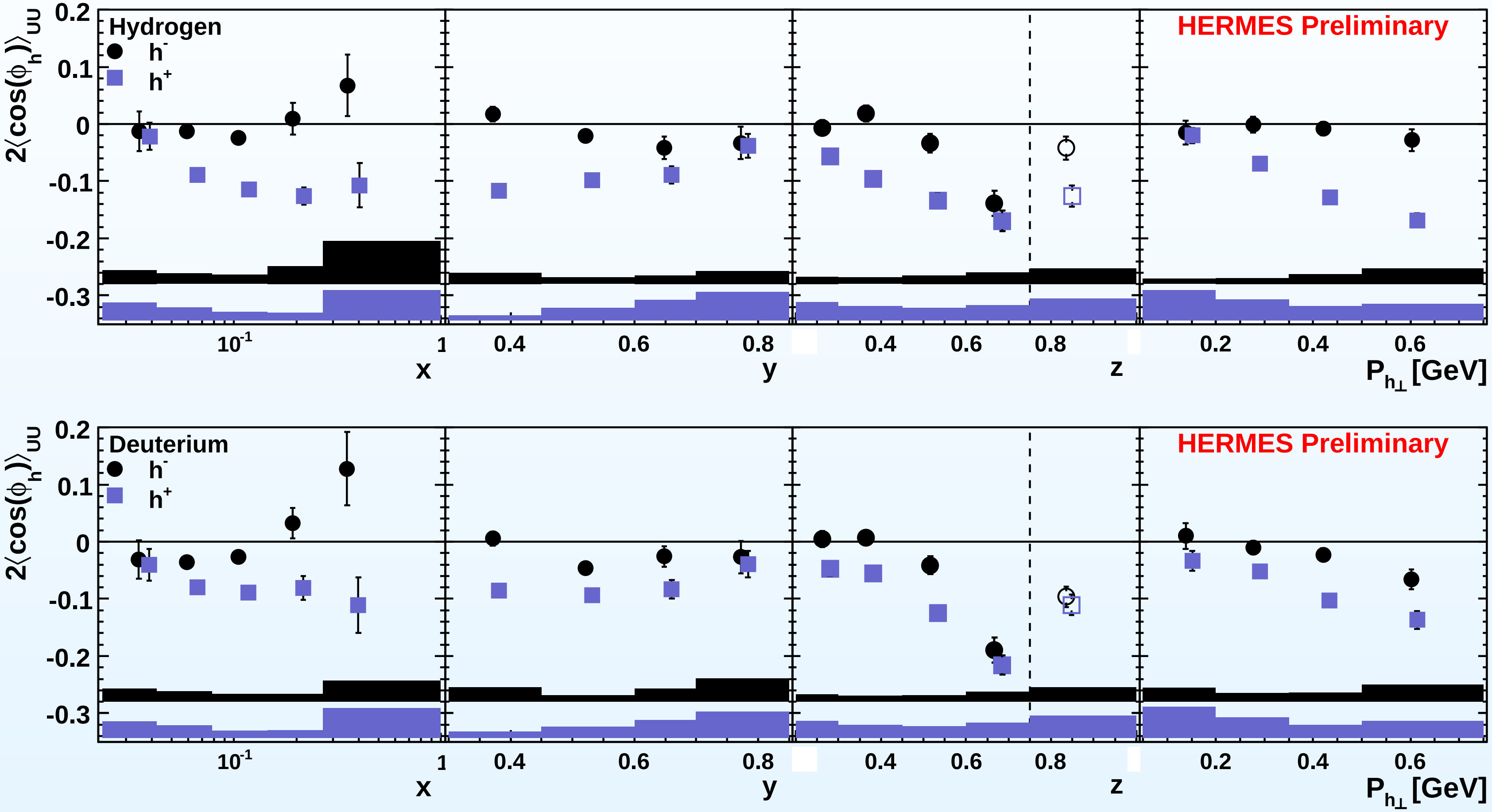


model by Barone, Prokudin, Ma, **Phys.Rev.D78:045022,2008**



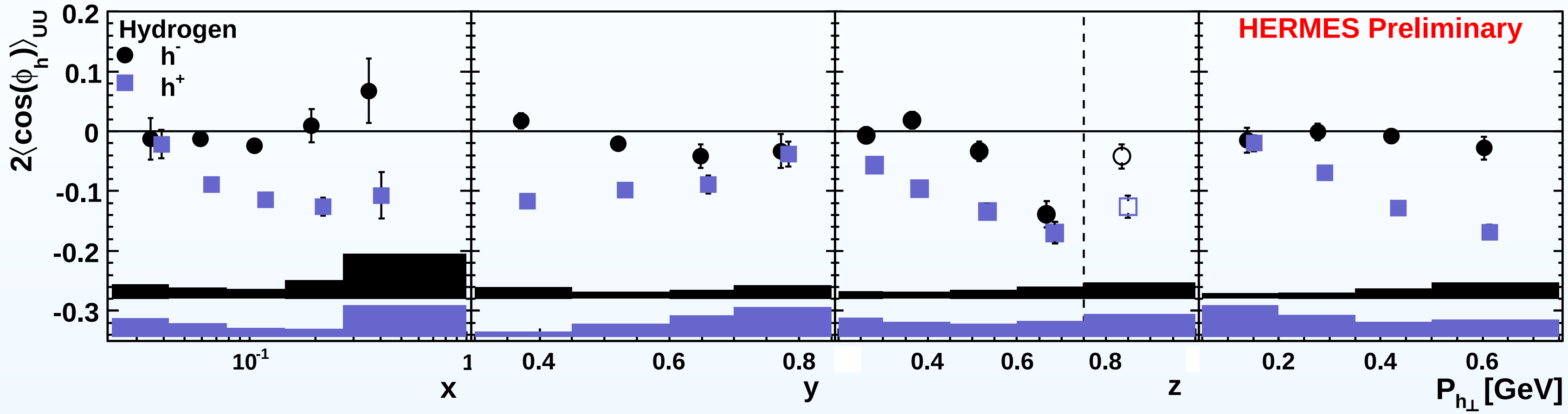
including Boer-Mulders and Cahn effect (twist-four contribution)

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

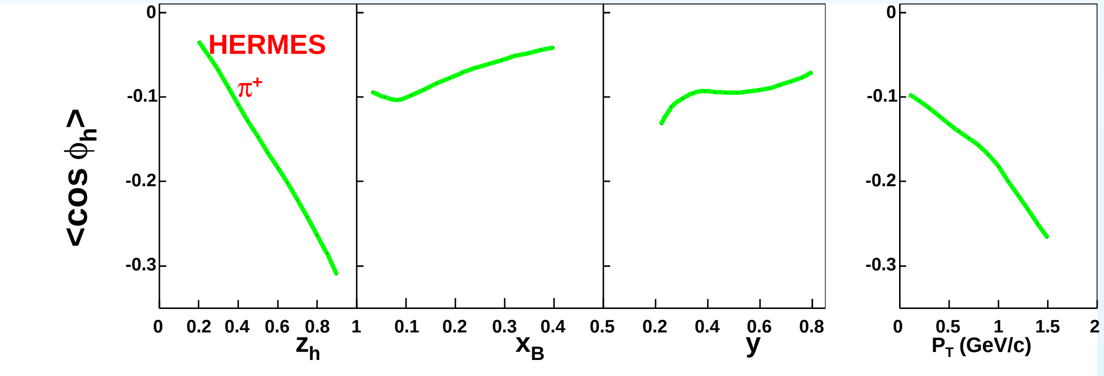


- almost zero for h^-
- significantly negative for h^+

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



prediction by Anselmino et al., **Eur.Phys.J.A31:373-381,2007**:



- quark-flavour dependent $\langle p_T \rangle$?
- significant Boer-Mulders contribution?

Towards the full cross-section measurement:

One-hadron production

$$
\begin{aligned}
d\sigma = \; & d\sigma^{0}_{UU} + \cos 2\phi \, d\sigma^{1}_{UU} + \frac{1}{Q} \cos\phi \, d\sigma^{2}_{UU} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma^{3}_{LU} \\
& + S_L \left\{ \sin 2\phi \, d\sigma^{4}_{UL} + \frac{1}{Q} \sin\phi \, d\sigma^{5}_{UL} + \lambda_e \left[d\sigma^{6}_{LL} + \frac{1}{Q} \cos\phi \, d\sigma^{7}_{LL} \right] \right\} \\
& + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right. \\
& \quad + \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
& \left. \quad + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q} \left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}
\end{aligned}
$$

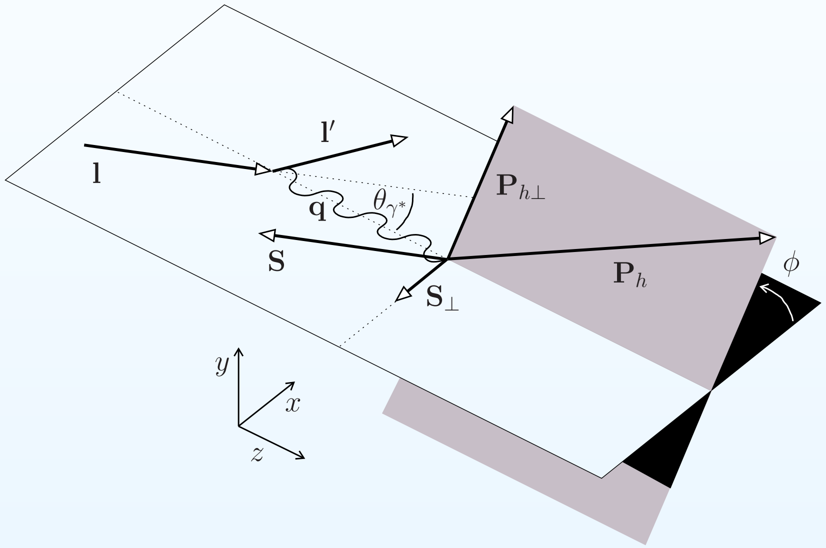
σ_{XY}

Beam **Target**

Polarization

Longitudinal single-spin asymmetries:

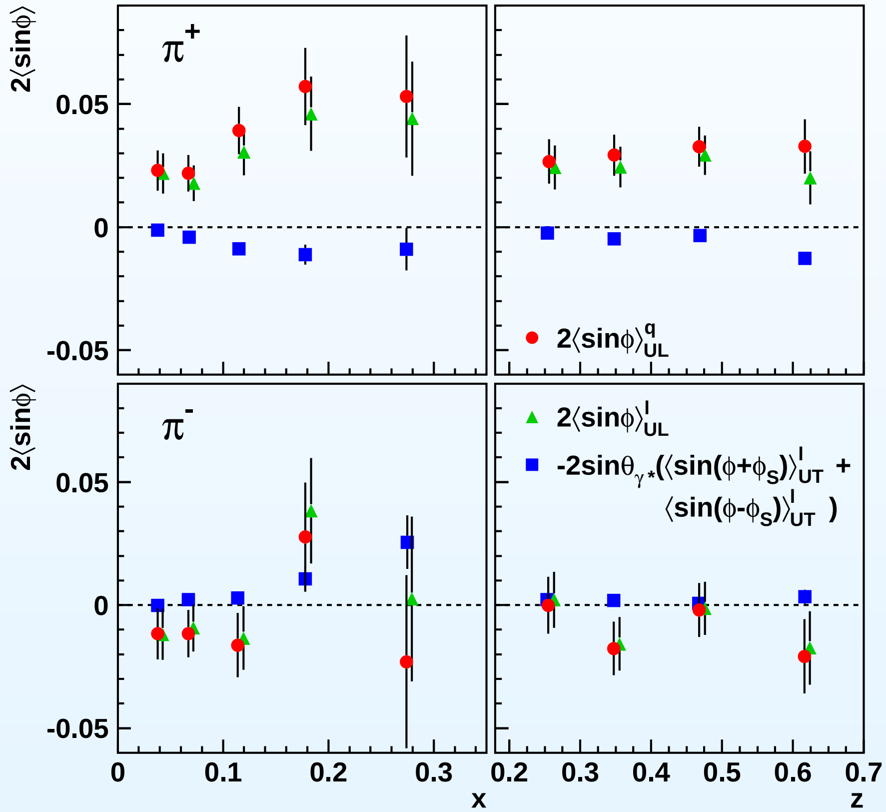
mixing of azimuthal moments:



target spin axis w.r.t.:

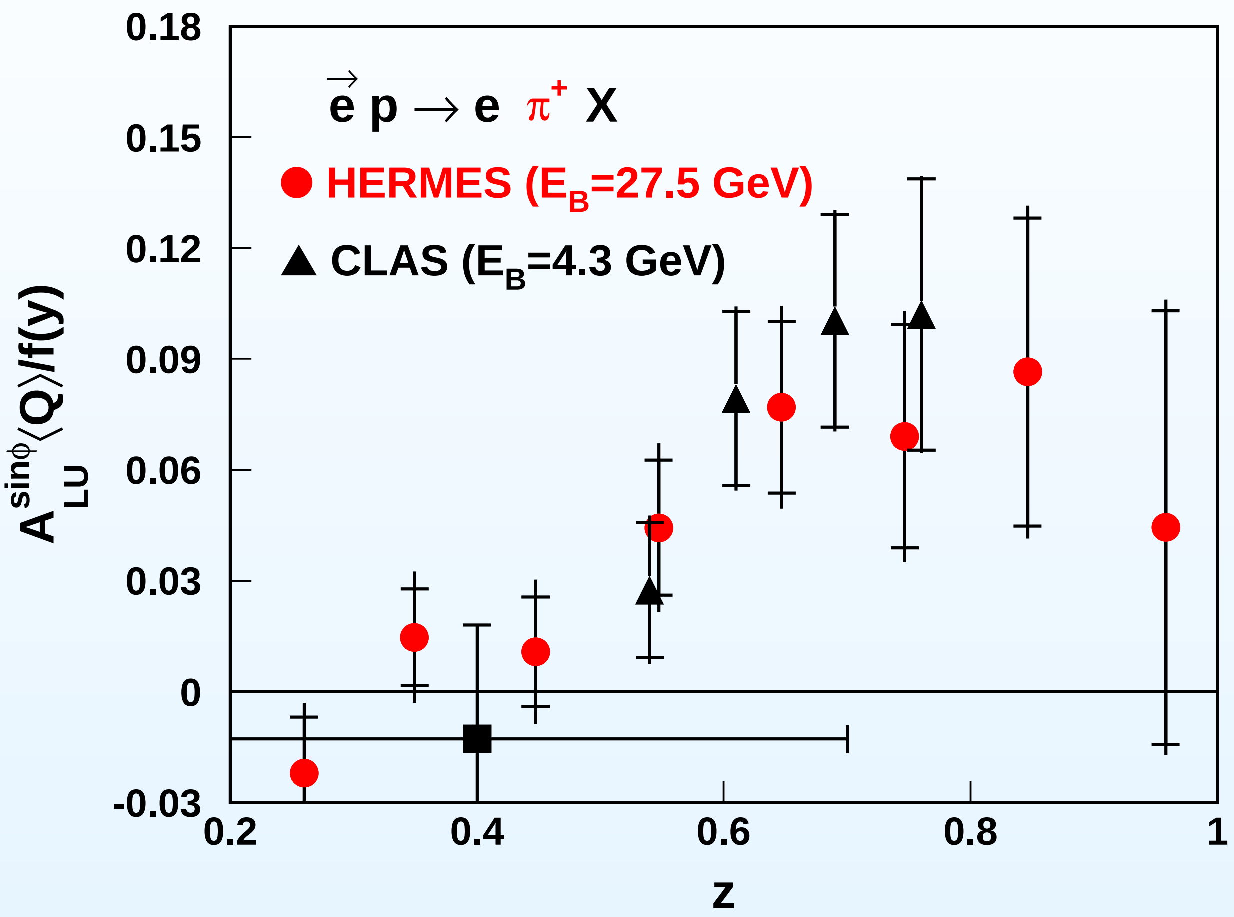
- virtual photon axis (^{q},$_L$,$_T$)
- lepton beam axis (^{l},$_\parallel$,$_\perp$)

evidence for subleading twist SSA:



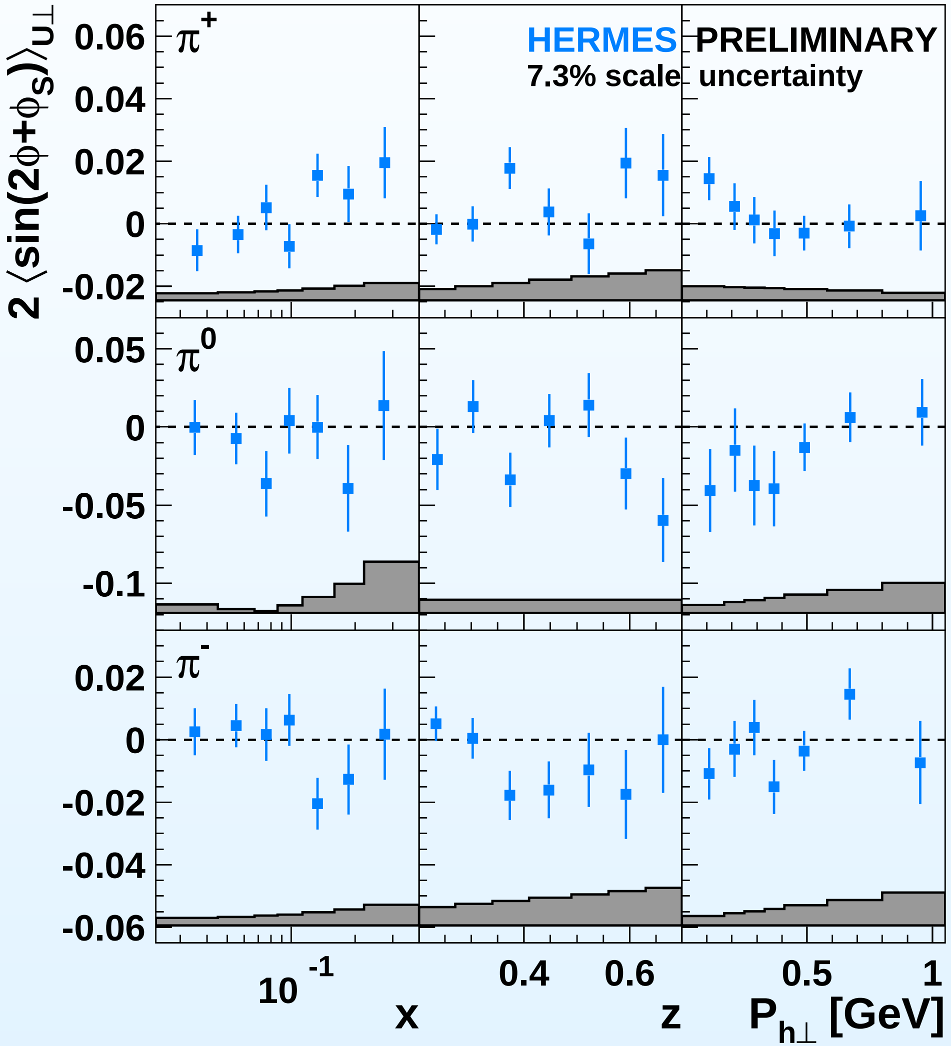
$$\langle \sin\phi \rangle^q_{\text{UL}} = \langle \sin\phi \rangle^l_{\text{UL}} + \sin\theta_{\gamma^*} \left(\langle \sin \phi + \phi_S \rangle^l_{\text{UT}} + \langle \sin \phi - \phi_S \rangle^l_{\text{UT}} \right)$$

Longitudinal beam-spin asymmetry:



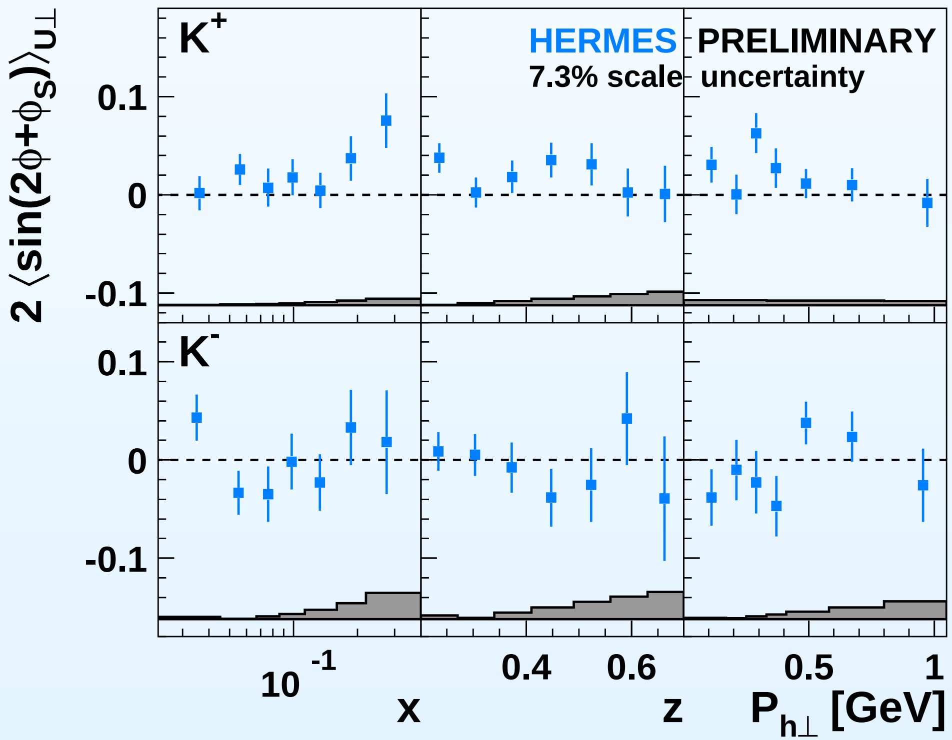
- **good agreement with CLAS**
- sensitive to $E(x)$ (but difficult to separate)

The $\langle \sin(2\phi + \phi_S) \rangle_{U\perp}$ Fourier component:



expected to scale as:

$$\frac{1}{2}\sin\theta_{\gamma^*}\,\langle \sin(2\phi)\rangle_{UL} \approx 0.01$$



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

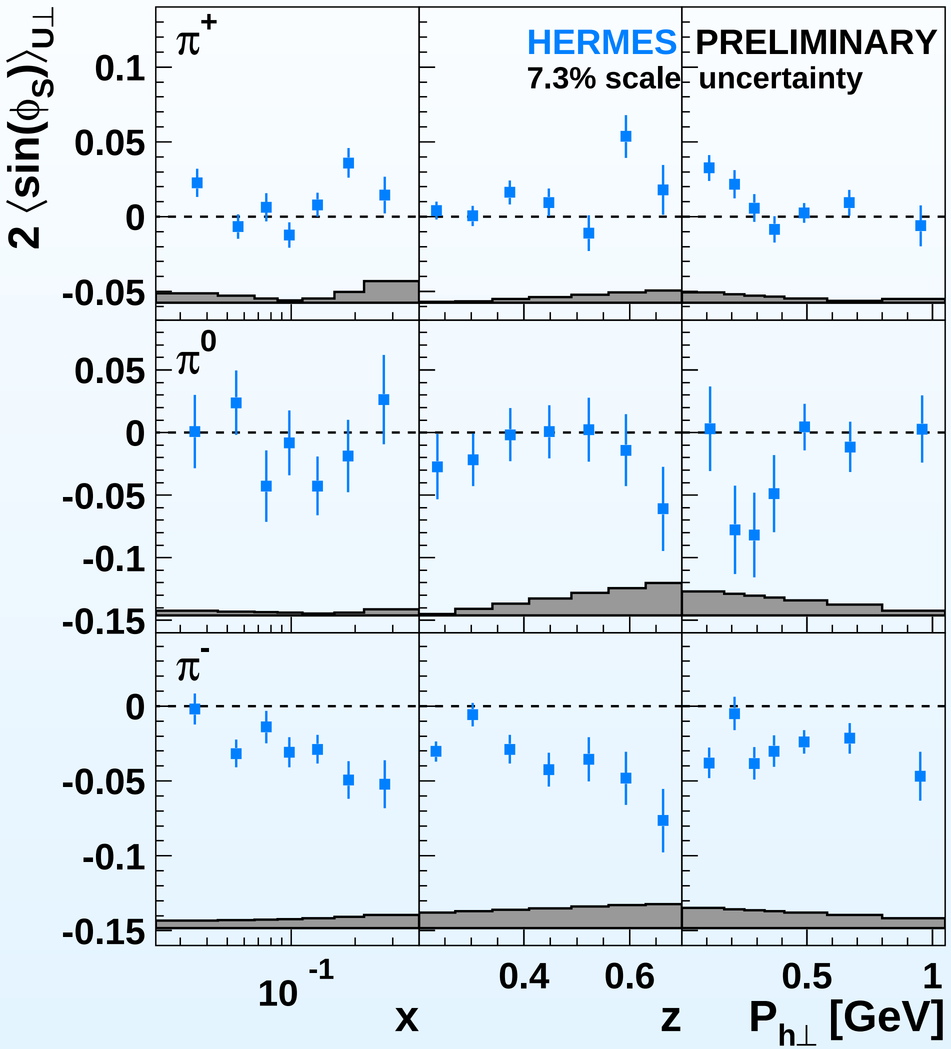
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} \quad \mathcal{C} \quad \Bigg\{ \quad \left(x f_T D_1 - \frac{M_h}{M}\, h_1 \frac{\tilde{H}}{z} \right)$$
$$- \quad \frac{\boldsymbol{k}_T \boldsymbol{p}_T}{2M M_h} \left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \, \frac{\tilde{G}^{\perp}}{z} \right) \right.$$
$$\left. \left. - \quad \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp} \, \frac{\tilde{D}^{\perp}}{z} \right) \right] \right\}$$

- using relations between T-even functions:

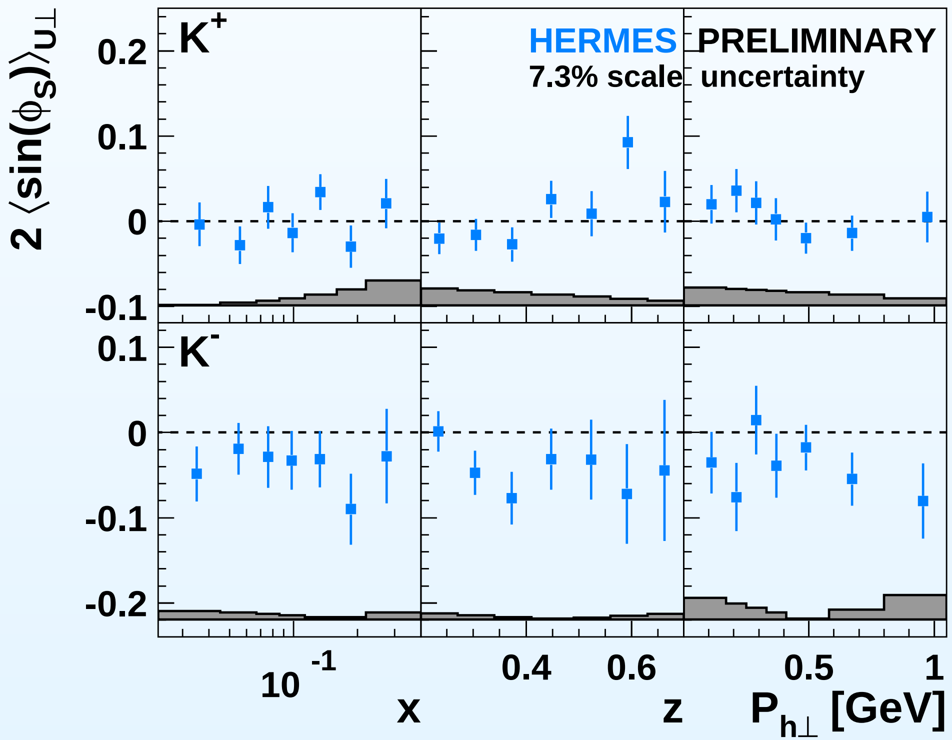
$$x h_T \quad = \quad x\tilde{h}_T - h_1 + \frac{\boldsymbol{p}_T^2}{2M^2} h_{1T}^{\perp} + \frac{m}{M} g_{1T}$$
$$x h_T^{\perp} \quad = \quad x\tilde{h}_T^{\perp} + h_1 + \frac{\boldsymbol{p}_T^2}{2M^2} h_{1T}^{\perp}$$

- and the Wandzura-Wilczek approximation ➥ $F_{UT}^{\sin\phi_S} \propto F_{UT}^{\sin(\phi+\phi_S)}$

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



shape similar to Collins amplitudes expected

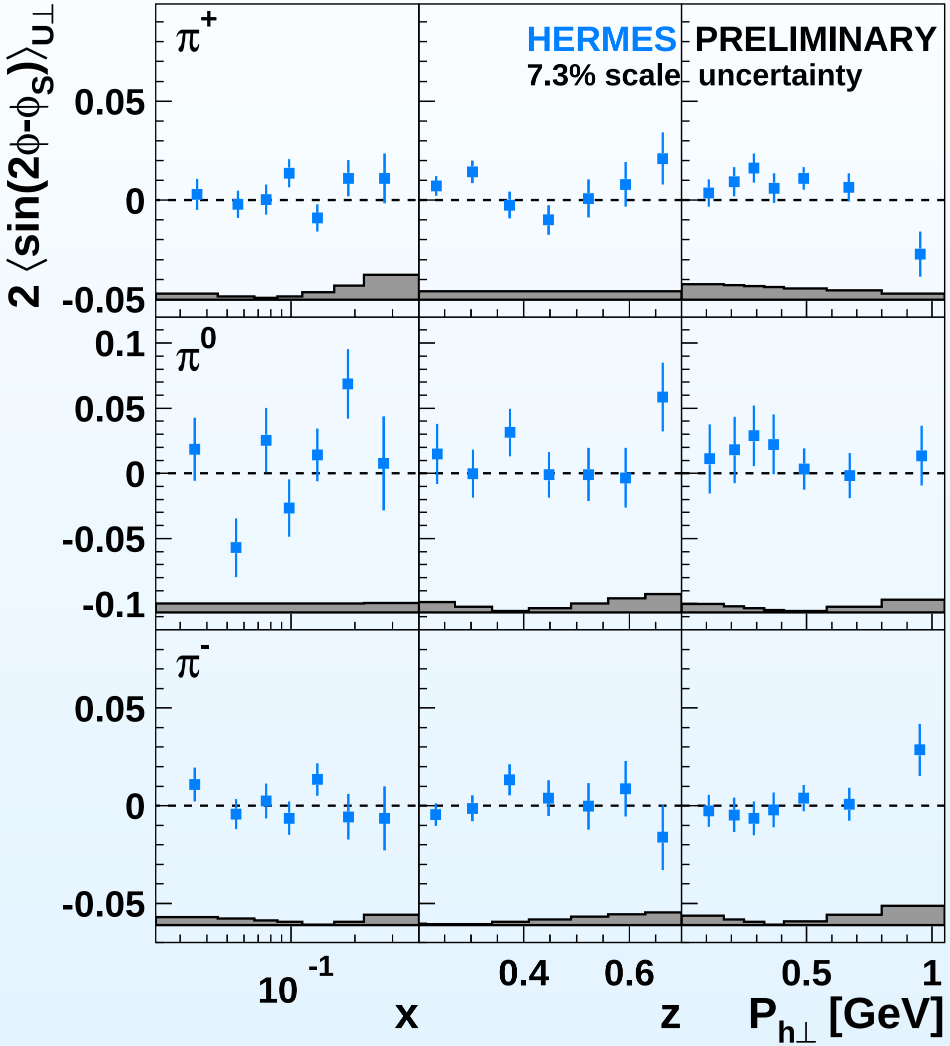


The $\langle \sin(2\phi - \phi_S) \rangle_{U\perp}$ Fourier component:

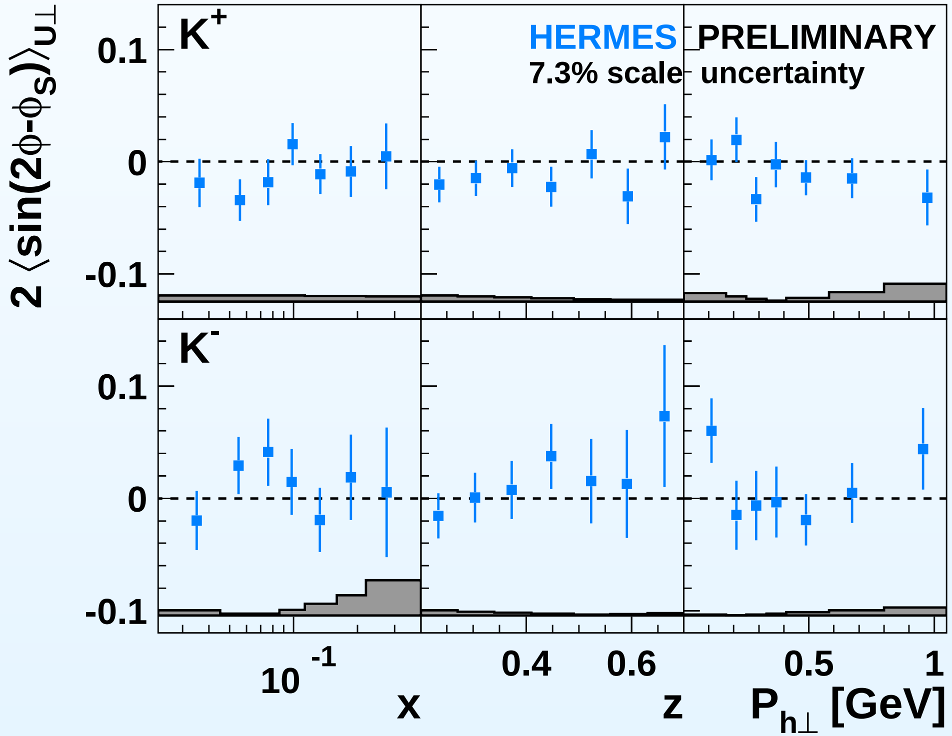
$$
\begin{aligned}
F_{UT}^{\sin(2\phi_h - \phi_S)} &= \frac{2M}{Q}\mathcal{C}\Bigg\{ \frac{2\,(\hat{\boldsymbol{h}}\boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{2M^2} \left(x f_T^{\perp} D_1 - \frac{M_h}{M}\, h_{1T}^{\perp} \frac{\tilde{H}}{z} \right) \\
&- \frac{2\,(\hat{\boldsymbol{h}}\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\boldsymbol{p}_T) - \boldsymbol{k}_T\boldsymbol{p}_T}{2MM_h} \Bigg[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^{\perp}}{z} \right) \\
&+ \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp} \frac{\tilde{D}^{\perp}}{z} \right) \Bigg] \Bigg\}
\end{aligned}
$$

- $F_{UT}^{\sin(\phi \pm \phi_S)}$ expected to scale as $P_{h\perp}$
- $F_{UT}^{\sin(2\phi - \phi_S)}$ expected to scale as $(P_{h\perp})^2$
  ➥ **suppressed w.r.t. Collins and Sivers amplitudes**

The $\langle \sin(2\phi - \phi_S) \rangle_{U\perp}$ Fourier component:



suspressed w.r.t. Collins and Sivers amplitudes

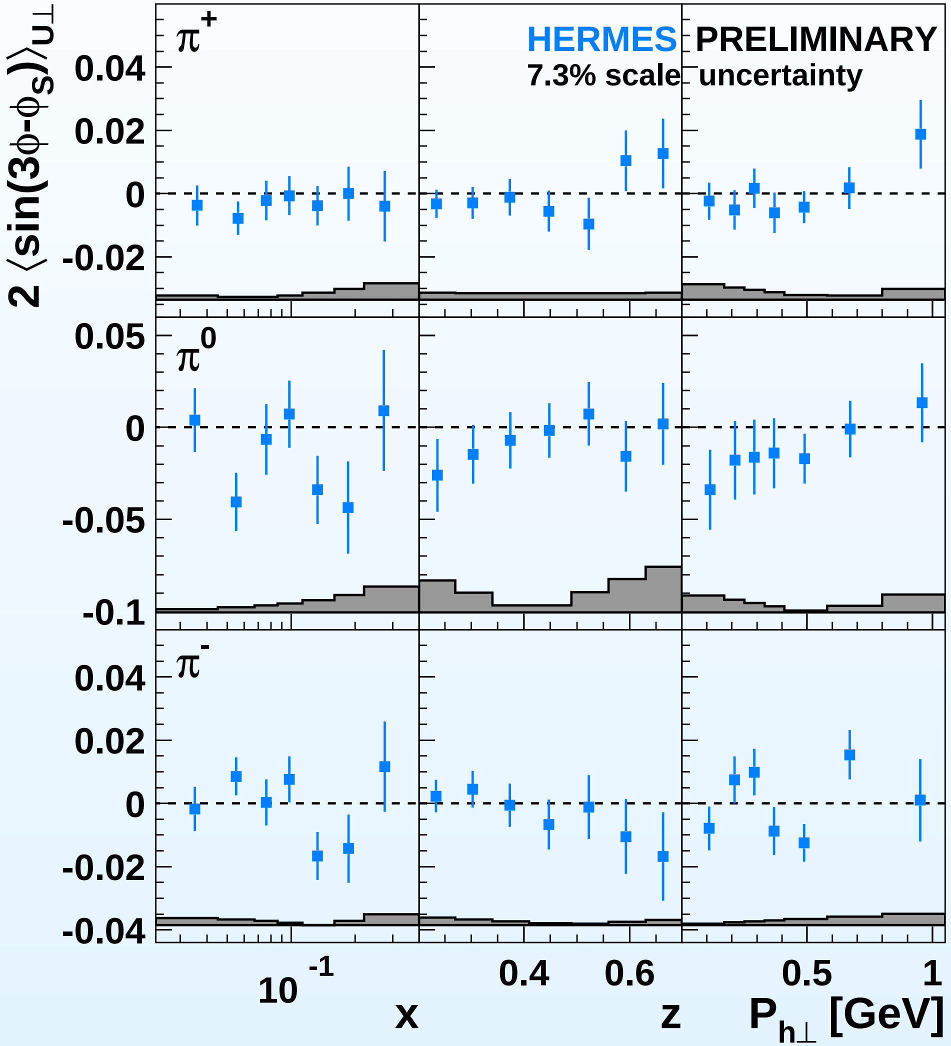


The $\langle \sin(3\phi - \phi_S) \rangle_{U\perp}$ Fourier component:

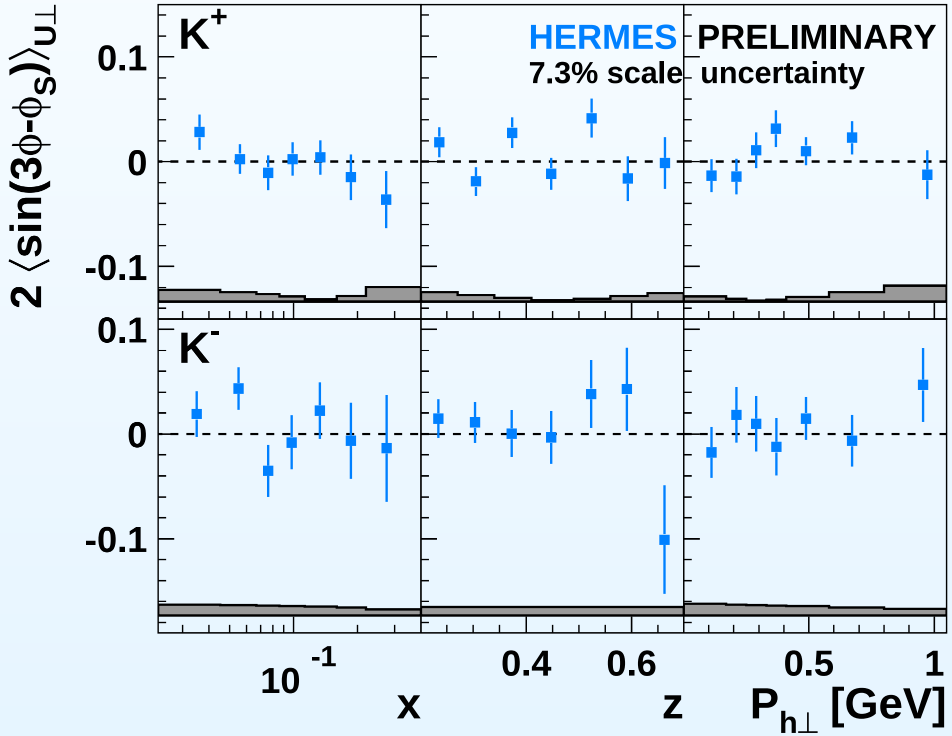
$$F_{UT}^{\sin(3\phi_h - \phi_S)} = \mathcal{C}\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\boldsymbol{p}_T\cdot\boldsymbol{k}_T\right) + \boldsymbol{p}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right) - 4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)}{2M^2M_h}\, h_{1T}^{\perp} H_1^{\perp}\right]$$

- leading-twist $F_{UT}^{\sin(3\phi-\phi_S)}$ sensitive to pretzelosity $h_{1T}^{\perp}$
- $F_{UT}^{\sin(\phi\pm\phi_S)}$ expected to scale as $P_{h\perp}$
- $F_{UT}^{\sin(2\phi-\phi_S)}$ expected to scale as $(P_{h\perp})^2$
- $F_{UT}^{\sin(3\phi-\phi_S)}$ expected to scale as $(P_{h\perp})^3$
  ➥ **suppressed w.r.t. Collins and Sivers amplitudes**

The $\langle \sin(3\phi - \phi_S)\rangle_{U\perp}$ Fourier component:



suppressed w.r.t.
Collins and Sivers amplitudes



In a nutshell:

- investigation of σ_{UU}, σ_{UL}, σ_{UT}, σ_{LU}
- significant $2\left\langle\cos\left(\phi\right)\right\rangle_{\mathrm{UU}}$ and $2\left\langle\cos\left(2\phi\right)\right\rangle_{\mathrm{UU}}$ amplitudes for hydrogen and deuterium target
  ➥ sensitivity to Boer-Mulders function
- (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^+, π^0, $K^+$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