The HERMES *contribution to the global* TMD *analysis*

Markus Diefenthaler

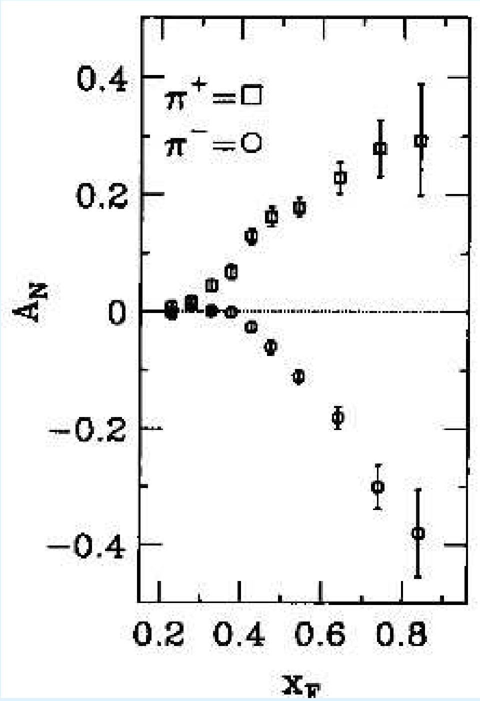
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

on behalf of the hermes collaboration

Where worlds collide:

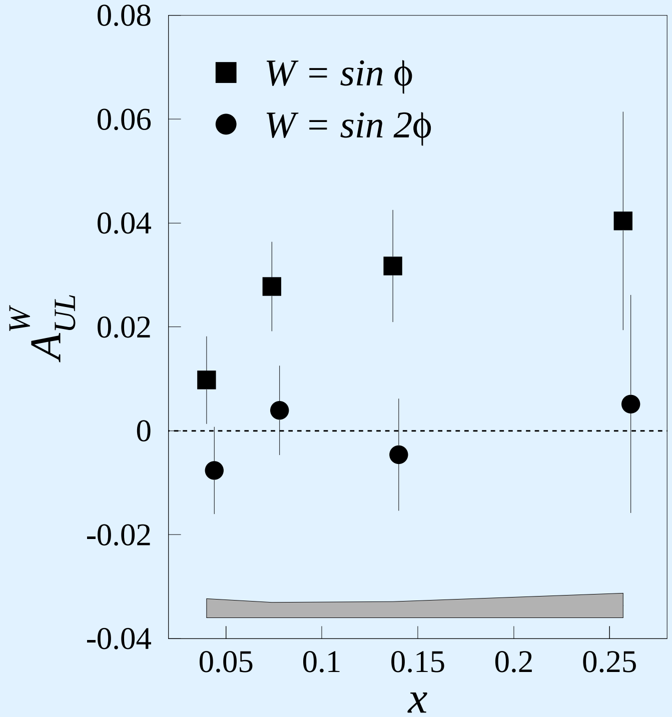
- **Observation of single-spin asymmetries (SSA)**:

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 (TMD)

$h_1^q\left(x, \boldsymbol{p_T}^2\right)$ - Chiral symmetry breaking in pQCD:

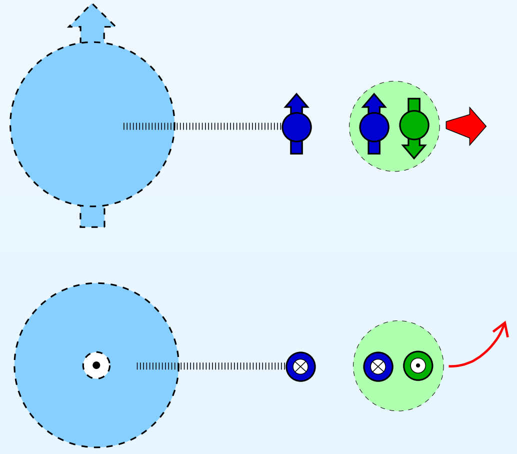
Name: transversity

Key properties: leading twist, chiral-odd

survives $\boldsymbol{p}_T$-integration (↪ collinear PDF)

Measurement:

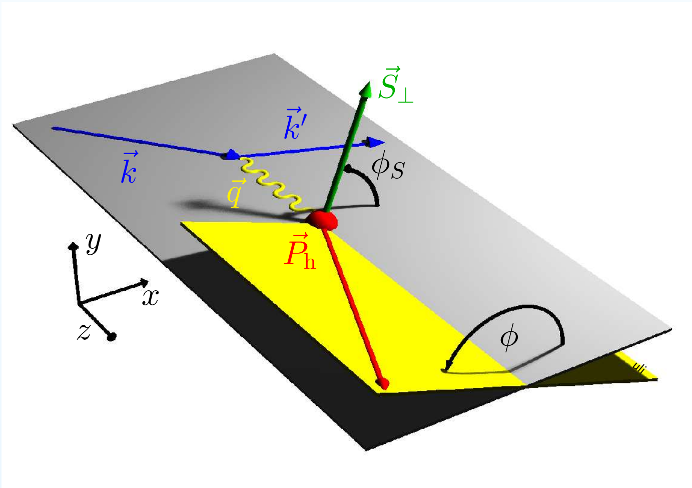
- **transverse SSA in single-hadron production:**
  - Collins mechanism ($F_{\text{UT}}^{\sin(\phi-\phi_S)}$)



  - $\sin\phi_S$ modulation ($F_{\text{UT}}^{\sin(\phi_S)}$)
- **transverse SSA in di-hadron production**

Fourier analysis of transverse SSA:

- **semi-inclusive measurement of DIS**: $lp^{\Uparrow} \to lhX$
- reconstruction of **transverse SSA** $A_{\mathrm{UT}}(\phi,\phi_S)$:



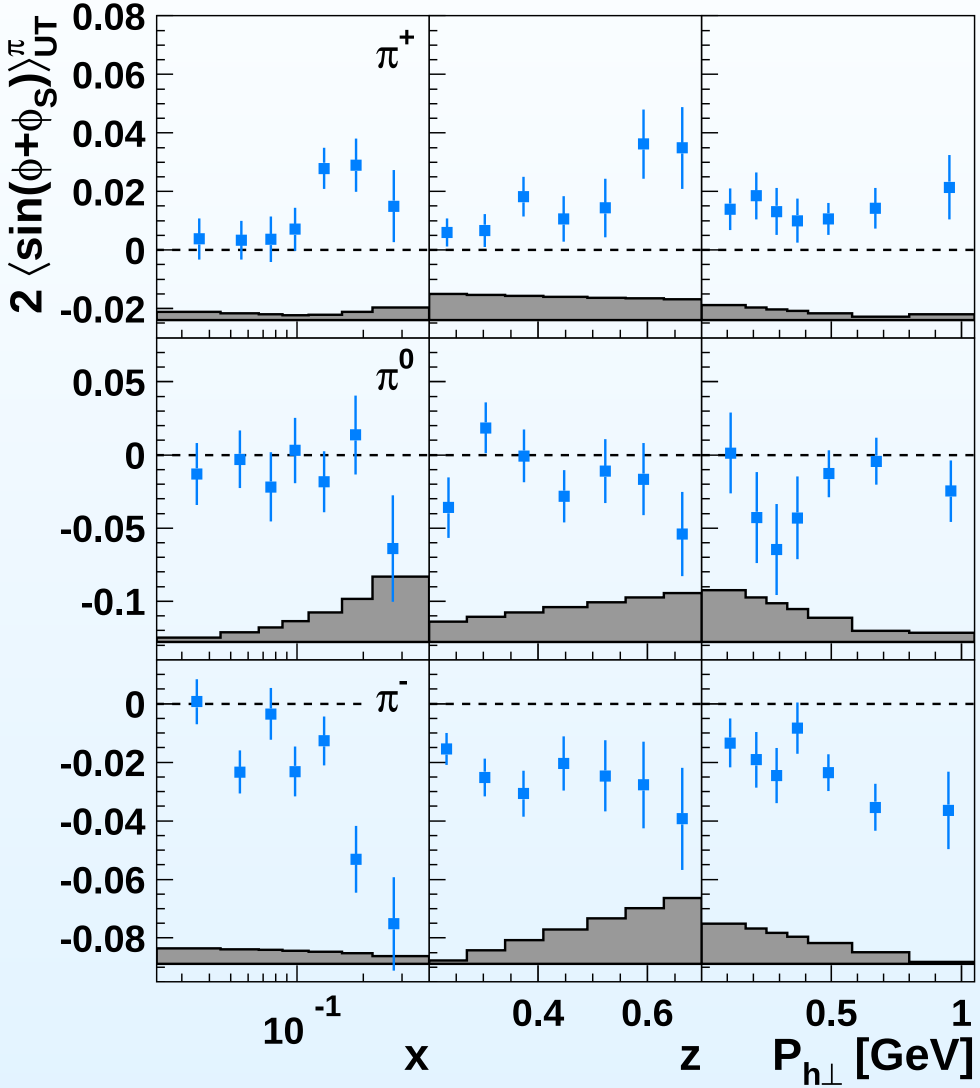
$$\boldsymbol{P}_{h\perp} = z(\boldsymbol{p}_T - \boldsymbol{k}_T)$$

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\boldsymbol{P}_{h\perp}^2} \propto \ldots \sin(\phi - \phi_S)\, F_{UT,T}^{\sin(\phi-\phi_S)} + \sin(\phi + \phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} \ldots$$

Sivers mechanism: $\sin(\phi - \phi_S)$

Collins mechanism: $\sin(\phi + \phi_S)$

The Collins amplitudes for π-mesons:



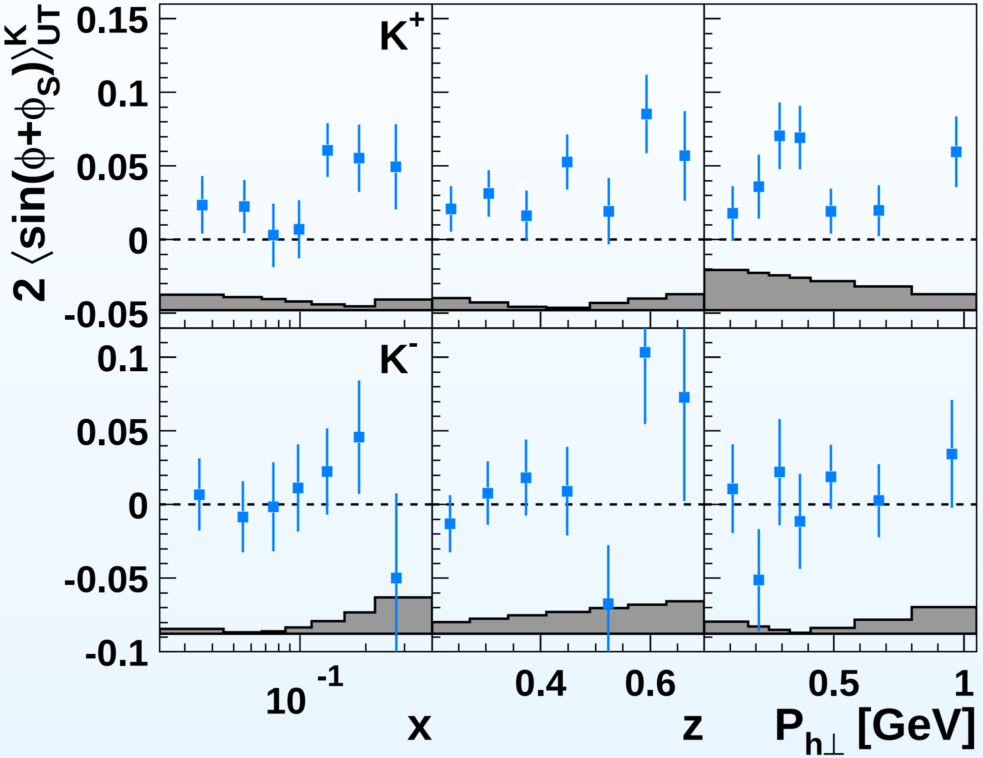
Published Collins amplitudes:

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

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
- Phys.Lett. **B693** (2010) 11-16
- PRL **94**, 012002 (2005)

The Collins amplitudes for charged K-mesons:



Published Collins amplitudes:

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

from 2002–2005 data:

- positive amplitudes for K^+, larger than those for π^+
- K^- amplitudes consistent with zero
- Phys.Lett. **B693** (2010) 11-16

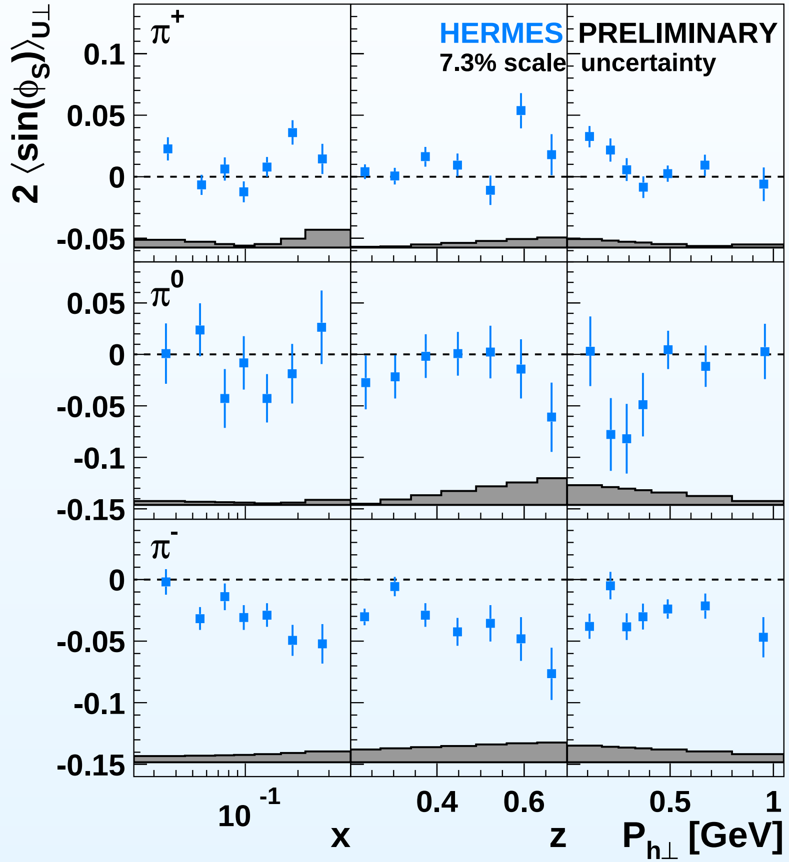
The $\langle \sin(\phi_S) \rangle_{U\perp}$ Fourier component:

- calculated at leading-twist and subleading-twist accuracy

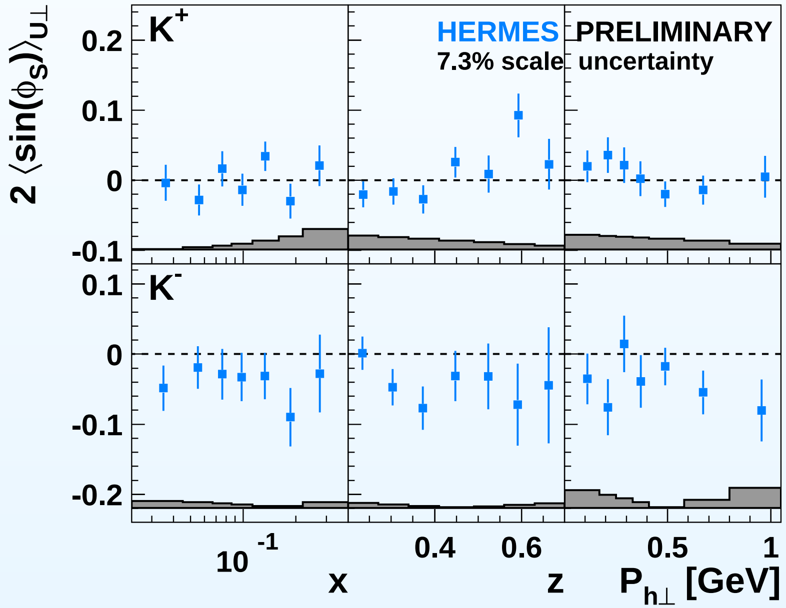
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} \quad \mathcal{C} \quad \Bigg\{ \quad \left(x f_T D_1 - \frac{M_h}{M}\, h_1 \frac{\tilde{H}}{z} \right) \\ - \quad \frac{\boldsymbol{k}_T \boldsymbol{p}_T}{2M M_h} \left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^{\perp}}{z} \right) \\ - \quad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

- $1/Q$-suppressed w.rt. $F_{UT}^{\sin(\phi+\phi_S)}$
- $F_{UT}^{\sin(\phi+\phi_S)}$ $P_{h\perp}$-suppressed w.r.t. $F_{UT}^{\sin\phi_S}$

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



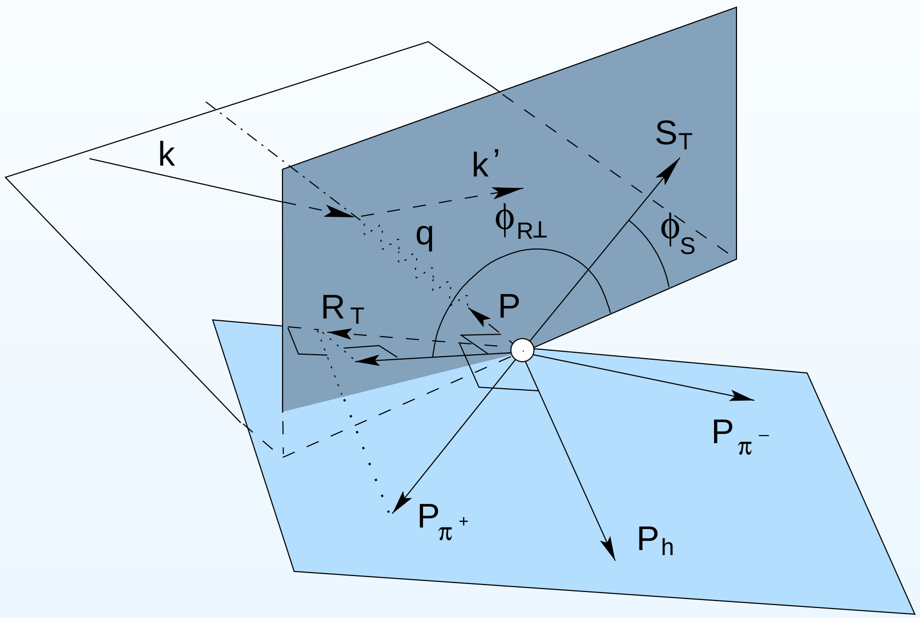
$F_{UT}^{\sin\phi_S} \sim F_{UT}^{\sin(\phi+\phi_S)}$ for π-mesons

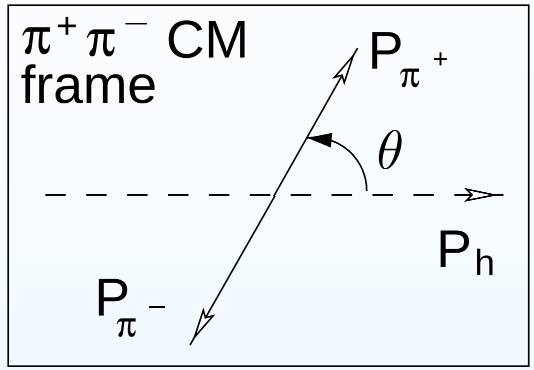


integration over transverse hadron momentum:

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

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}:

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

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

Transversity measurement in a collinear approach:

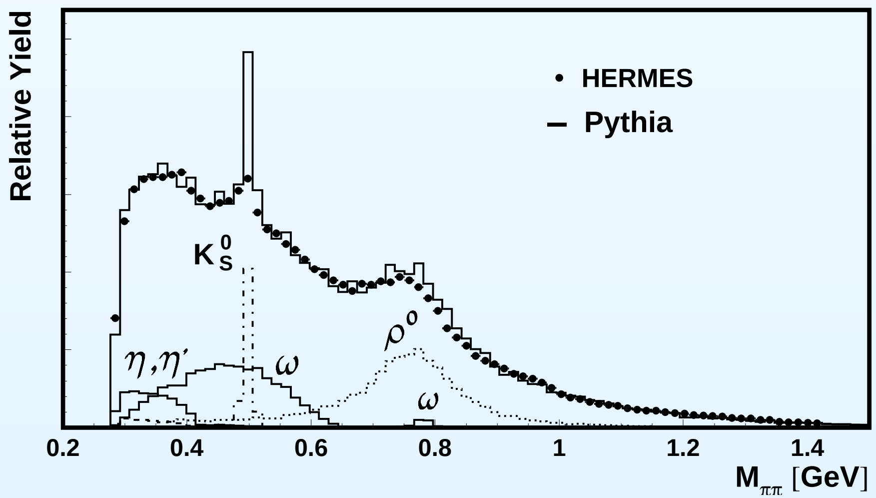
- **Fourier and Legendre expansion:**

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

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

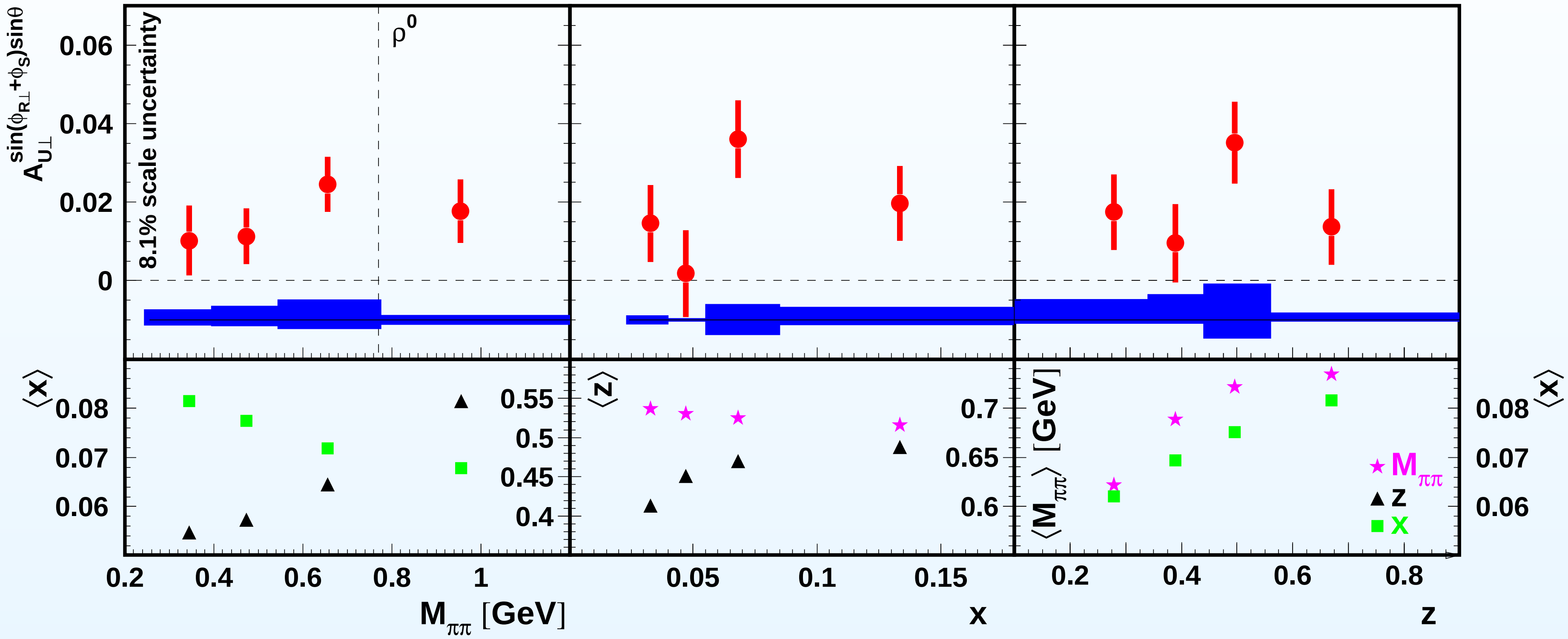
➥ $D_{1,q} \simeq D_{1,q} + D_{1,q}^{sp}\cos\theta + D_{1,q}^{pp}\frac{1}{4}(3\cos^2\theta - 1)$

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



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

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



- first evidence for chiral-odd, naive-T-odd $H_{1,q}^{\sphericalangle}$
- transversity can be studied in dihadron production
  ➥ **collinear extraction of transversity**

$f_{1T}^{\perp,\,q}$ - Probing quark orbitalal angular momentum:

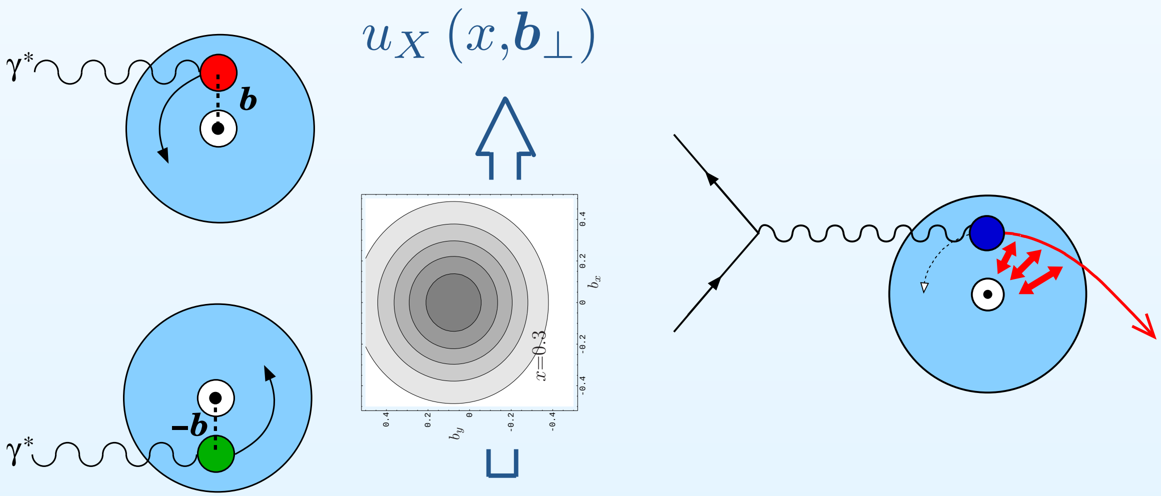
Name: Sivers TMD

Correlation: $S_T^i \epsilon^{ij} p_T^j \frac{1}{M} f_{1T}^{\perp,\,q}\left(x, \boldsymbol{p_T}^2\right)$

Key properties: leading twist, naive-T-odd, $N^{\Uparrow} q^{\uparrow} \rightarrow N^{\Downarrow} q^{\uparrow}$

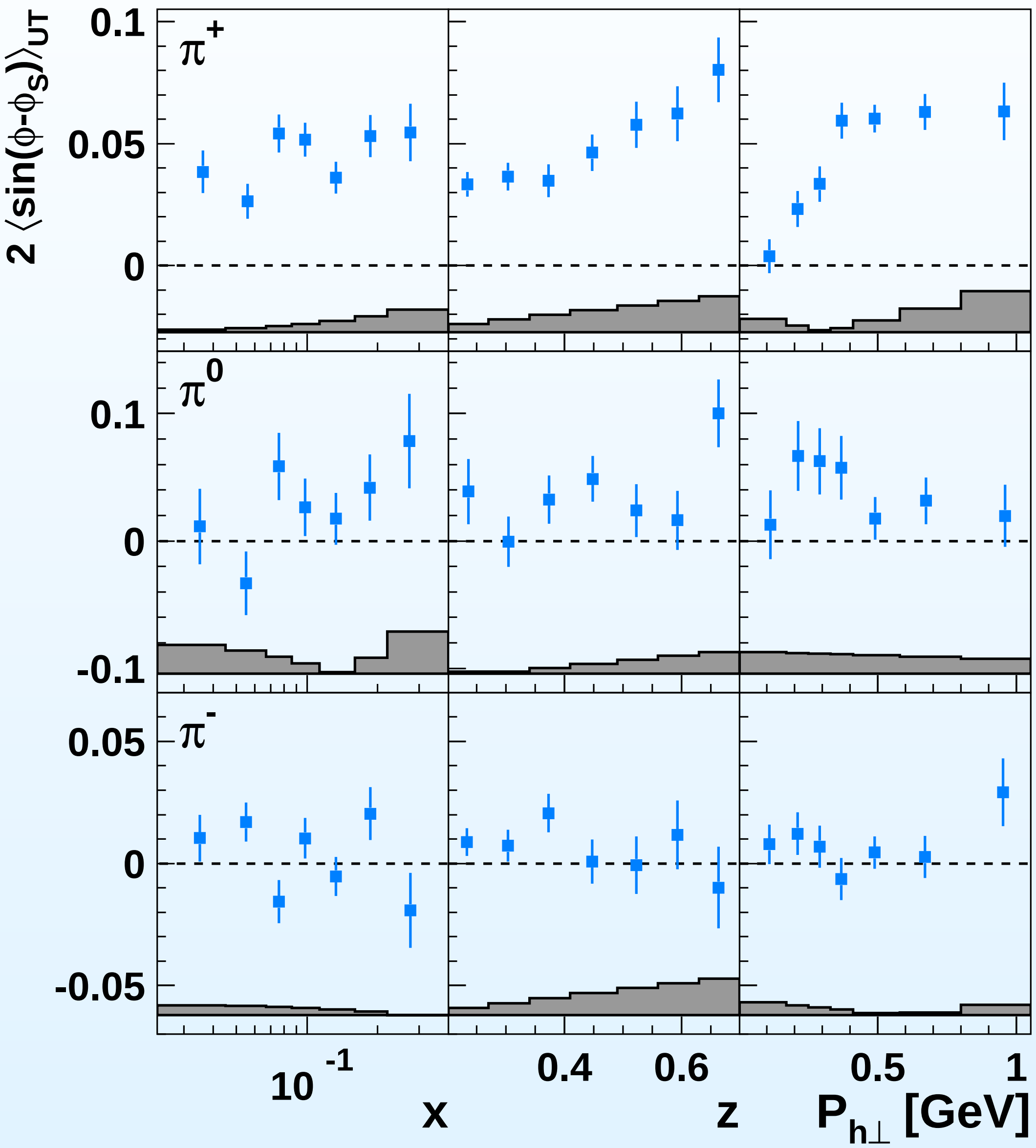
Measurements: **Sivers mechanism:**

- **orbital angular momentum of quarks:**



- **final-state interaction:** left-right asymmetry of quark distribution ➥ left-right-asymmetry of the momentum distribution of hadrons

The Sivers amplitudes for π-mesons:



Published Sivers amplitudes:

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

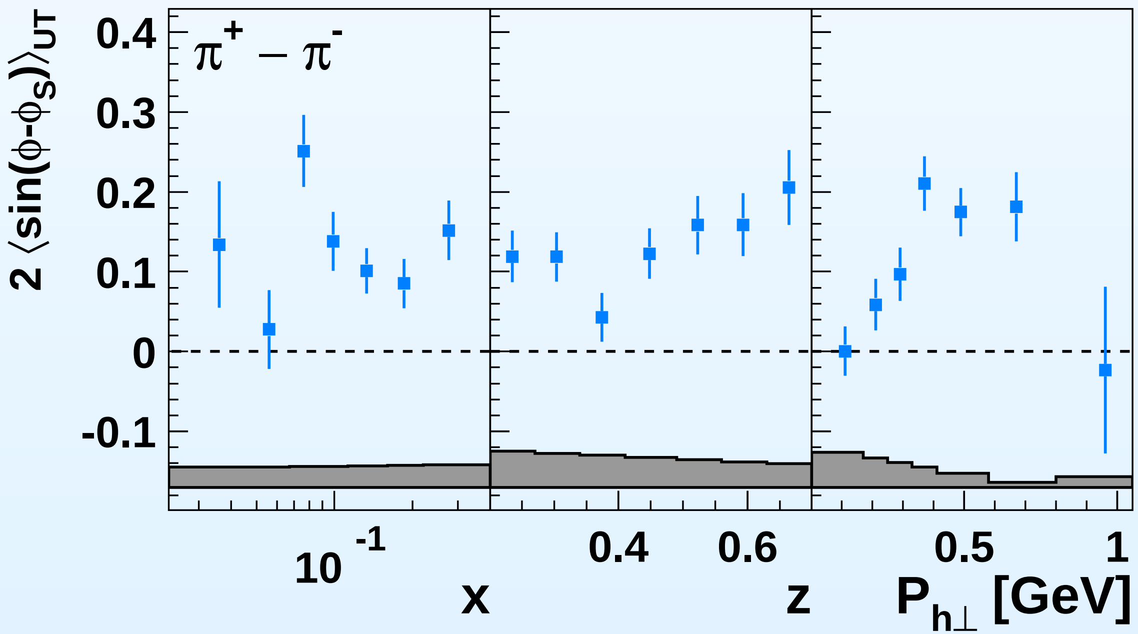
from 2002–2005 data:

- 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
- $P_{h\perp} \to 0.0$ GeV: linear decrease
- $P_{h\perp} > 0.4$ GeV: saturation for π^+
- isospin symmetry fulfilled
- PRL **103**, 152002 (2009)
- PRL **94**, 012002 (2005)

The Sivers amplitudes for the pion-difference SSA:

- remove contribution from exclusive ρ^0-production and decay
- interpretation in terms of **valence-quark distribution** solely:

$$A_{UT}^{\pi^+-\pi^-} \equiv \frac{1}{|S_T|}\frac{(\sigma_{U\Uparrow}^{\pi^+}-\sigma_{U\Uparrow}^{\pi^-})-(\sigma_{U\Downarrow}^{\pi^+}-\sigma_{U\Downarrow}^{\pi^-})}{(\sigma_{U\Uparrow}^{\pi^+}-\sigma_{U\Uparrow}^{\pi^-})+(\sigma_{U\Downarrow}^{\pi^+}-\sigma_{U\Downarrow}^{\pi^-})} = -\frac{4f_{1T}^{\perp,u_v}-f_{1T}^{\perp,d_v}}{4f_1^{u_v}-f_1^{d_v}}$$

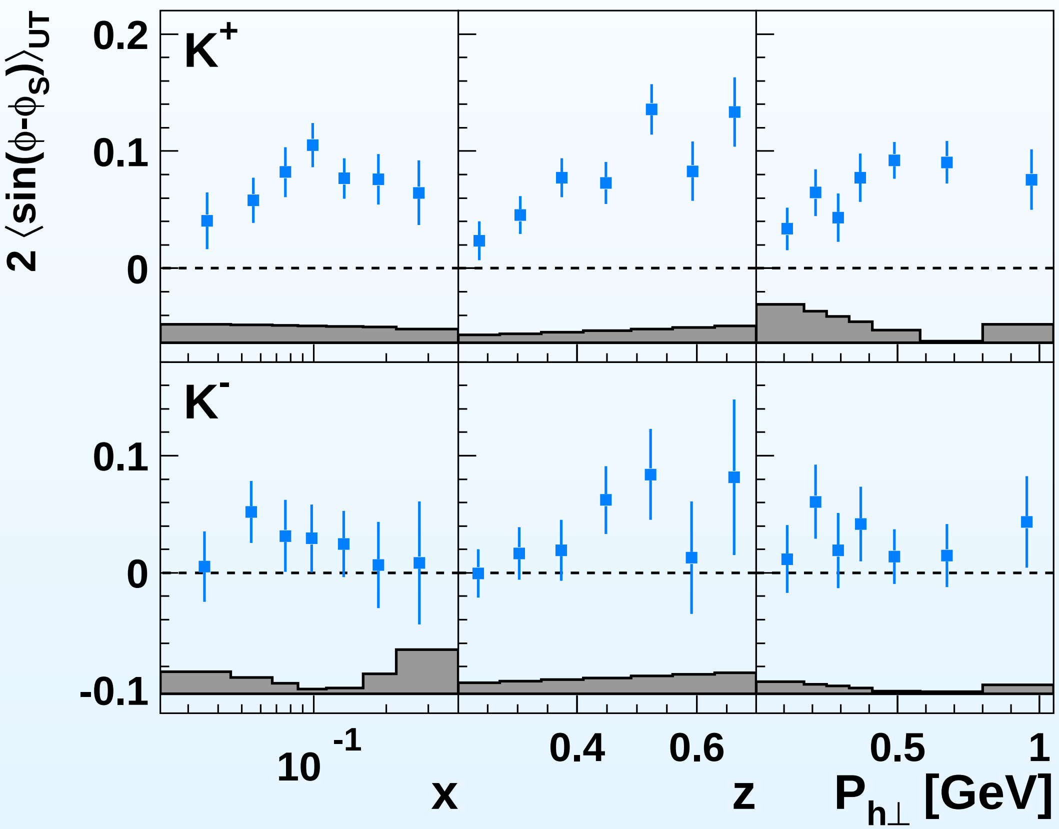


- $f_{1T,\text{DIS}}^{\perp,u} < 0$ ➥ $L_z^u > 0$
- **QCD prediction:**

$$f_{1T,\text{DIS}}^{\perp} = -f_{1T,\text{DY}}^{\perp}$$

➥ Drell-Yan measurement

The Sivers amplitudes for charged K-mesons:



Published Sivers amplitudes:

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

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^+
- PRL **103**, 152002 (2009)

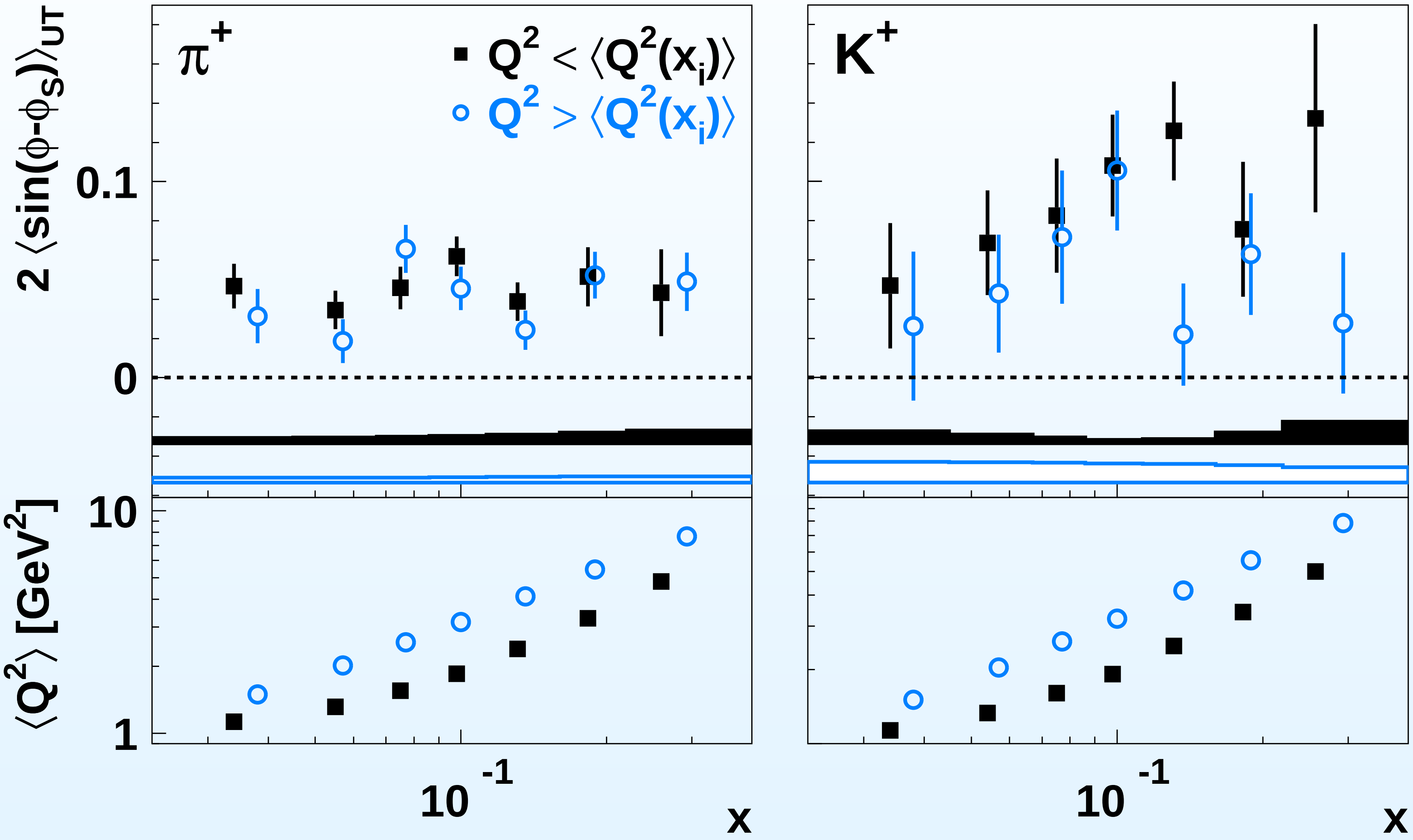
The role of higher twist terms:

- **Sivers amplitude:**

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

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

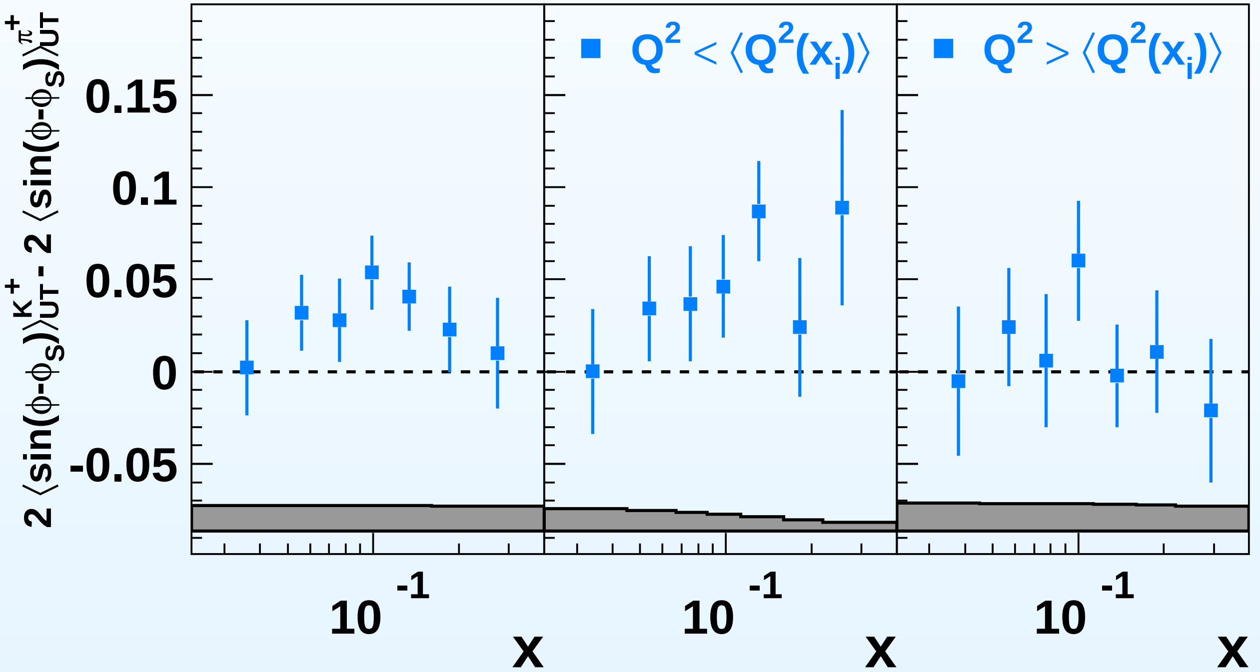
Examination of other $1/Q^2$-suppressed contributions:



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 flavors?
- higher twist effects in kaon-production?

$h_{1T}^{\perp,q}$ - What is the shape of the nucleon?:

Name: pretzelosity

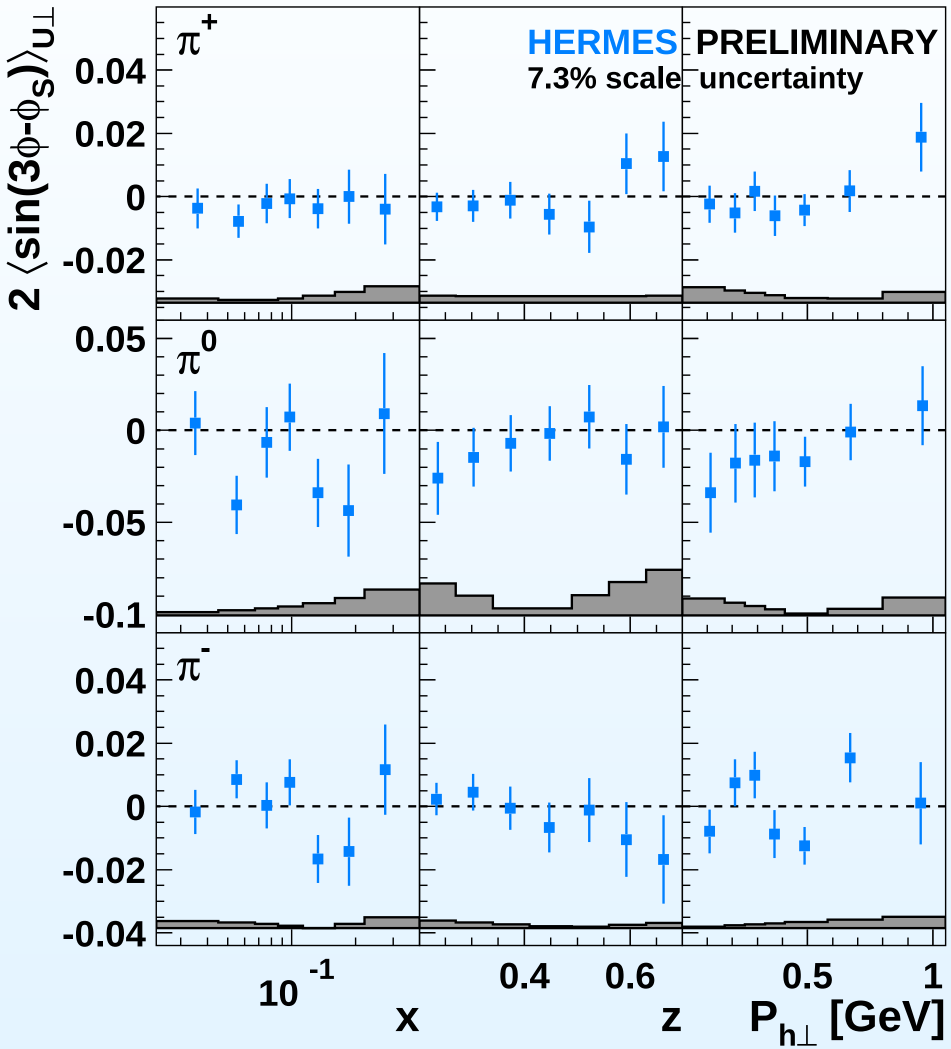
Correlation $s_T^i \left(2 p_T^i p_T^j - \boldsymbol{p}_T^2 \delta^{ij}\right) S_T^j \frac{1}{2M^2} h_{1T}^{\perp,q}\left(x, \boldsymbol{p}_T^2\right)$

Key properties: leading twist, chiral-odd, $N^{\Uparrow} q^{\uparrow} \longrightarrow N^{\Downarrow} q^{\uparrow}$

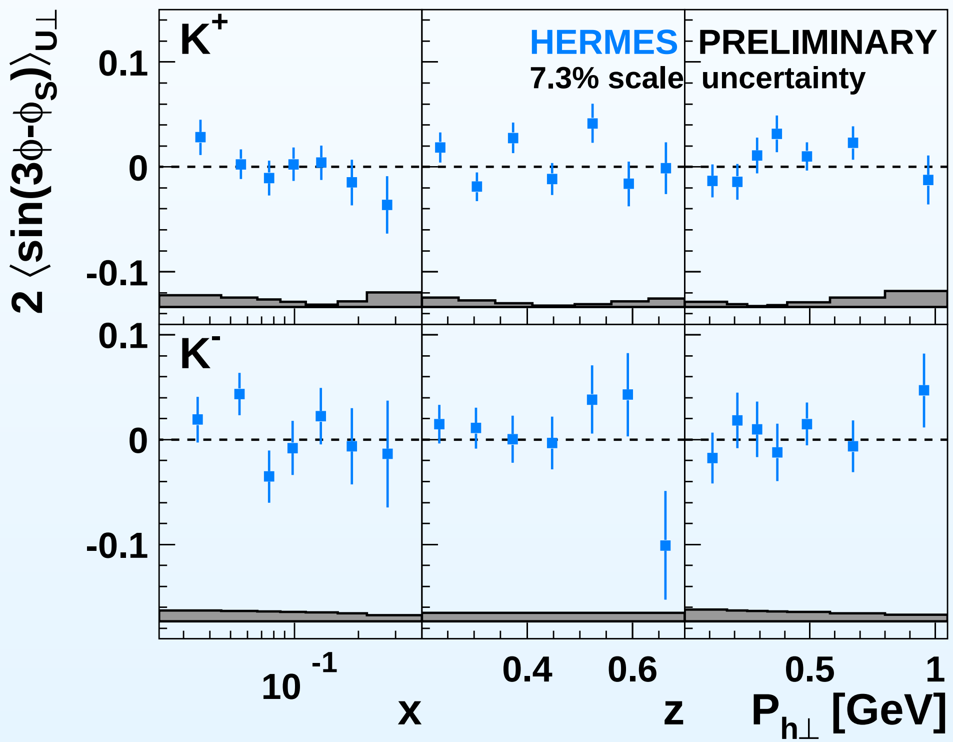
Measurement:

- $F_{UT}^{\sin(3\phi-\phi_S)}$ sensitive to pretzelosity $h_{1T}^{\perp}$:
  $F_{UT}^{\sin(3\phi_h-\phi_S)} =$
  $\mathcal{C}\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\boldsymbol{p}_T\cdot\boldsymbol{k}_T\right)+\boldsymbol{p}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)}{2M^2 M_h} h_{1T}^{\perp} H_1^{\perp}\right]$
- $F_{UT}^{\sin(\phi+\phi_S)} \propto P_{h\perp}$, $F_{UT}^{\sin(3\phi-\phi_S)} \propto P_{h\perp}^3$
  ➥ suppressed w.r.t. Collins amplitudes

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



suppressed w.r.t. Collins amplitudes



$h_{1L}^{\perp,q}$ - Boost relations within the nucleon:

Name: worm-gear distribution

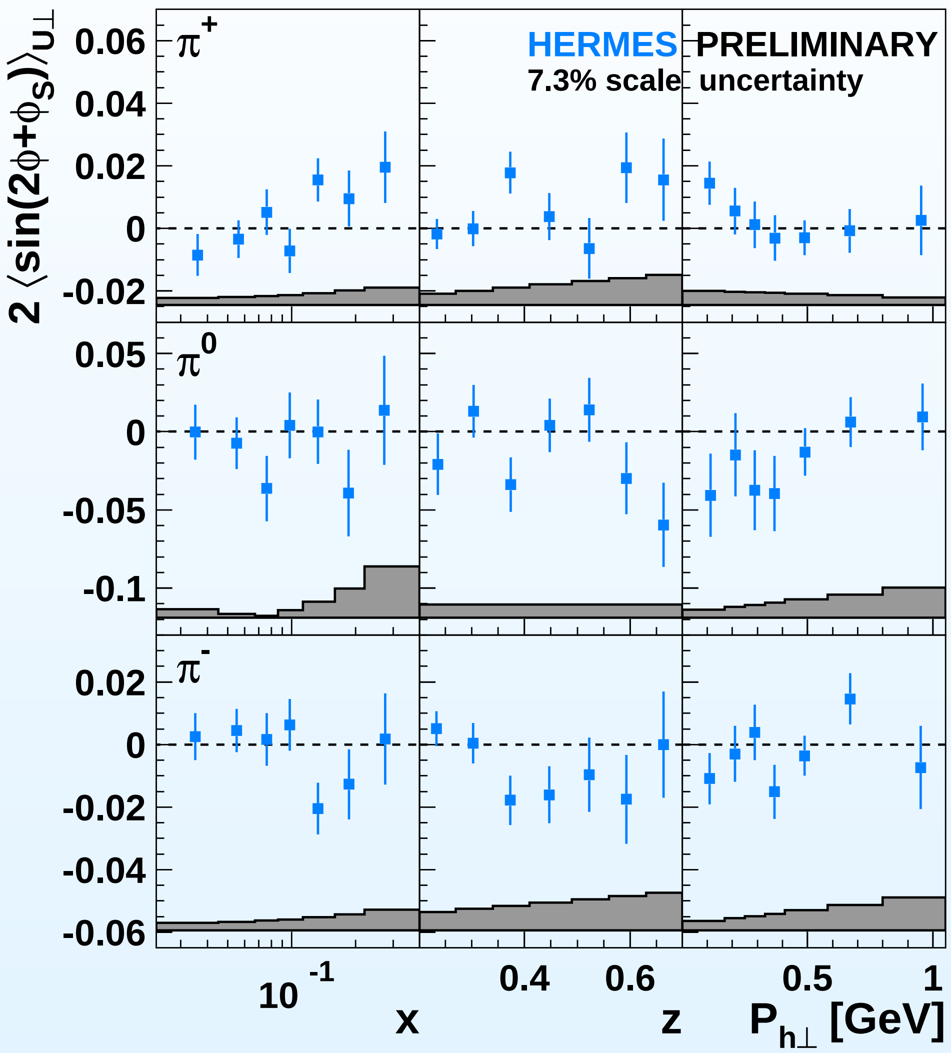
Correlation $\Lambda s_T^i p_T^i \frac{1}{M}\, h_{1L}^{\perp,q}\left(x,\boldsymbol{p}_T^2\right)$

Key properties: leading twist, chiral-odd

Measurement:

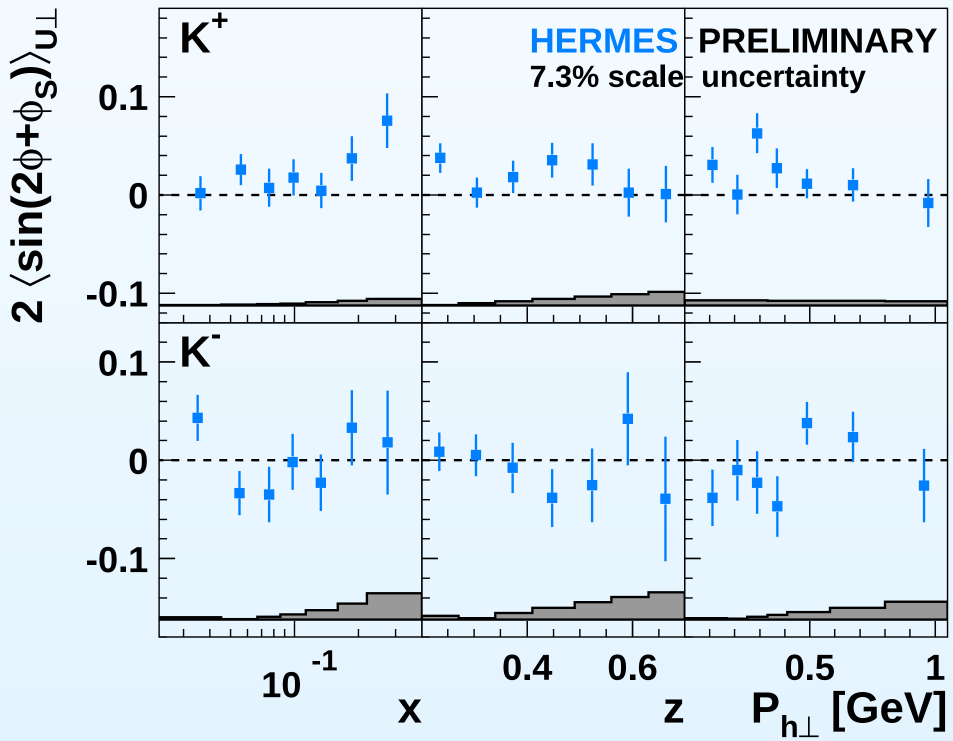
- small longitudinal target-spin component with respect to virtual-photon direction:
$2\left\langle\sin\left(2\phi+\phi_S\right)\right\rangle_{U\perp}^{h} \propto \frac{1}{2}\sin\left(\theta_{l\gamma^*}\right)2\left\langle\sin\left(2\phi\right)\right\rangle_{UL}^{h}$
- $\sin\left(\theta_{l\gamma^*}\right)\approx 0.1$
- $F_{UL}^{sin(2\phi)} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h}\, h_{1L}^{\perp,q}\, H_1^{\perp,q}\right]$

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



expected to scale as:

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



$g_{1T}^{(\perp,)q}$ - Boost relations within the nucleon:

Name: worm-gear distribution

Correlation $\lambda S_T^i p_T^i \frac{1}{M}\, g_{1T}^{\perp,q}\left(x,\boldsymbol{p}_T^2\right)$

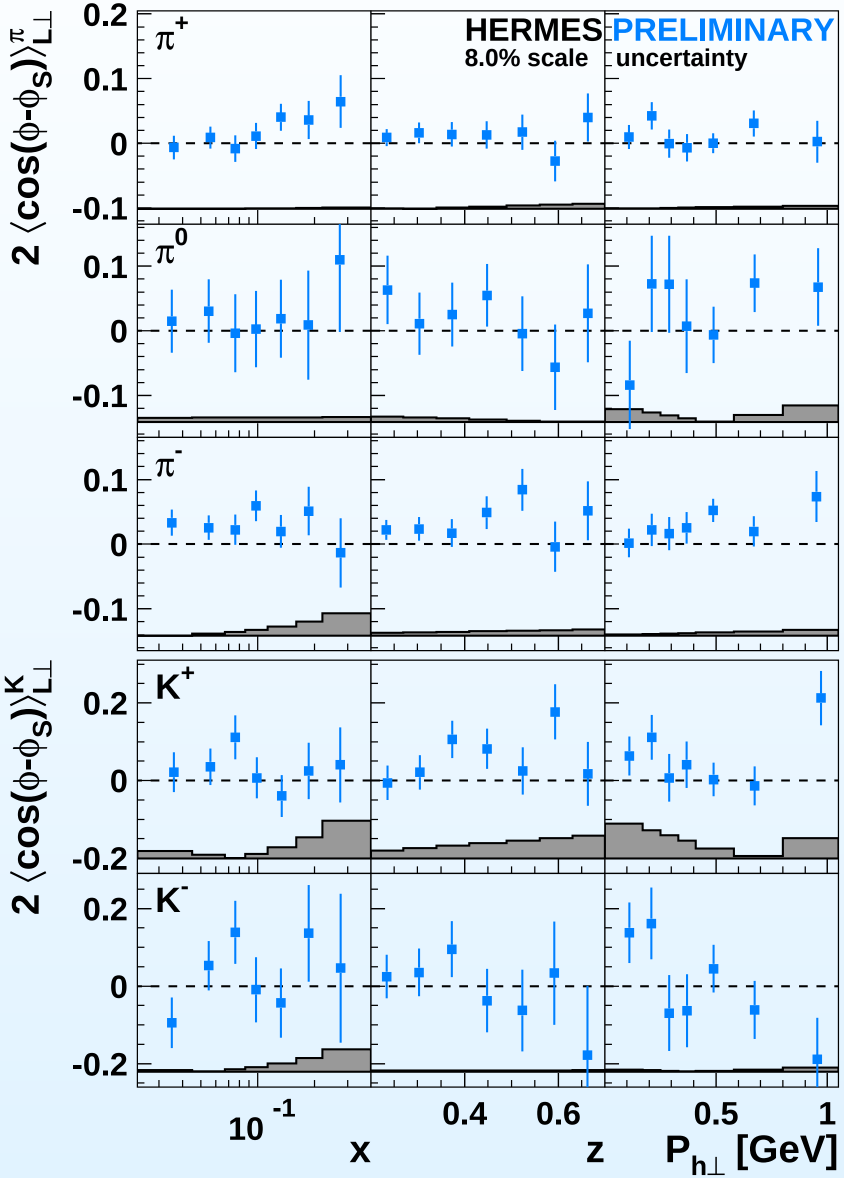
Key properties: leading twist, chiral-even and naive-T-even

➥ not affected by final-state interactions

Measurement: **reconstruction of double-spin asymmetries:**

$$F_{LT}^{cos(\phi-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{h\perp}}{M}\, h_{1L}^{\perp,q}\, H_1^{\perp,q}\right]$$

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



Preliminary DSA amplitudes:

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

from 2002–2005 data:

- positive for π^-
- slightly positive for K^+

$h_1^{\perp, q}$ - Spin effects in unpolarized reactions:

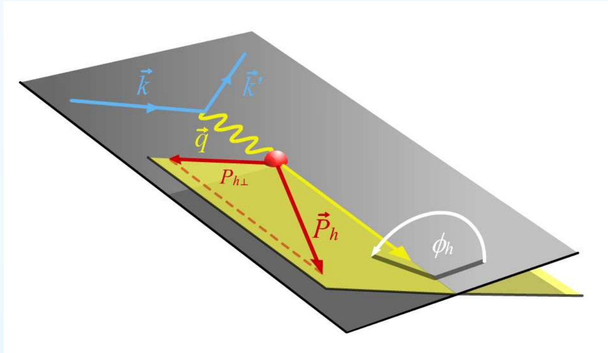
Name: Boer-Mulders TMD

Correlation: $s_T^i \epsilon^{ij} p_T^j \frac{1}{M} h_1^{\perp, q}(x, \boldsymbol{p_T}^2)$

Key properties: leading twist, chiral-odd, naive-T-odd

Measurements:

- **unpolarized SIDIS:**



- leading-twist $\cos(2\phi)$ modulation, arising from **Boer-Mulders-Collins mechanism:**

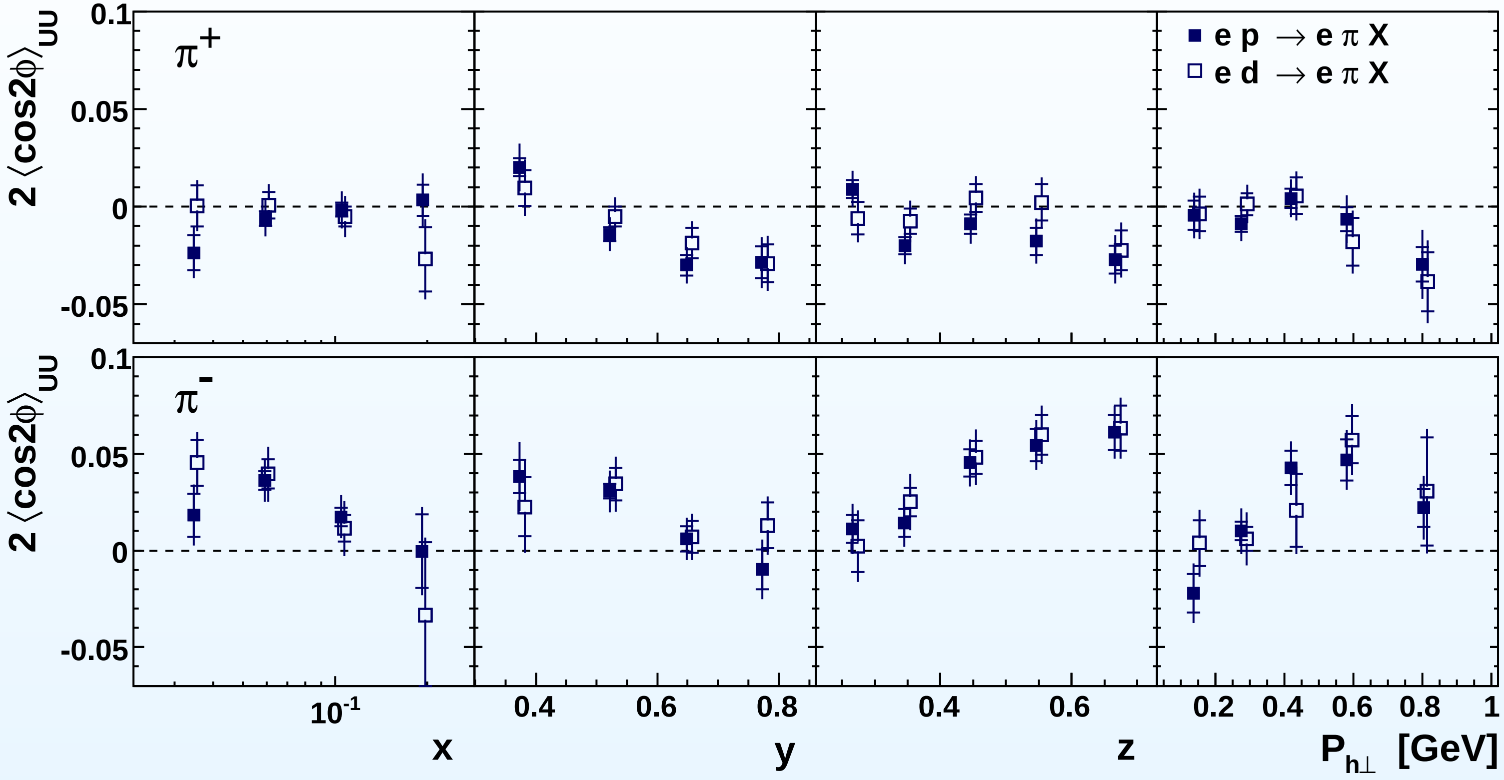
$$F_{\text{UU}}^{cos(2\phi)} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_1^{\perp,q} H_1^{\perp,q}\right]$$

- subleading-twist $\cos(\phi)$ modulation, related to **Cahn effect**

Final $2\left\langle\cos\left(2\phi\right)\right\rangle_{\mathrm{UU}}^{h}$ and $2\left\langle\cos\left(\phi\right)\right\rangle_{\mathrm{UU}}^{h}$ moments:

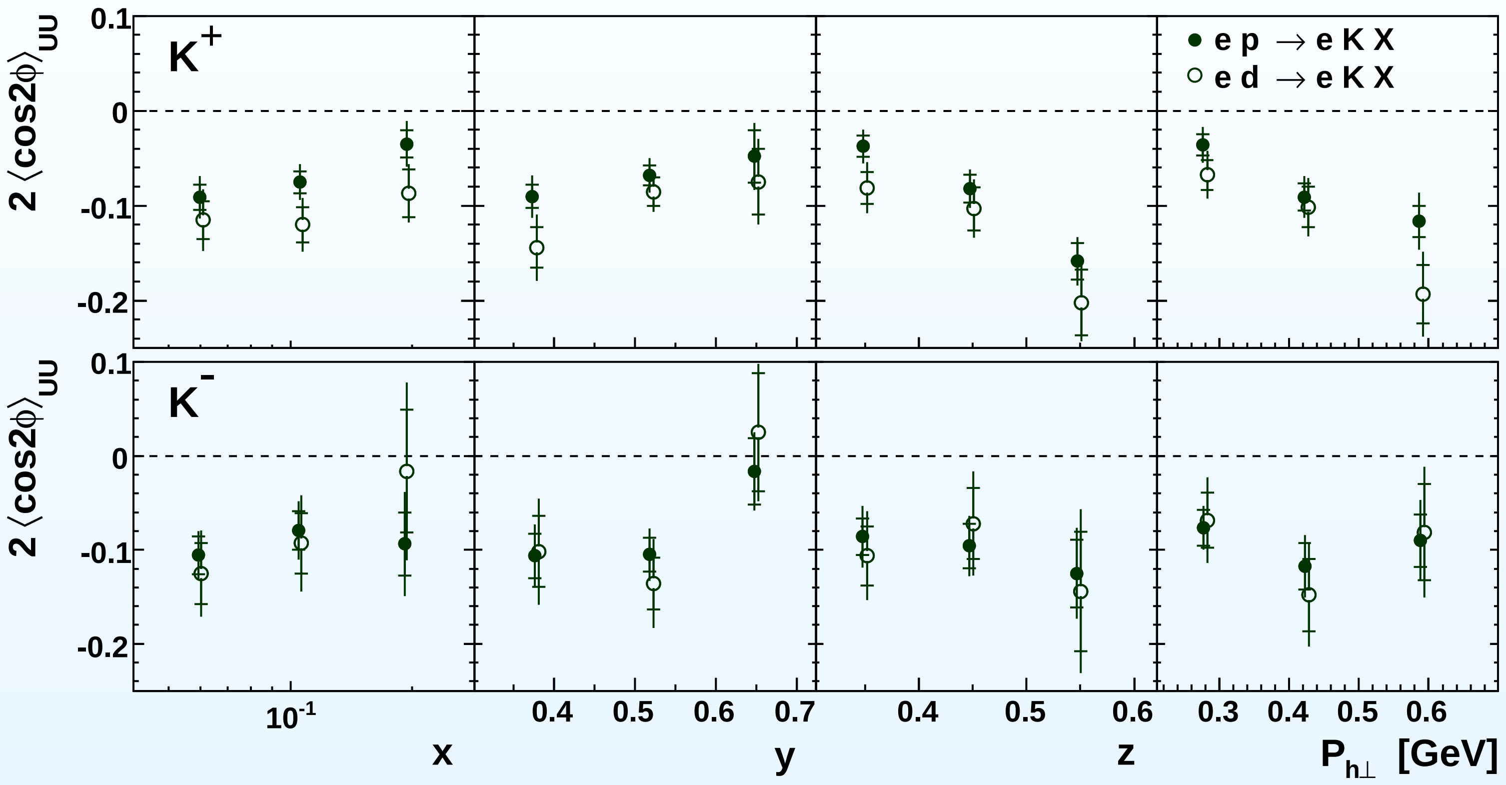
- **Fully differential analysis** $(x,y,z,P_{h\perp})$ of:
  - $\mathbf{2\left\langle\cos\left(2\phi\right)\right\rangle_{\mathrm{UU}}^{h}}$ and
  - $\mathbf{2\left\langle\cos\left(\phi\right)\right\rangle_{\mathrm{UU}}^{h}}$ amplitudes
- corrected for finite acceptance, QED radiation, detector smearing via five-dimensional **unfolding procedure**
- for SIDIS off unpolarized hydrogen and deuterium targets
- available on **http://www-hermes.desy.de/cosnphi/**
  - not only archive for data files but also
  - web tool to specify a kinematic region and to calculate one-dimensional projections of the fully differential amplitudes in the specified kinematic region

Final $2 \langle \cos(2\phi) \rangle_{UU}^{\pi^\pm}$ amplitudes for pions:



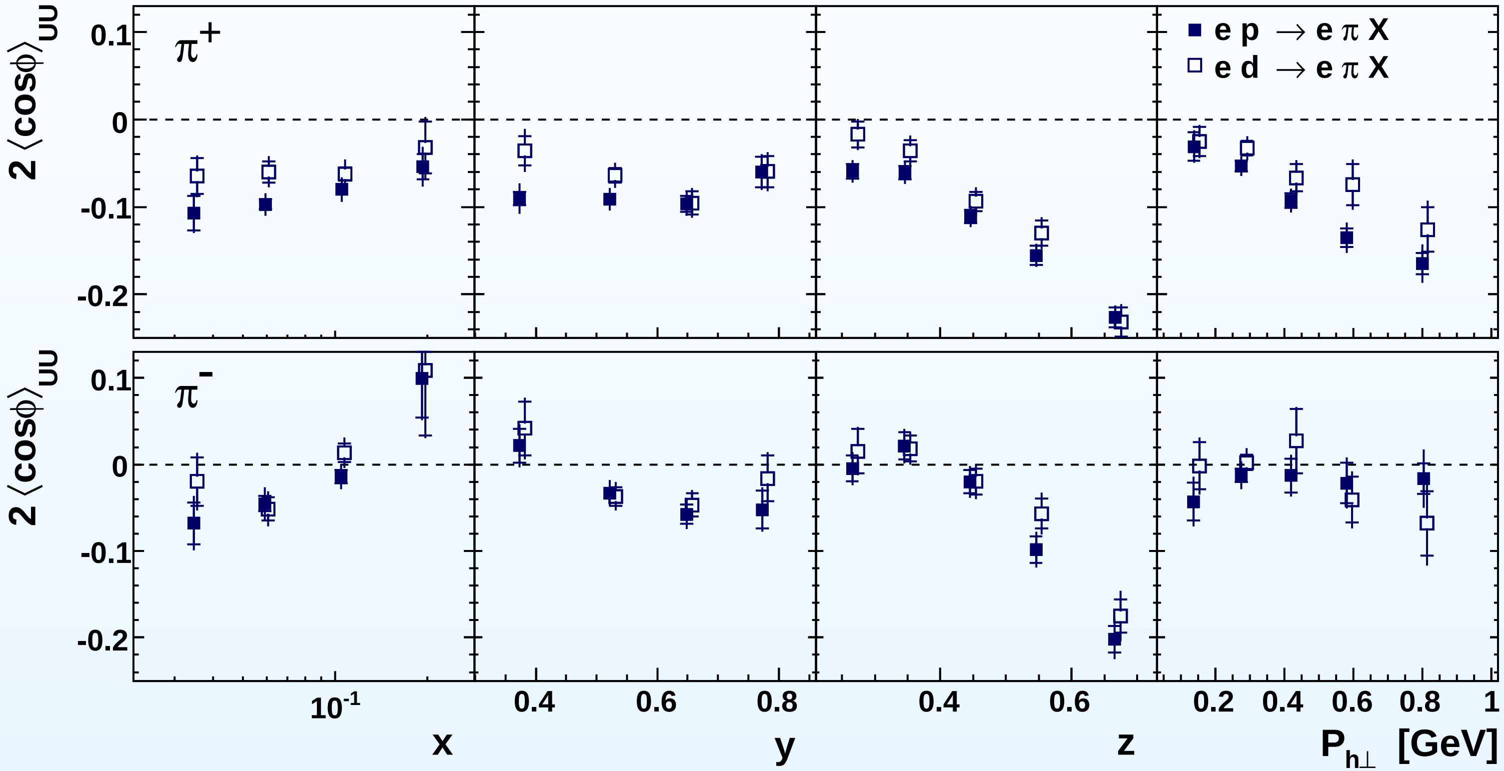
- π^+amplitudes consistent with zero, positive amplitudes for π^-, consistent with opposite sign of favored and unfavored Collins FF
- evidence for non-zero Boer-Mulders function
- similarity between p and d ➥ same sign for $h_1^{\perp,\,u}$ and $h_1^{\perp,\,d}$

Final $2\langle\cos(2\phi)\rangle^{K^\pm}_{\mathrm{UU}}$ amplitudes for kaons:



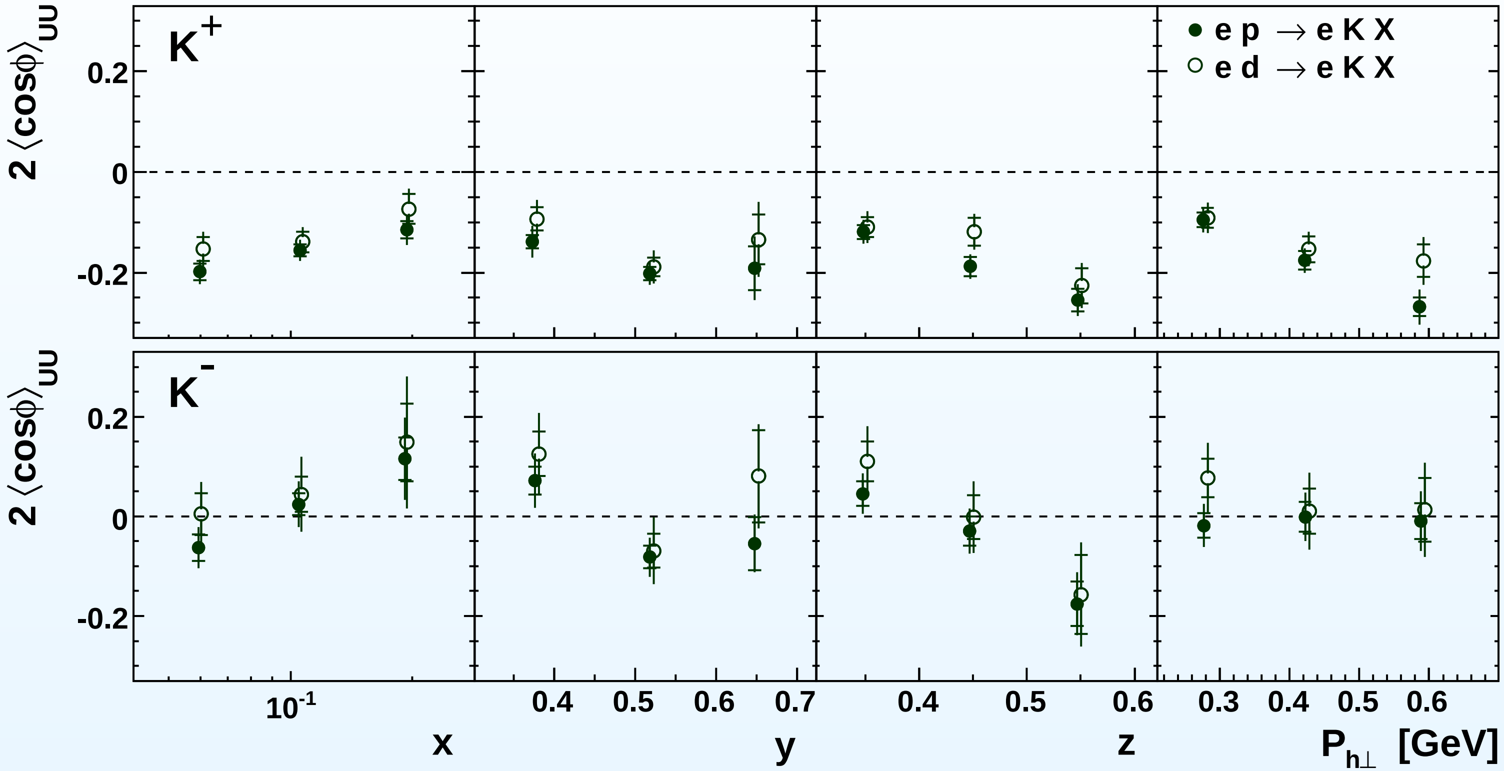
- large negative $K^+$and K^-moments
  ➥ same sign for strange favored and unfavored Collins FF?
- similarity between p and d
  ➥ similar contributions from u and d quarks but also **substantial contribution from strange quark fragmentation**

Final $2 \langle \cos(\phi) \rangle_{\mathrm{UU}}^{p^{\pm}}$ amplitudes for pions:



- z-dependence can be interpreted in terms of Cahn effect
- but other contributions, e.g. Boer-Mulders-Collins effect, required to explain difference between $\pi^+$and π^-results

Final $2\langle\cos(\phi)\rangle^{K^\pm}_{\text{UU}}$ amplitudes for kaons:



- large negative amplitudes for K^+
- K^- amplitudes compatible with zero
- flavor dependence of the Cahn contribution?
- significant other interaction-dependent contributions?

HERMES contribution to the global TMD analysis:

- **pioneering measurements** of the azimuthal distribution of hadrons produced in DIS off:
  - transversely polarized proton target
  - unpolarized proton and deuteron targets
- **non-zero transversity TMD** via Collins mechanism and study of the $s-p$ interference in dihadron production
- **non-zero Sivers TMD**
  ➥ fundamental QCD prediction of sign change
- **non-zero Boer-Mulders TMD**
- so far no evidence for non-zero pretzelosity TMD
- **first evidence for the worm-gear TMDs**
- rich phenomenology and various interesting facets of the data
  ➥ **an extremely active field will remain active**

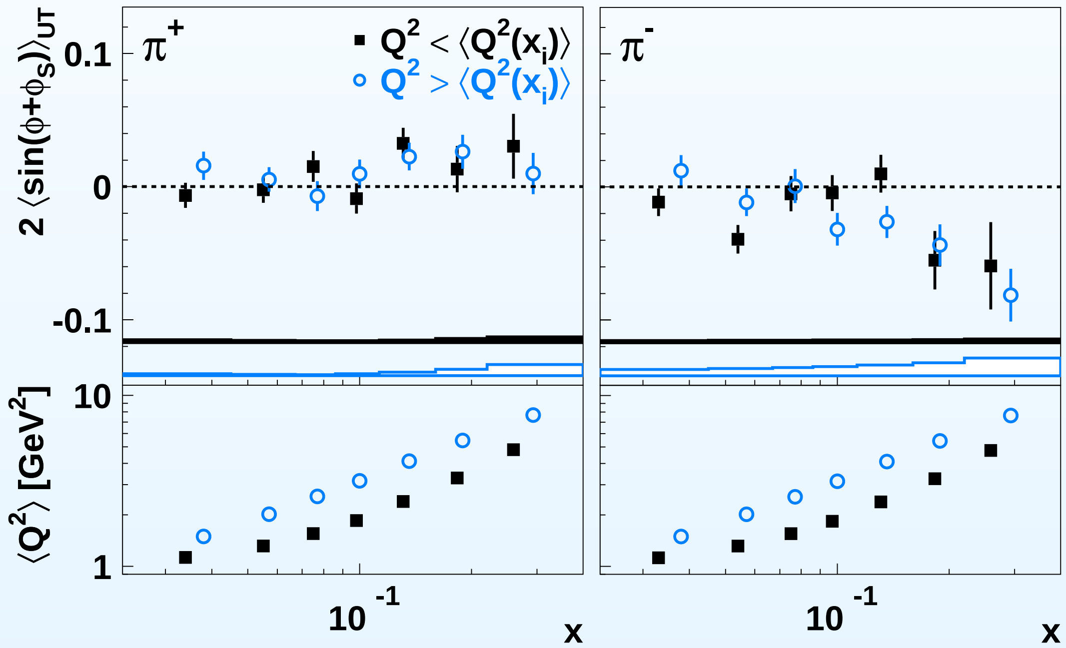
Backup:

Backup

Comparison of twist-2 and twist-3 transversity signals:

Collins amplitudes

leading twist



$\langle\sin(\phi_S)\rangle_{U\perp}$ amplitudes

subleading twist