Signals for transverse-momentum dependent quark distributions studied at the HERMES *experiment*

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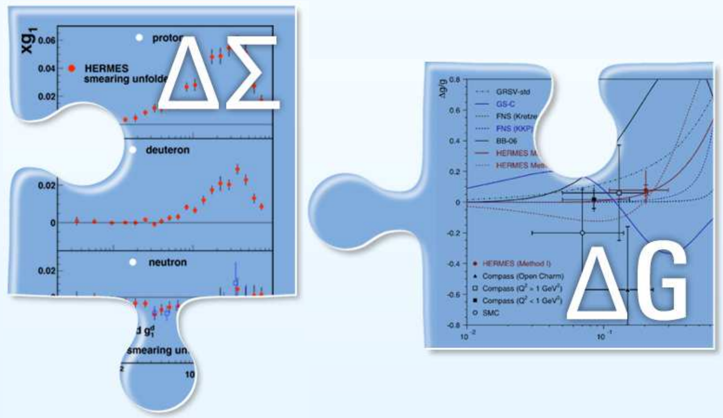
on behalf of the hermes collaboration

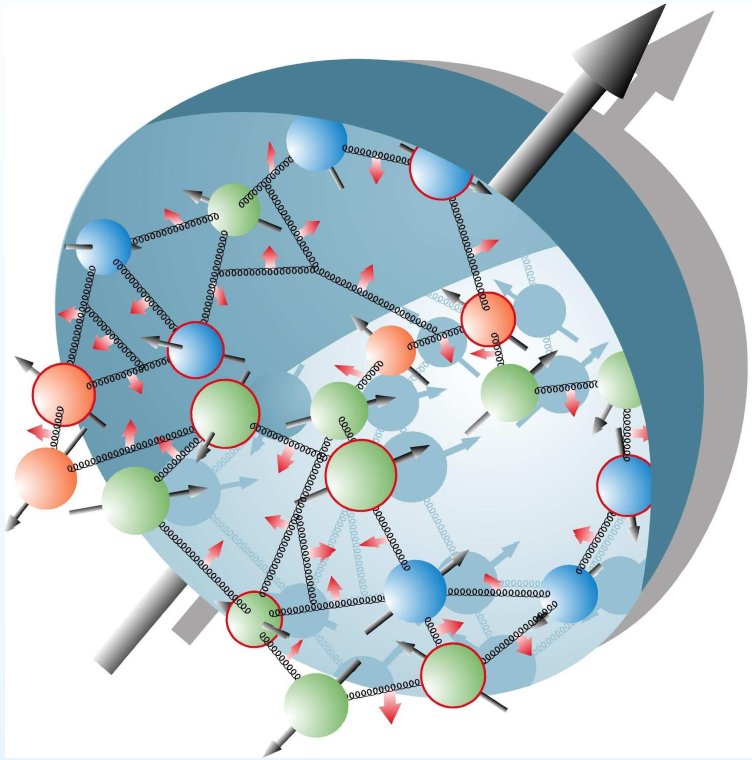
The spin structure of the nucleon:

Angular momentum sum rule:

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

Known contributions:





$$|\,p\,\rangle = |\,uud\,\rangle\,,\,|\,n\,\rangle = |\,ddu\,\rangle$$

Investigation of quark orbital angular momentum:

correlating the position of partons with their momenta
➥ probing spin-orbit correlations

Leading-twist representation of the nucleon structure:

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

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

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

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

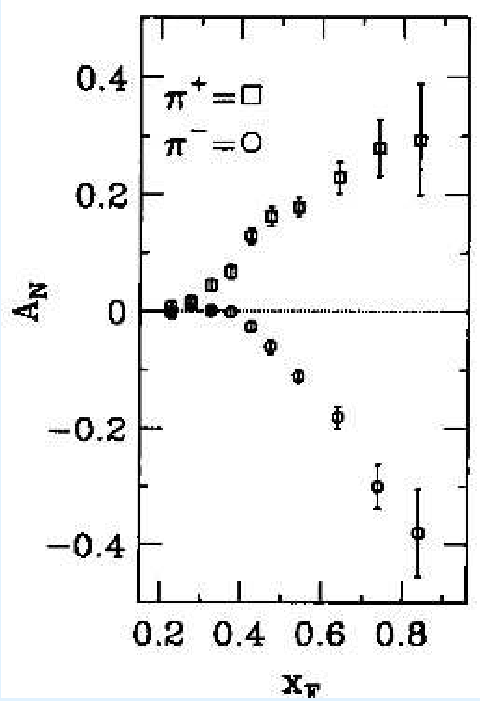
- **transverse-momentum-dependent PDF**
  ➥ related to **spin-orbit correlations**
  ➥ constraints on orbital angular momentum (contributions)?

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

Transverse single-spin asymmetries:

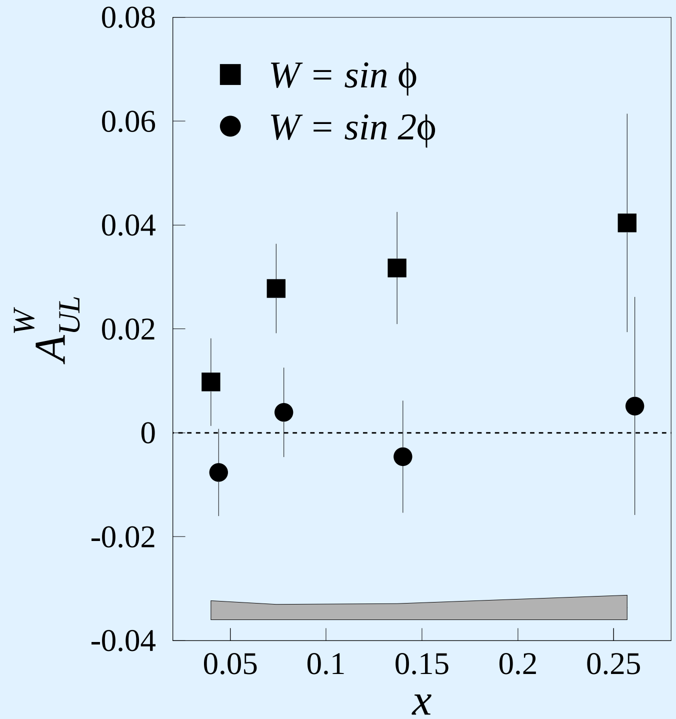
- **Observation of single-spin asymmetries**:

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



PL**B261**, 201–206, 1991

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



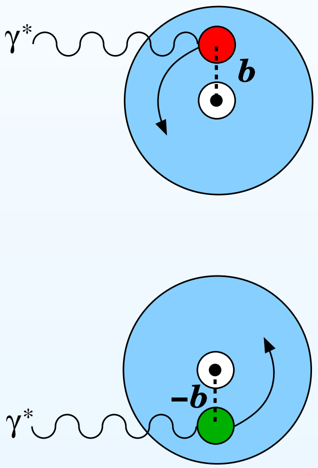
PRL**84**, 4047–4051, 2000

- Global analysis of:

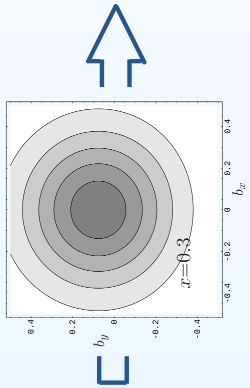
transverse-momentum-dependent PDF

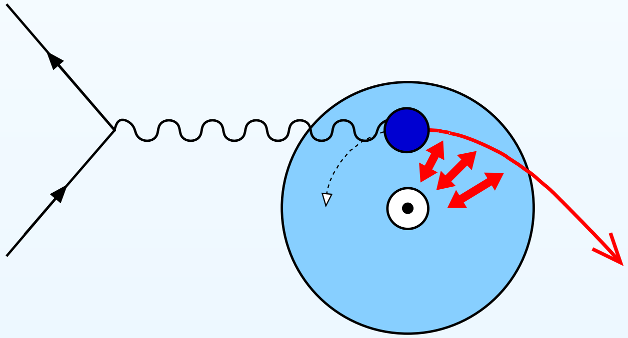
The Sivers mechanism:

- **Sivers function** $\boldsymbol{f_{1T}^{\perp}\left(x, p_T{}^2\right)}$: $N^{\Uparrow} q^{\uparrow} \to N^{\Downarrow} q^{\uparrow}$
- **orbital angular momentum of quarks:**



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





- **final-state interaction:**

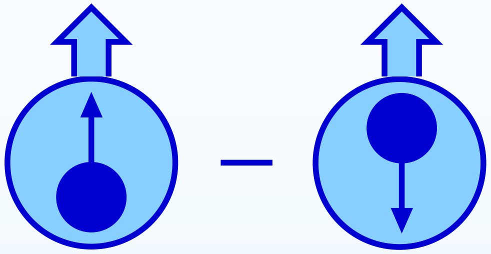
  left-right asymmetry of quark distribution

  ➥ left-right-asymmetry of momentum distribution of hadrons

- **structure function**: $F_{UT,T} = -\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M} f_{1T}^{\perp}\left(x, \boldsymbol{p_T}^2\right) D_1\left(z, z^2 \boldsymbol{k_T}^2\right)\right]$

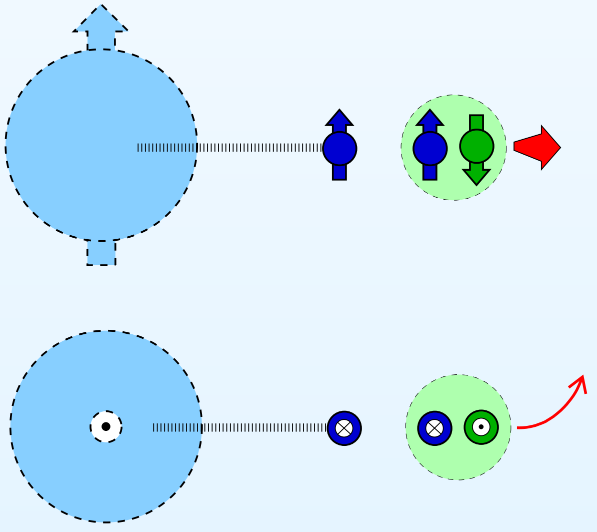
The Collins mechanism:

- **transversity distribution h_1:**



helicity flip: $N^{\Uparrow} q^{\downarrow} \rightarrow N^{\Downarrow} q^{\uparrow}$
➥ chiral odd

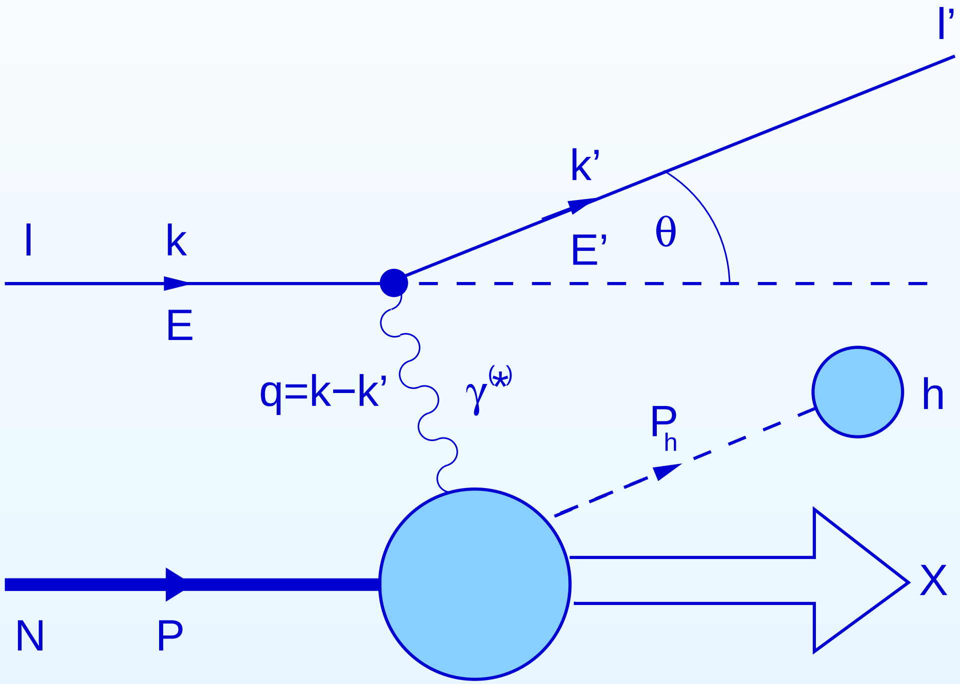
- **Collins fragmentation function $H_1^{\perp}\left(z, z^2 k_T{}^2\right)$:**



- **structure function**: $F_{UT} = -\mathcal{C}\left[\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{k_T}}{M_h} h_1\left(x, \boldsymbol{p_T}^2\right) H_1^{\perp}(z, z^2 \boldsymbol{k_T}^2)\right]$

The deep-inelastic scattering process:

Lepton scattering by single-photon exchange:



kinematics:

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

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

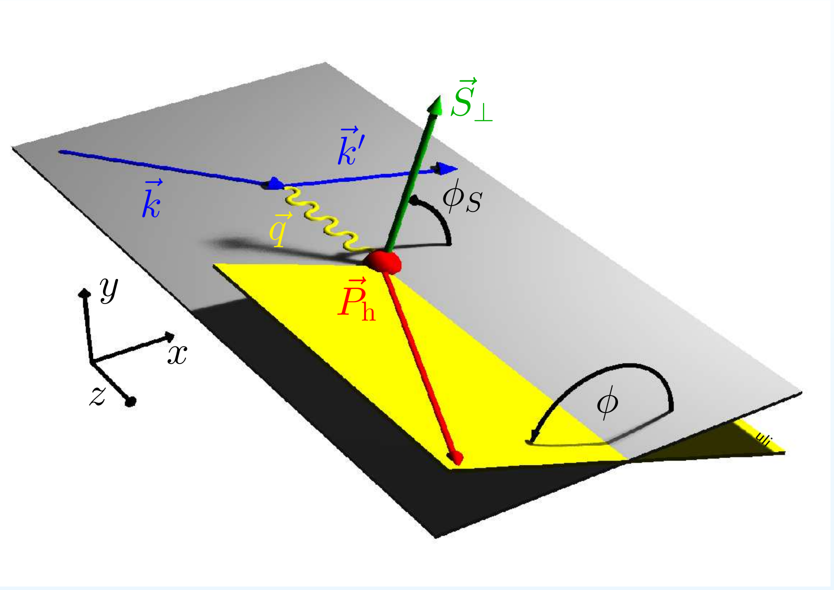
$$x = \frac{Q^2}{2p \cdot q} \overset{\text{lab}}{=} \frac{Q^2}{2M(E-E')}$$

$$z = \frac{P \cdot P_h}{P \cdot q} \overset{\text{lab}}{=} \frac{E_h}{E-E'}$$

semi-inclusive measurement: $lN \to lhX$

Fourier decomposition of transverse SSA:

Measurement of **azimuthal single-spin asymetries** $A_{\mathrm{UT}}(\phi,\phi_S)$:



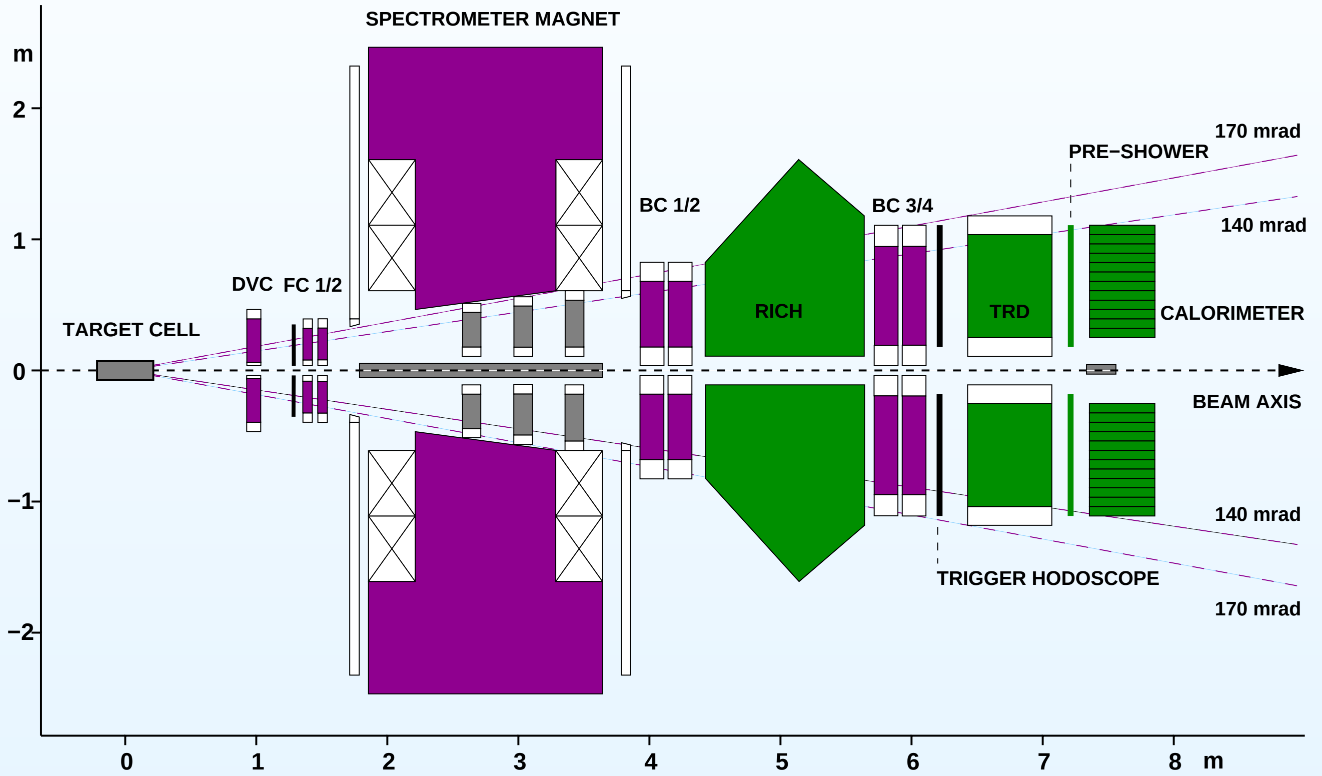
$$\boldsymbol{P}_{h\perp} = z(\boldsymbol{p}_T - \boldsymbol{k}_T)$$

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

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

The HERMES polarised DIS scattering experiment:

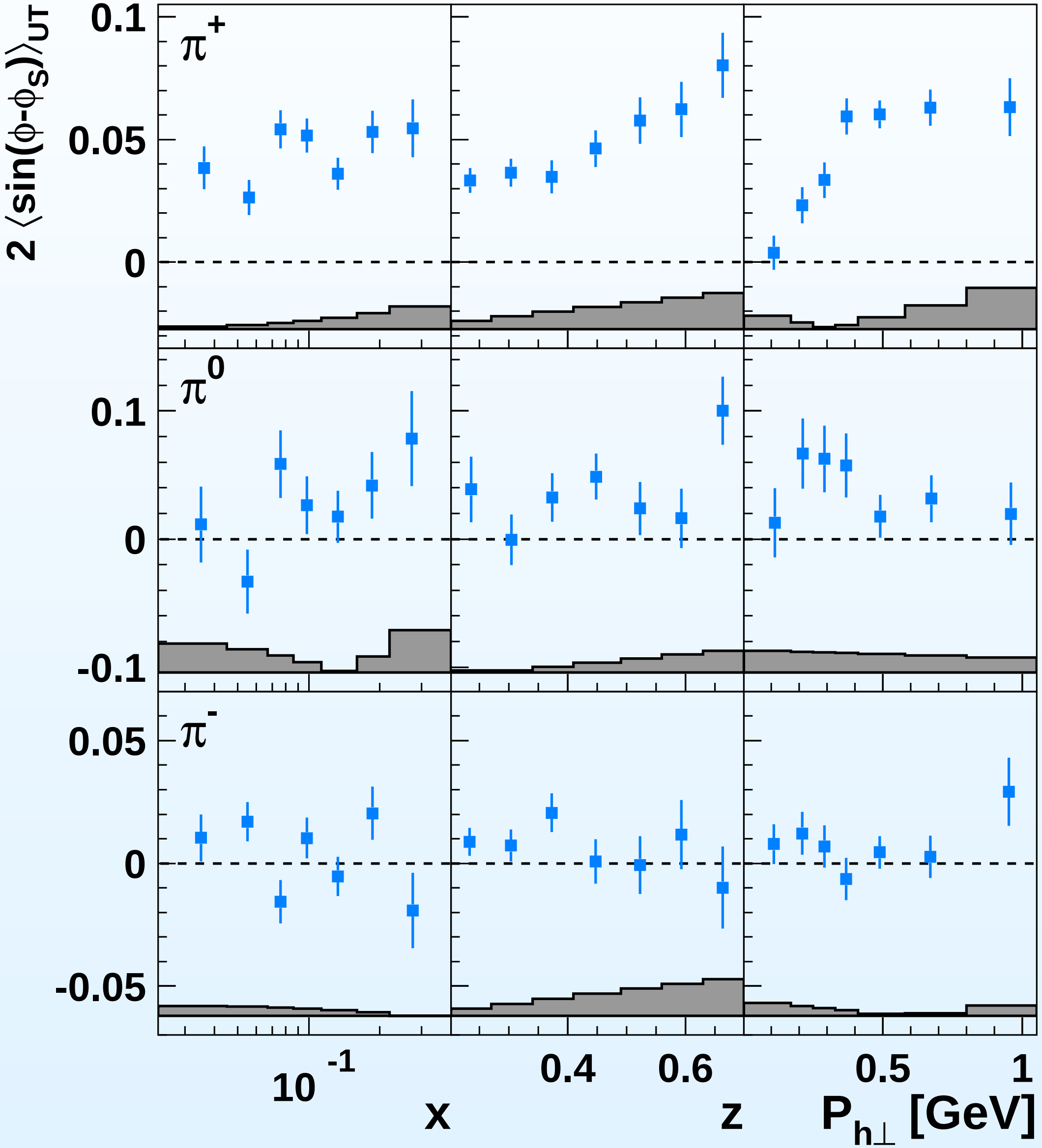
- well-suited for **measurements of azimuthal asymmetries**



- polarised hydrogen **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

Evidence for naive-T-odd Sivers function

The Sivers amplitudes for π-mesons:



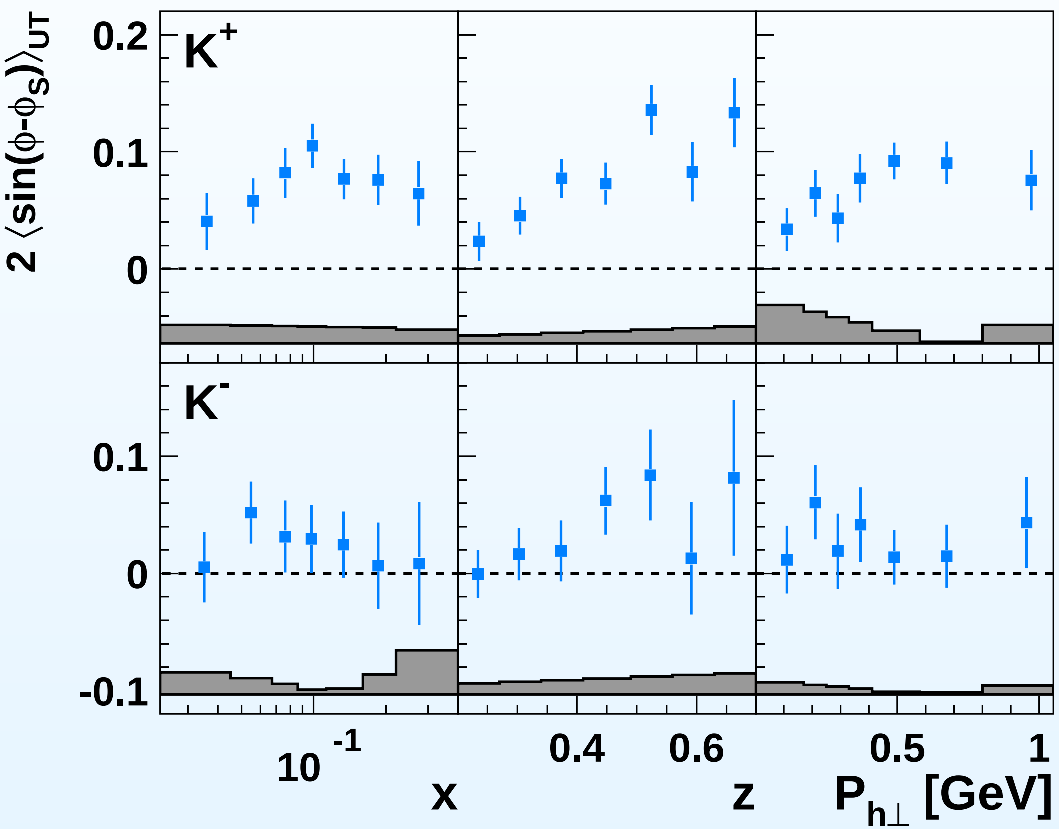
Results for Sivers amplitude:

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

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

The Sivers amplitudes for charged K-mesons:



Results for Sivers amplitude:

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

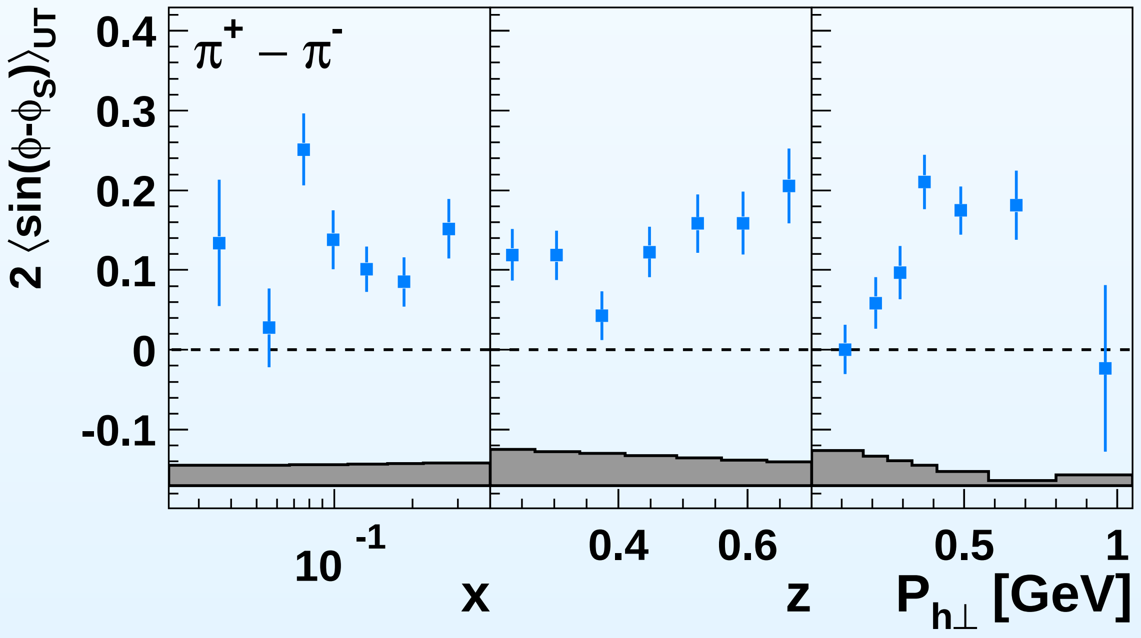
from 2002–2005 data:

- 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^+

The Sivers amplitudes for the pion-difference SSA:

interpretation in terms of **valence-quark distribution** solely:

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



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

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

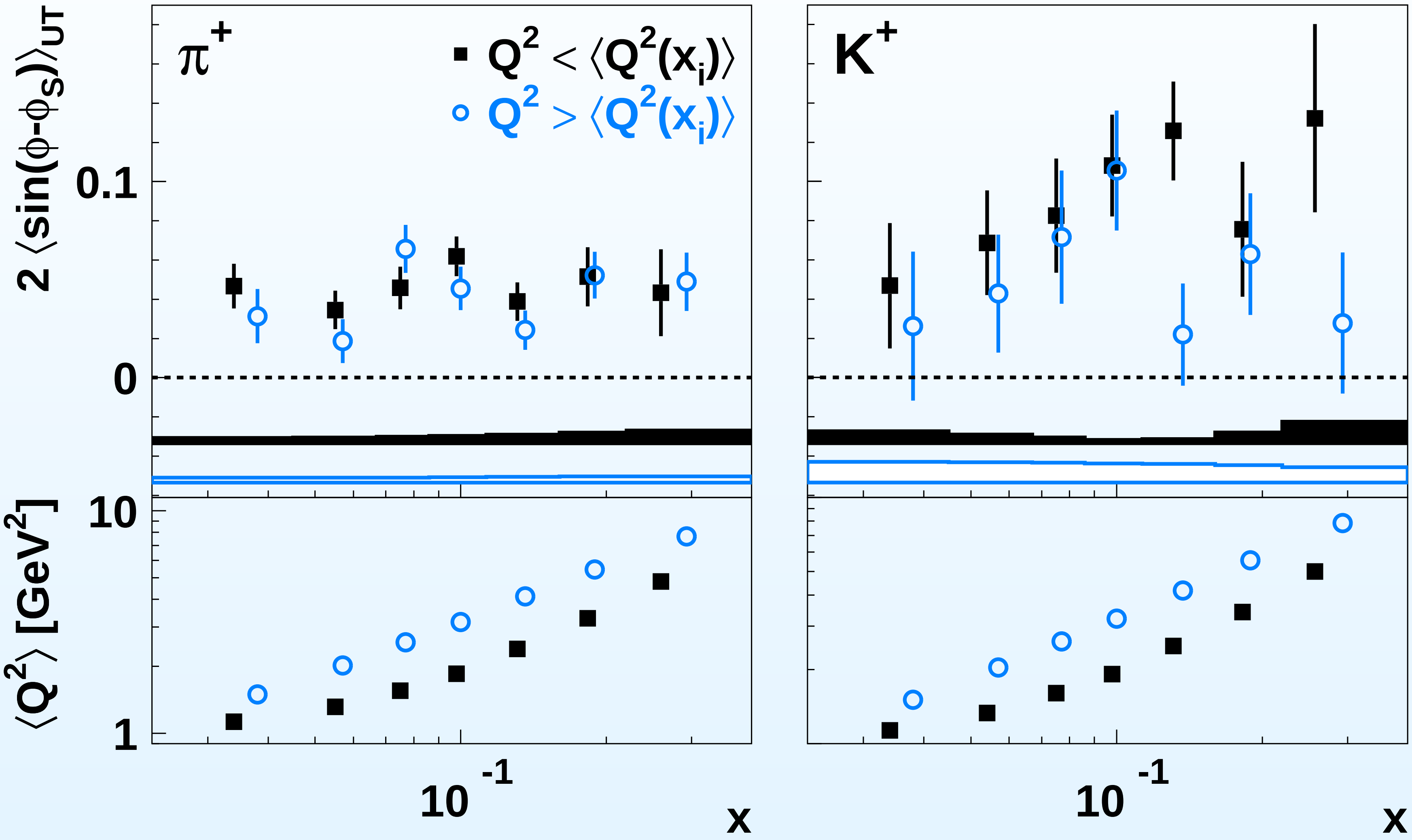
The role of higher twist terms:

- **Sivers amplitude:**

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

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

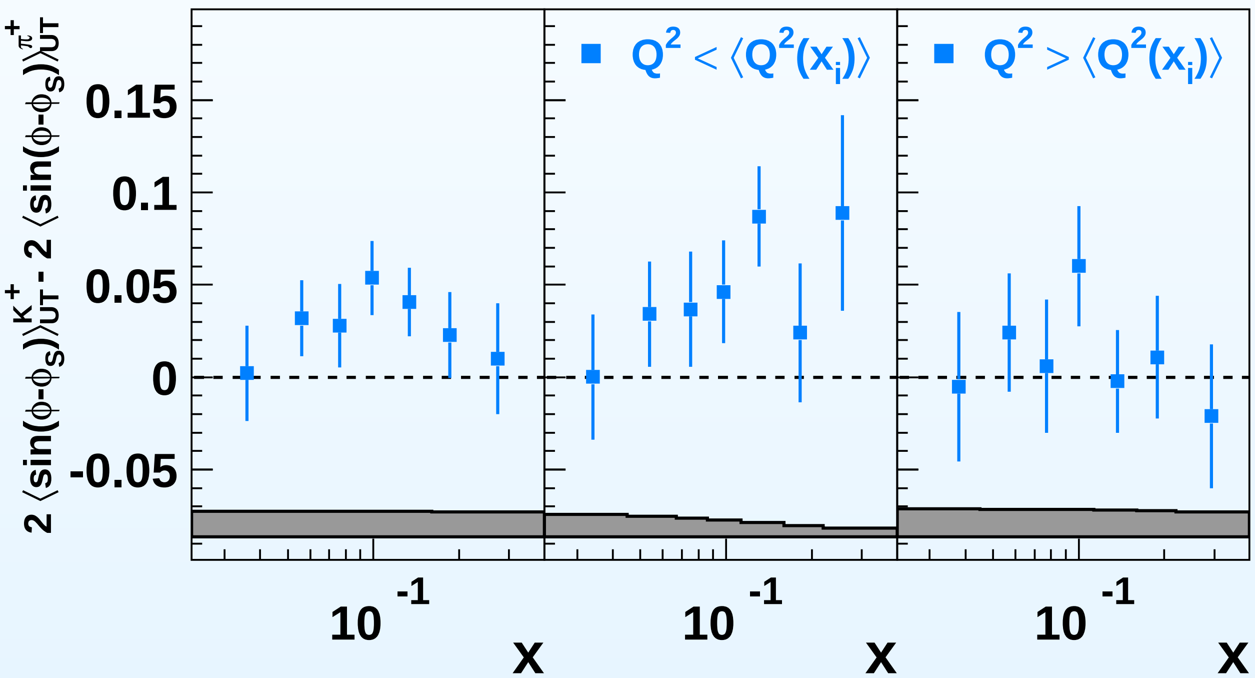
Examination of other $1/Q^2$-suppressed contributions:



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

Sivers amplitudes for K^+ and π^+:

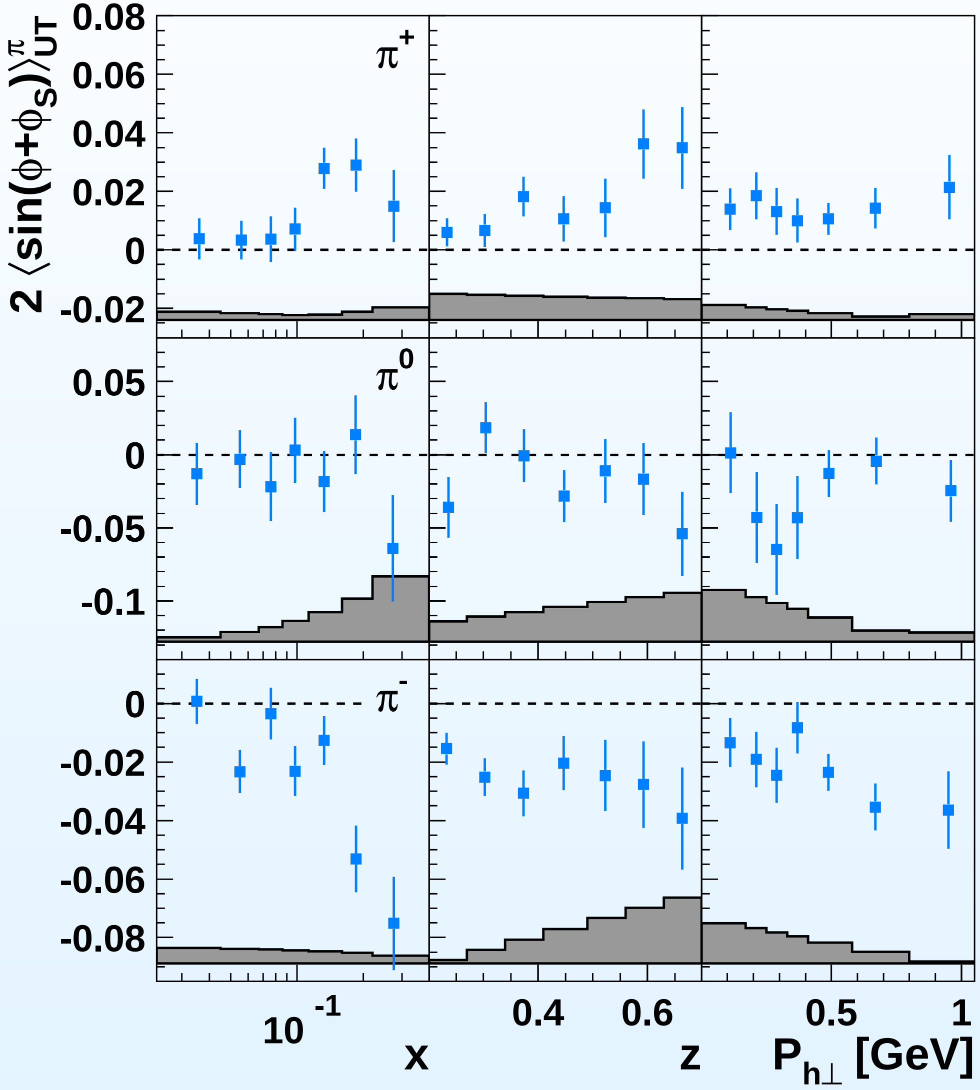
- **u-quark dominance:** $2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}}^{\pi^+} \sim 2\,\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}}^{K^+}$
- **difference in K^+ and π^+ Sivers amplitudes:**



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

The hunt for transversity

The Collins amplitudes for pions:



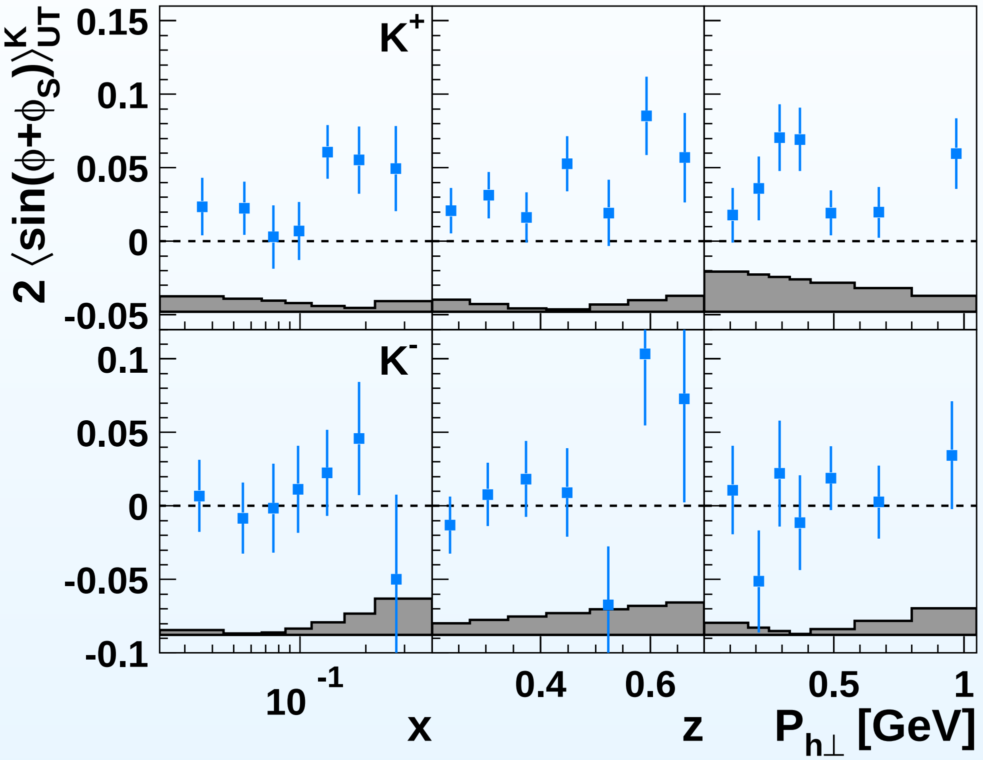
Results of the Collins amplitude:

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

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 Collins amplitudes for kaons:



Results of the Collins amplitude:

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

from 2002–2005 data:

- positive amplitudes for K^+
- K^- amplitudes consistent with zero

Single-hadron production:

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

σ_{XY}

Beam **Target**

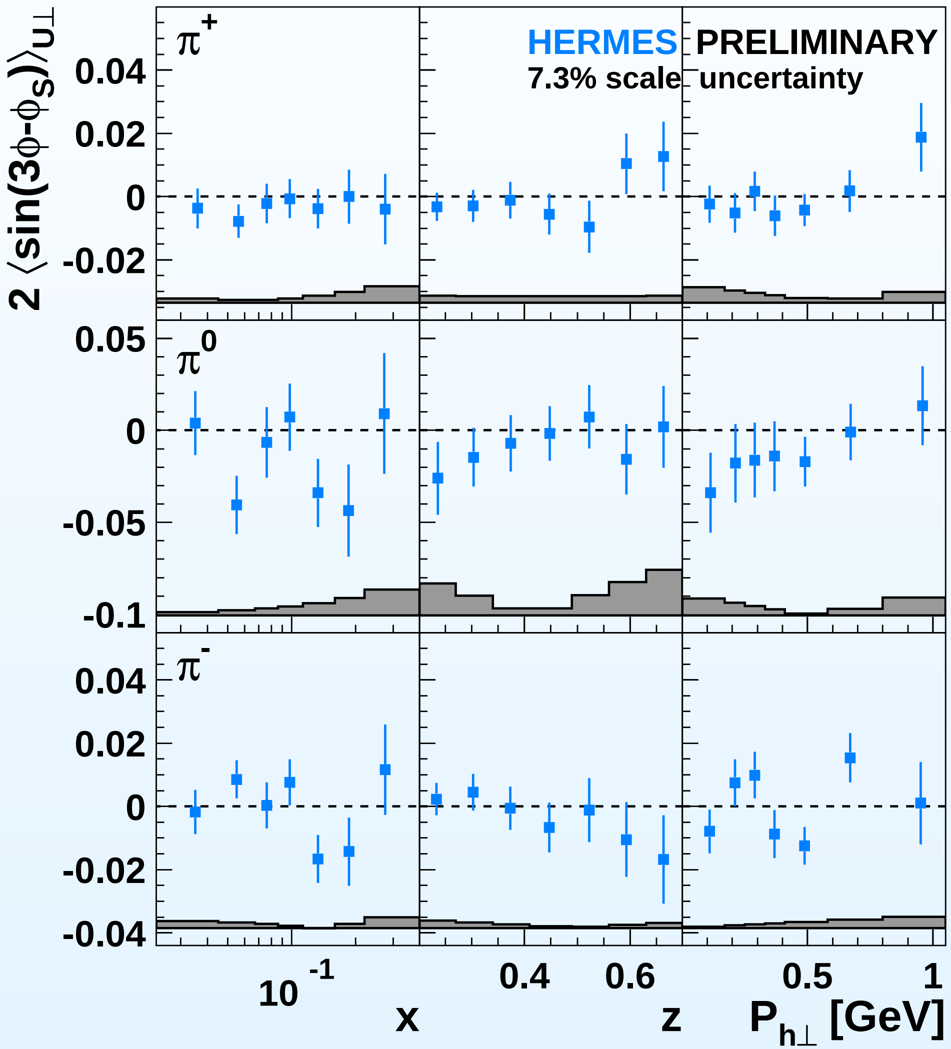
Polarization

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

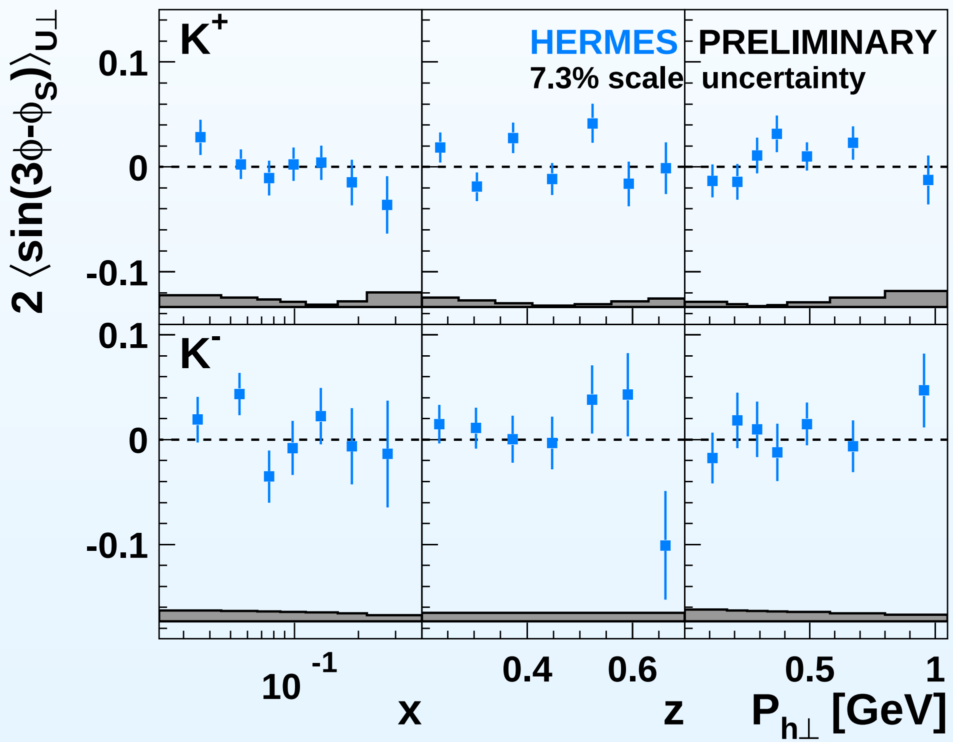
$$F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\boldsymbol{p}_T\cdot\boldsymbol{k}_T\right)+\boldsymbol{p}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)}{2M^2M_h}\,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

- 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

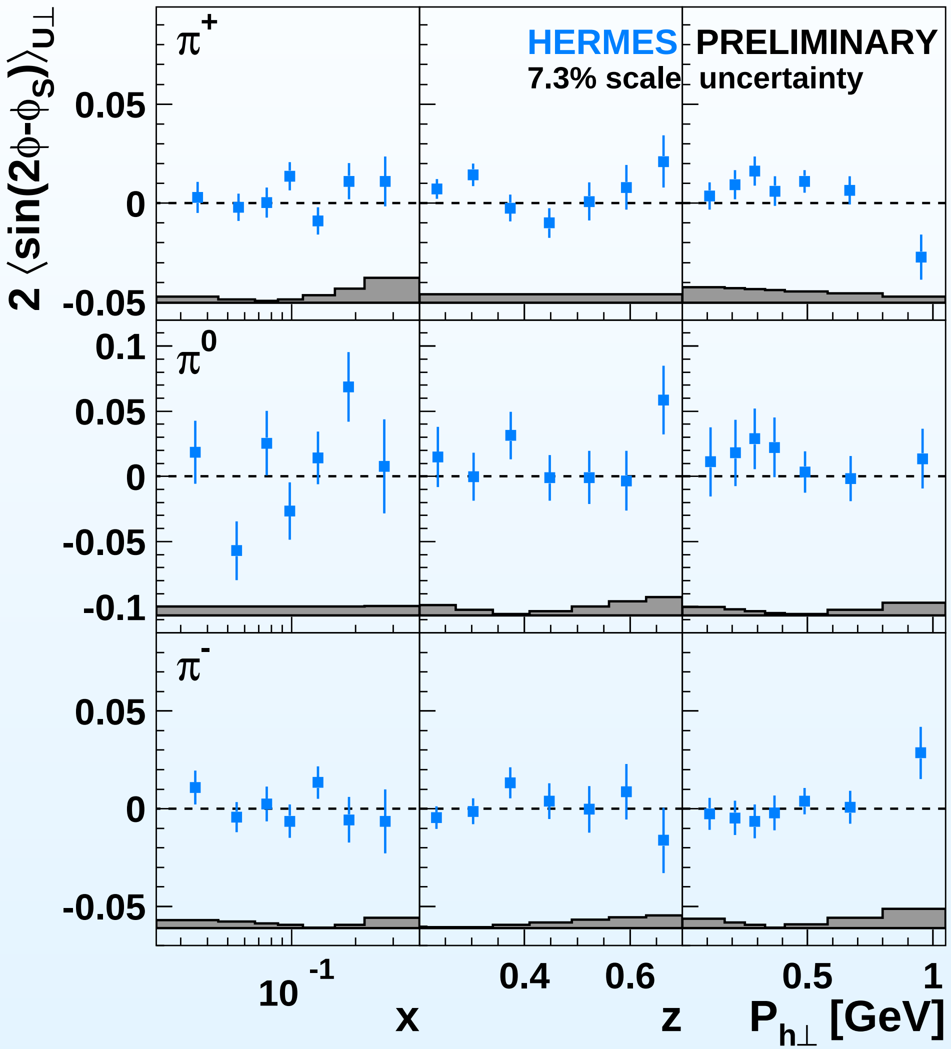


The $\langle \sin(2\phi - \phi_S) \rangle_{U\perp}$ Fourier component:

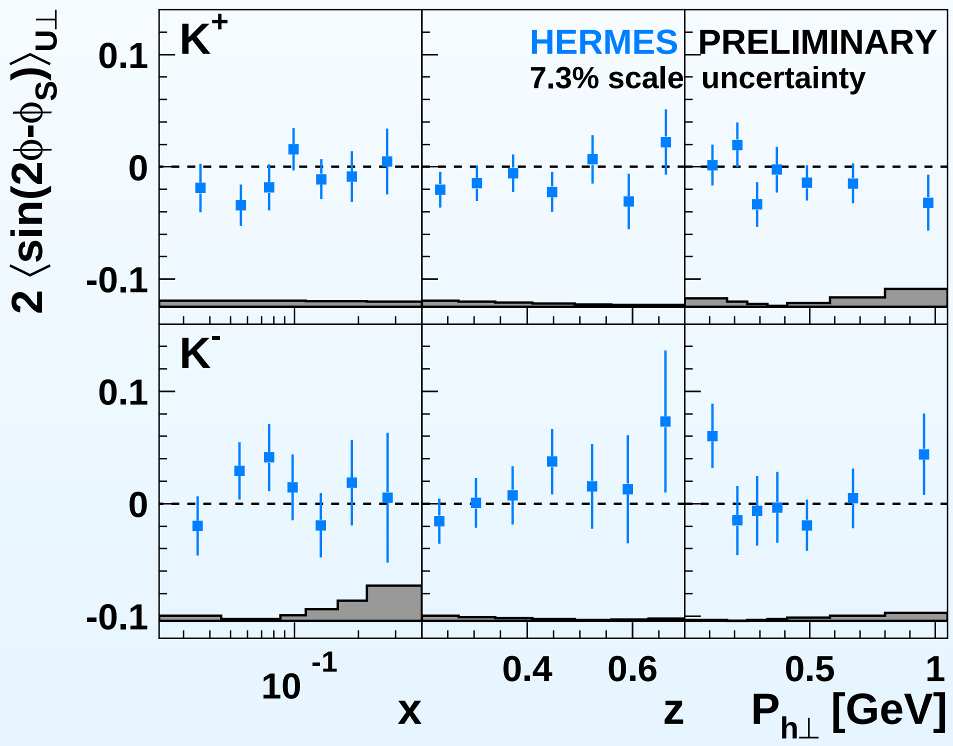
$$\boxed{\begin{aligned} F_{UT}^{\sin(2\phi_h-\phi_S)} &= \frac{2M}{Q}\mathcal{C}\left\{\frac{2\left(\hat{\boldsymbol{h}}\boldsymbol{p}_T\right)^2 - \boldsymbol{p}_T^2}{2M^2}\left(x f_T^\perp D_1 - \frac{M_h}{M}\, h_{1T}^\perp \frac{\tilde{H}}{z}\right)\right. \\ &- \frac{2\left(\hat{\boldsymbol{h}}\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\boldsymbol{p}_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

- $F_{UT}^{\sin(\phi\pm\phi_S)}$ 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**

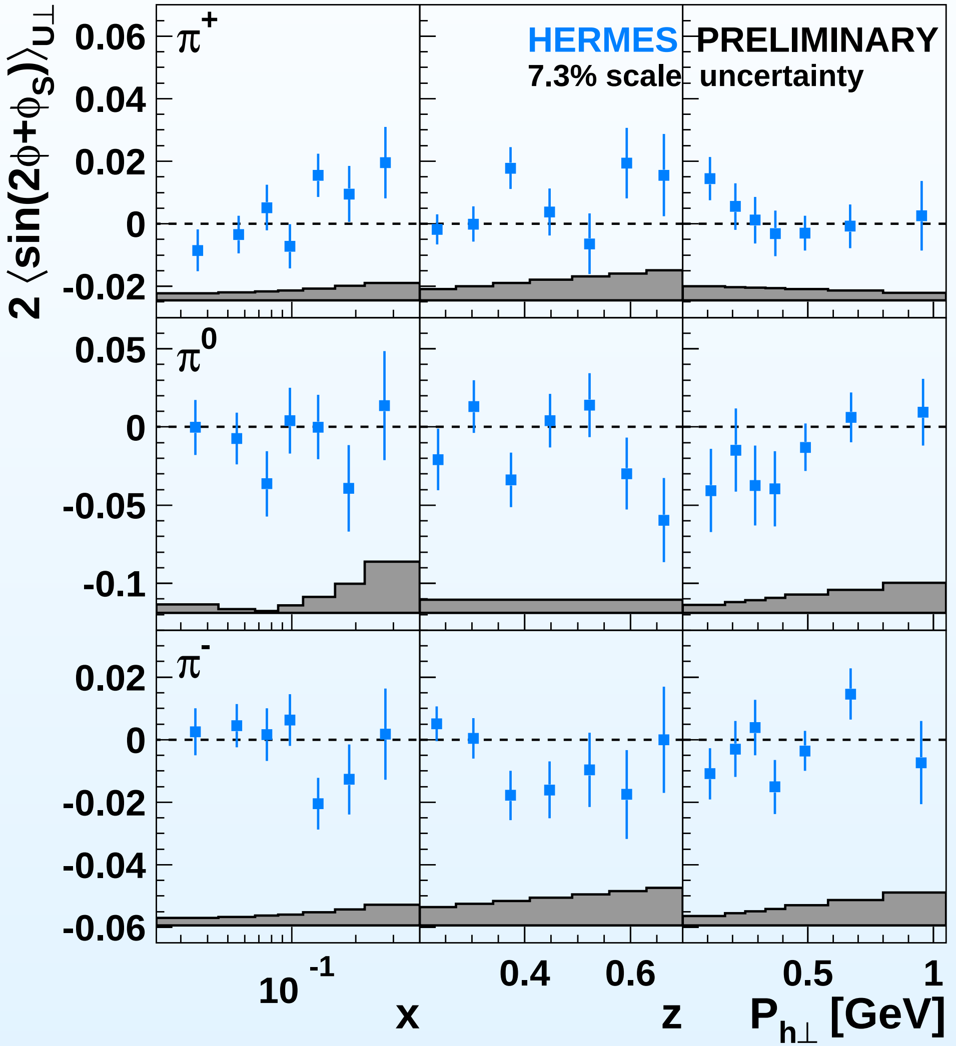
The $\langle \sin(2\phi - \phi_S) \rangle_{U\perp}$ Fourier component:



suppressed w.r.t. Collins and Sivers amplitudes

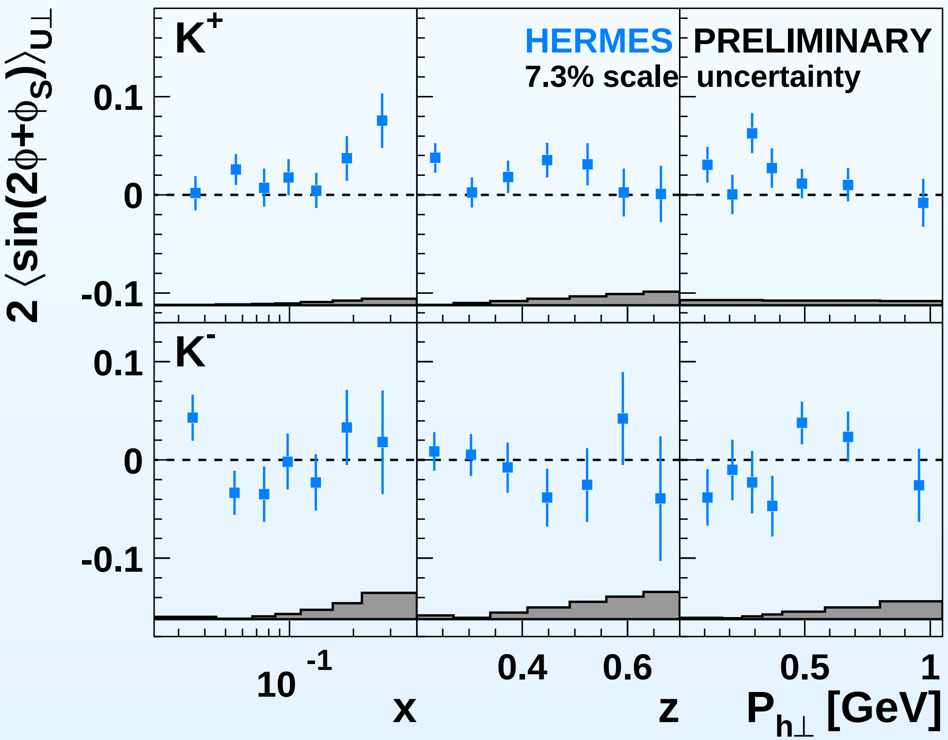


The $\langle \sin(2\phi + \phi_S) \rangle_{U\perp}$ Fourier component:



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:

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

- calculated at leading-twist and subleading-twist accuracy
- $1/Q$-suppressed w.rt. $F_{UT}^{\sin(\phi+\phi_S)}$, $F_{UT}^{\sin(\phi-\phi_S)}$ and $F_{UT}^{\sin(3\phi-\phi_S)}$
- $F_{UT}^{\sin(\phi+\phi_S)}$ and $F_{UT}^{\sin(\phi-\phi_S)}$ are $P_{h\perp}$-suppressed w.r.t. $F_{UT}^{\sin\phi_S}$

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

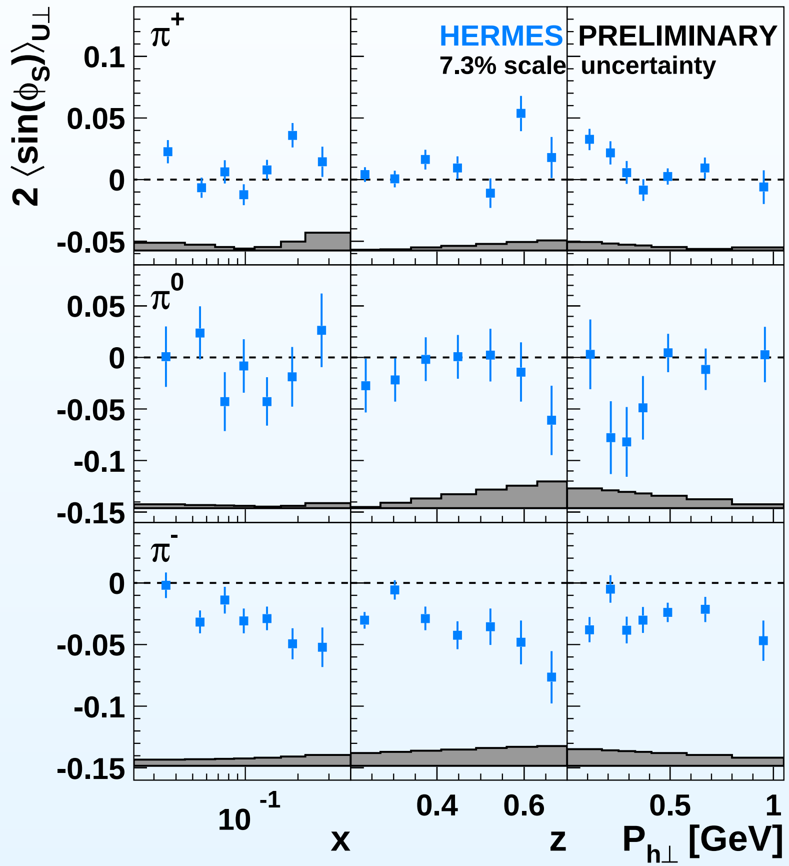
- using relations between T-even functions:

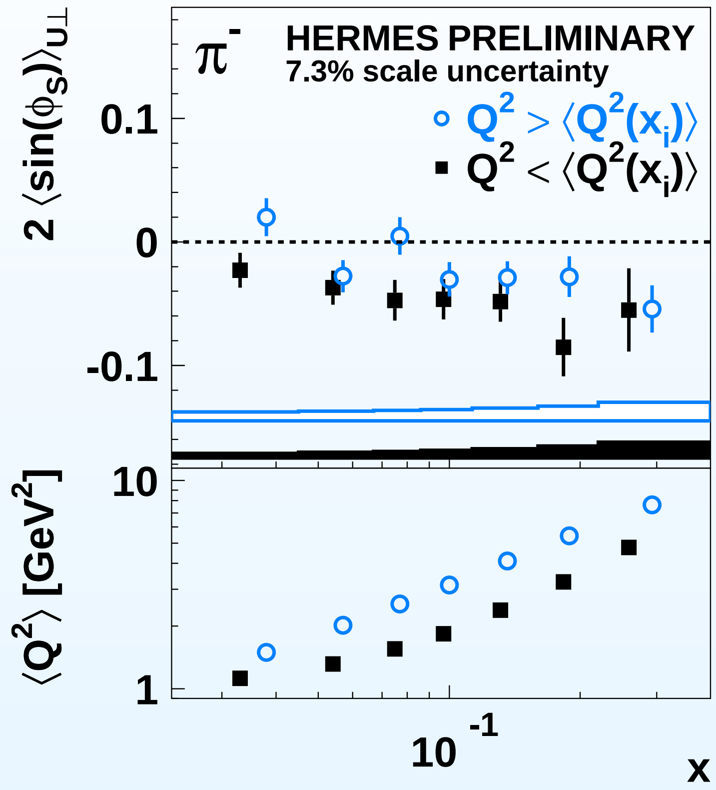
$$
\begin{aligned}
x h_T &= x\tilde{h}_T - h_1 + \frac{\boldsymbol{p}_T^2}{2M^2} h_{1T}^{\perp} + \frac{m}{M} g_{1T} \\
x h_T^{\perp} &= x\tilde{h}_T^{\perp} + h_1 + \frac{\boldsymbol{p}_T^2}{2M^2} h_{1T}^{\perp}
\end{aligned}
$$

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

- 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:





integration over transverse hadron momentum:

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

Pioneering HERMES results:

- (most) precise analysis of transverse SSA in semi-inclusive DIS
- investigation of σ_{UT}
- significant Collins amplitudes for π^+, π^- and K^+
  ➥ enables quantitative extraction of 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^q?
- signals for pretzelosity distribution cannot be isolated
- non-vanishing amplitudes for the $\sin(\phi_S)$ modulation
  ➥ alternative measurement of transversity?
  ➥ test of the Wandzura-Wilczek approximation?
- non-zero signals for worm-gear distribution $h_{1\mathrm{L}}^{\perp,q}$ only for K^+
- **Outlook:** study of worm-gear distribution $g_{1\mathrm{T}}^{\perp,q}$ in analysis of A_{LT}^h