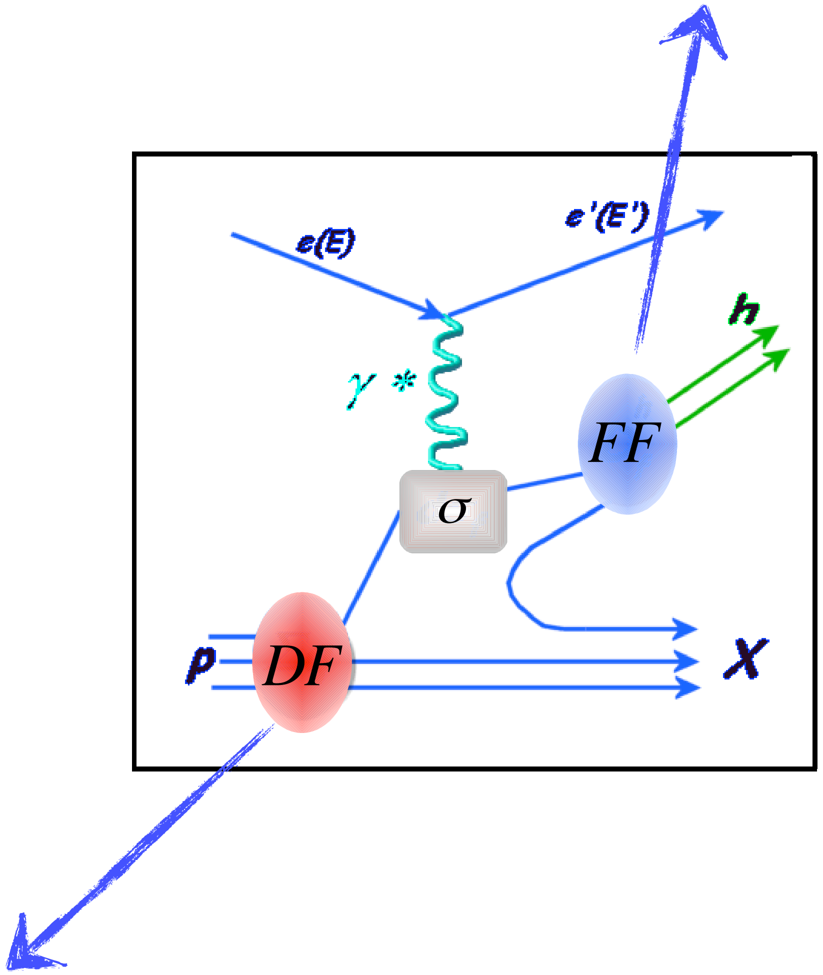
HERMES *results on* TMD *measurements in* SIDIS *off a transversely polarized hydrogen target*

Ami Rostomyan

Transversity 2011, Veli Lošinj, Croatia

quark structure of the nucleon

	U	L	T
U	D_1 unpolarized		$H_1^{\perp}$ - Collins

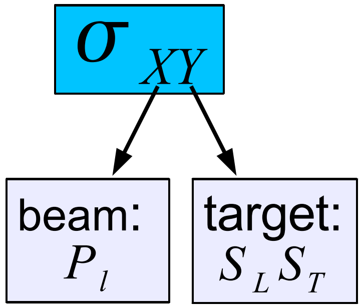


quark polarisation

nucleon polarisation

	U	L	T
U	f_1 number density		$h_1^{\perp}$ - Boer-Mulders
L		g_1 - helicity	$h_{1L}^{\perp}$ - worm-gear
T	$f_{1T}^{\perp}$ - Sivers	g_{1T} - worm-gear	h_1 - transversity $h_{1T}^{\perp}$ - pretzelosity

1-hadron production x-section

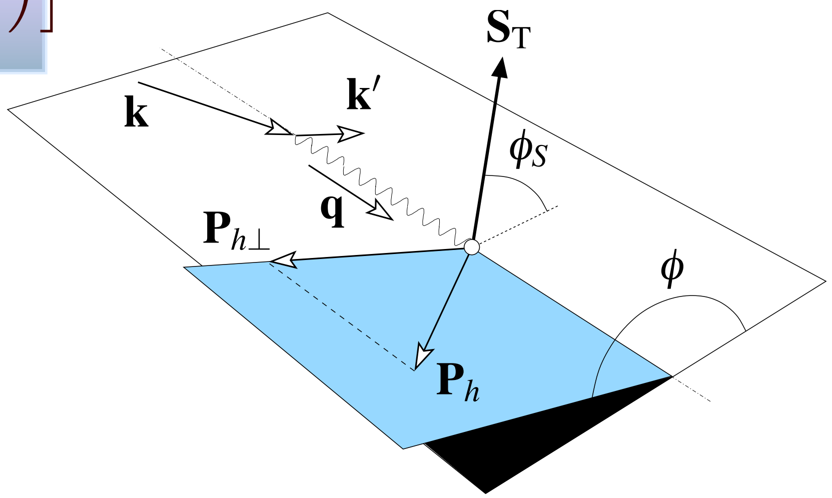


σ_{XY}

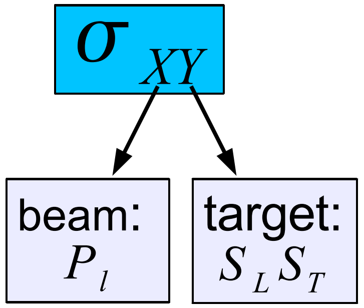
beam: P_l

target: $S_L S_T$

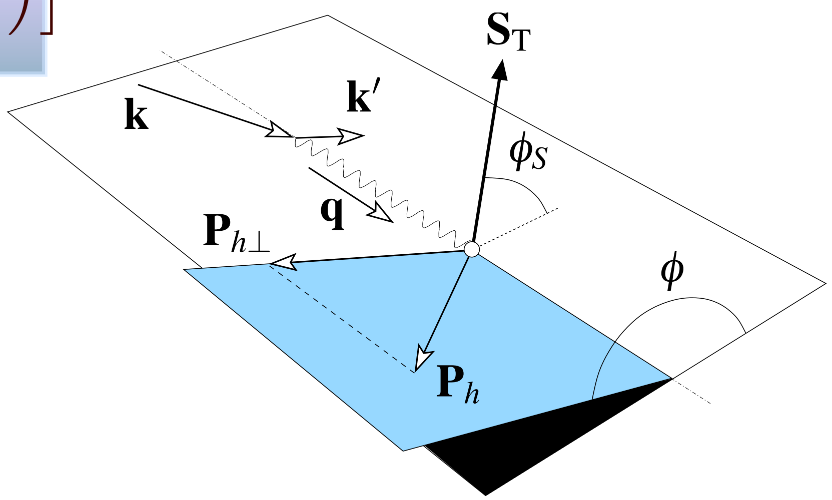
$$\begin{aligned} d\sigma &= d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} + P_l\frac{1}{Q}\sin(\phi)d\sigma^3_{LU}\\ &+ S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} + P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi)d\sigma^7_{LL}\right)\right]\\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



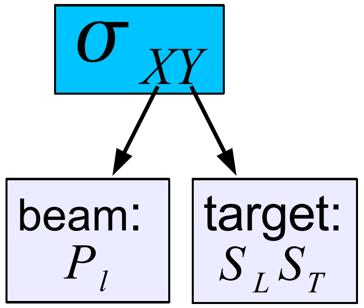
1-hadron production x-section



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

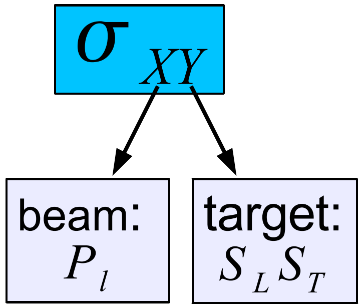


1-hadron production x-section



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

1-hadron production x-section



σ_{XY}

beam: P_l

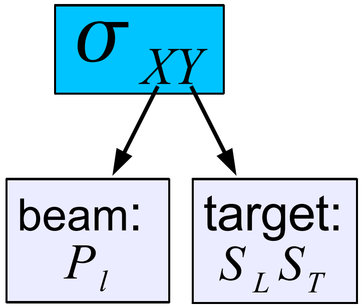
target: $S_L S_T$

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

- disentangling the contributions:
  - experiments with beam and target polarization states (U, L, T)
  - extract the relevant Fourier amplitudes based on their azimuthal dependences

$$\begin{aligned} N(\phi, \phi_s) \; = \; & \qquad \sigma^0_{UU} \Big\{ 1 + 2\langle \cos\phi \rangle_{UU} \cos\phi + 2\langle \cos 2\phi \rangle_{UU} \cos 2\phi \\ + \; & S_T \Big(2\langle \sin(\phi - \phi_s) \rangle_{UT} \sin(\phi - \phi_s) + 2\langle \sin(\phi + \phi_s) \rangle_{UT} \sin(\phi + \phi_s) + \\ & \qquad 2\langle \sin(3\phi - \phi_s) \rangle_{UT} \sin(\phi + \phi_s) + \ldots \Big) \\ + \; & S_T P_l \Big(2\langle \cos(\phi - \phi_s) \rangle_{UT} \cos(\phi - \phi_s) + 2\langle \cos\phi_s \rangle_{UT} \cos\phi_s + \\ & \qquad 2\langle \cos(2\phi - \phi_s) \rangle_{UT} \cos(\phi - \phi_s) \Big) \Big\} \end{aligned}$$

1-hadron production x-section



σ_{XY}

beam: P_l

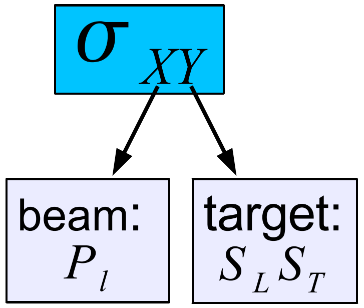
target: $S_L S_T$

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

- disentangling the contributions:
  - experiments with beam and target polarization states (U, L, T)
  - extract the relevant Fourier amplitudes based on their azimuthal dependences
- if no perfect detection efficieny:

$$
\begin{aligned}
N(\phi, \phi_s) \quad &= \quad \epsilon(\phi, \phi_s) \;\; \sigma^0_{UU} \Big\{ 1 + 2\langle \cos\phi \rangle_{UU} \cos\phi + 2\langle \cos 2\phi \rangle_{UU} \cos 2\phi \\
&+ \quad S_T \Big(2\langle \sin(\phi - \phi_s) \rangle_{UT} \sin(\phi - \phi_s) + 2\langle \sin(\phi + \phi_s) \rangle_{UT} \sin(\phi + \phi_s) + \\
&\qquad 2\langle \sin(3\phi - \phi_s) \rangle_{UT} \sin(\phi + \phi_s) + \dots \Big) \\
&+ \quad S_T P_l \Big(2\langle \cos(\phi - \phi_s) \rangle_{UT} \cos(\phi - \phi_s) + 2\langle \cos\phi_s \rangle_{UT} \cos\phi_s + \\
&\qquad 2\langle \cos(2\phi - \phi_s) \rangle_{UT} \cos(\phi - \phi_s) \Big) \Big\}
\end{aligned}
$$

1-hadron production x-section



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

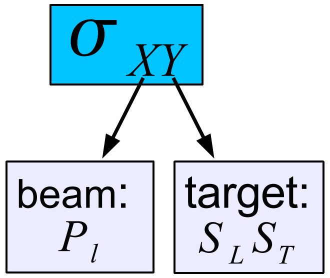
- disentangling the contributions:
  - experiments with beam and target polarization states (U, L, T)
  - extract the relevant Fourier amplitudes based on their azimuthal dependences
- if no perfect detection efficieny:

$$
\begin{aligned}
N(\phi,\phi_s) \;=\;& \epsilon(\phi,\phi_s)\;\; \sigma^0_{UU} \Big\{ 1 + 2\langle\cos\phi\rangle_{UU}\cos\phi + 2\langle\cos 2\phi\rangle_{UU}\cos 2\phi \\
&+\; S_T \Big(2\langle\sin(\phi-\phi_s)\rangle_{UT}\sin(\phi-\phi_s) + 2\langle\sin(\phi+\phi_s)\rangle_{UT}\sin(\phi+\phi_s) + \\
&\qquad 2\langle\sin(3\phi-\phi_s)\rangle_{UT}\sin(\phi+\phi_s) + \ldots \Big) \\
&+\; S_T P_l \Big(2\langle\cos(\phi-\phi_s)\rangle_{UT}\cos(\phi-\phi_s) + 2\langle\cos\phi_s\rangle_{UT}\cos\phi_s + \\
&\qquad 2\langle\cos(2\phi-\phi_s)\rangle_{UT}\cos(\phi-\phi_s) \Big) \Big\}
\end{aligned}
$$

- fit the cross section asymmetry for opposite spin states
- systematics of neglecting cosine terms found to be negligible

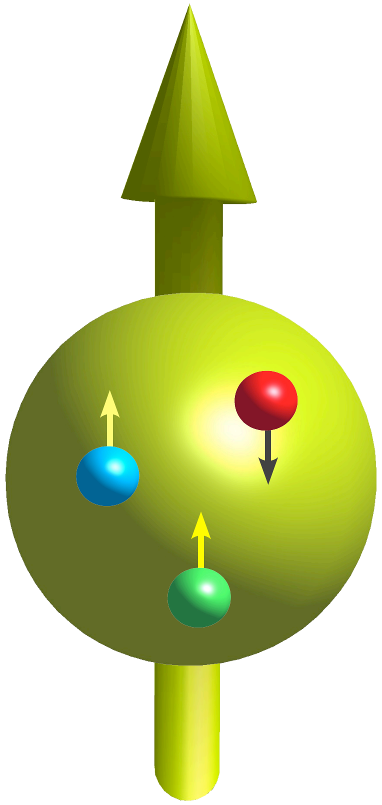
leading twist amplitudes

Collins effect



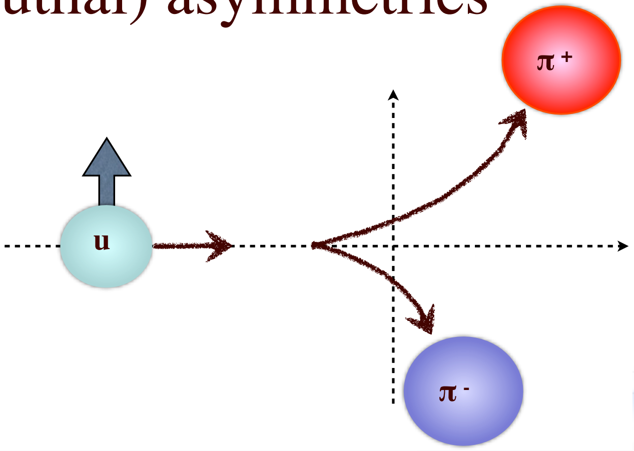
$$\begin{aligned}
d\sigma \quad &= \quad d\sigma^0_{UU} + \cos(2\phi) d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi) d\sigma^2_{UU} \quad + \quad P_l \frac{1}{Q}\sin(\phi) d\sigma^3_{LU} \\
&+ \quad S_L \Big[\sin(2\phi) d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi) d\sigma^5_{UL} \quad + \quad P_l \Big(d\sigma^6_{LL}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

☛ the transversity DF $h_1^q(x)$ is sensitive to the difference of the number densities of transversely polarized quarks aligned along or opposite to the polarization of the nucleon



☛ "Collins-effect" accounts for the correlation between the transverse spin of the fragmenting quark and the transverse momentum of the produced unpolarized hadron

☛ generates left-right (azimuthal) asymmetries

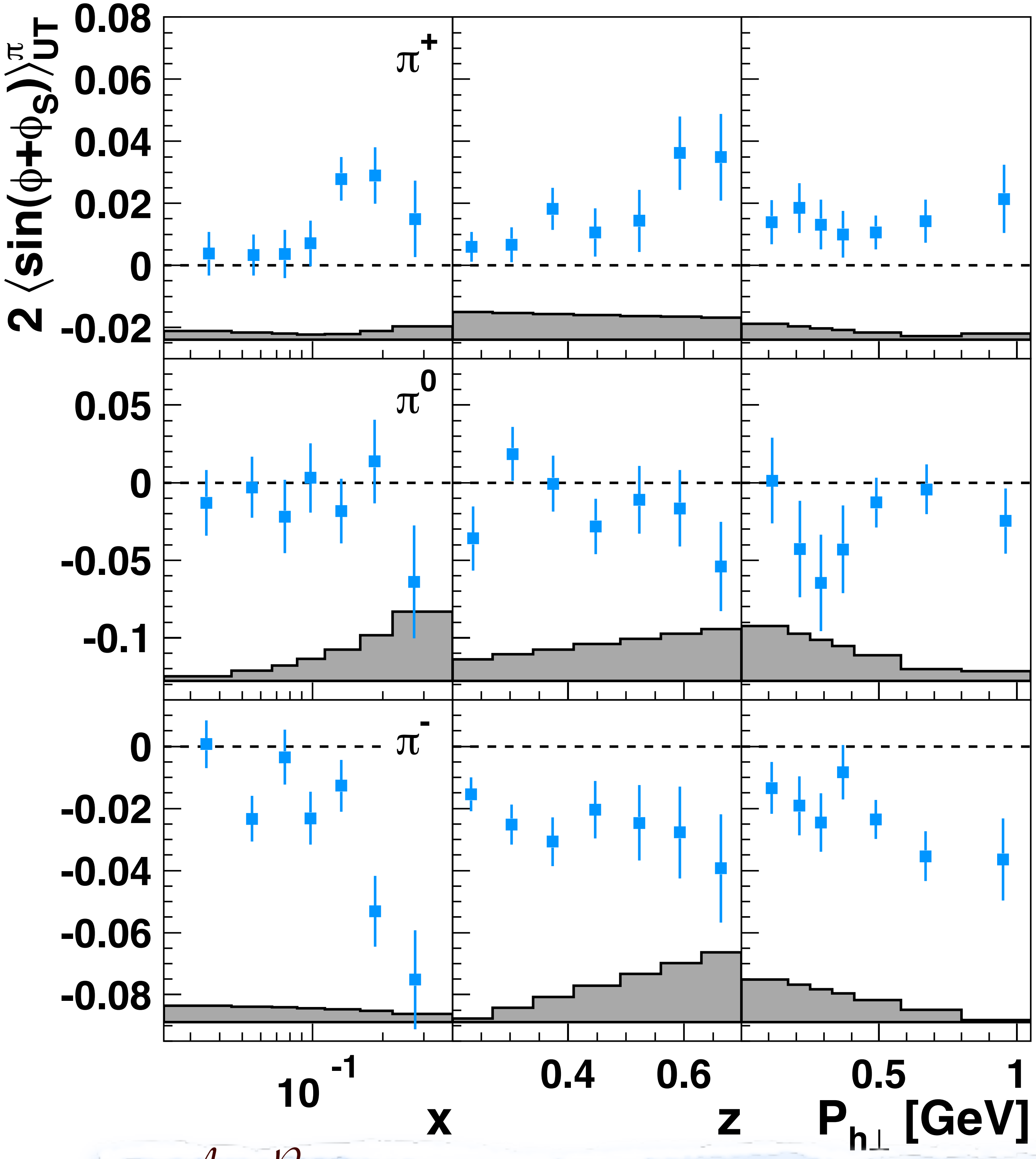


Collins amplitudes for pions

Phys. Lett. B 693 (2010) 11-16

- non-zero Collins effect observed!
  - both Collins FF and transversity sizable

$$2\langle \sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_{\mathrm{T}}}{M_h}\, h_1^q(x,p_{\mathrm{T}}^2)\, H_1^{\perp q\to h}(z,k_{\mathrm{T}}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_{\mathrm{T}}^2)\, D_1^{q\to h}(z,k_{\mathrm{T}}^2)\right]}$$

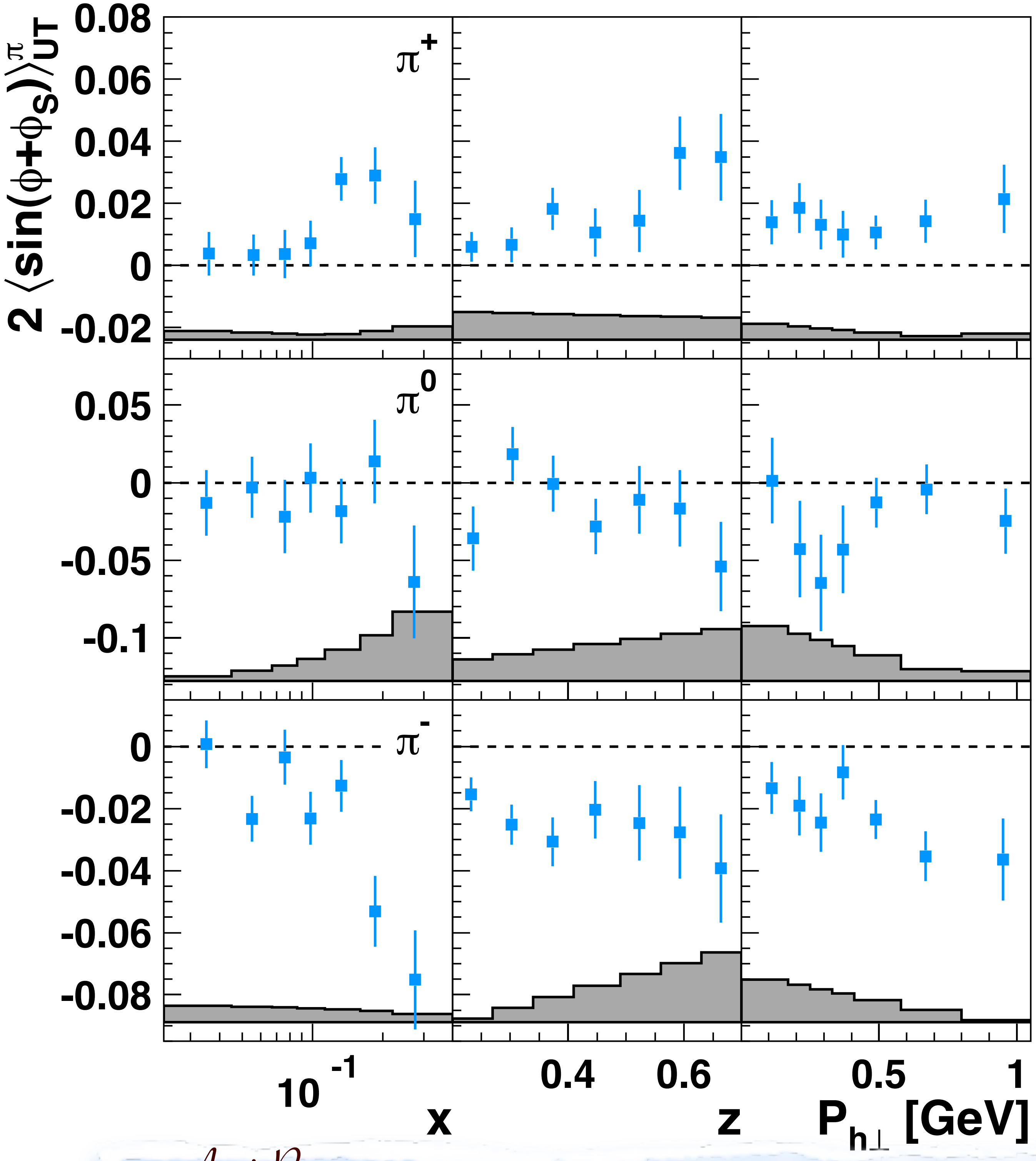


Collins amplitudes for pions

Phys. Lett. B 693 (2010) 11-16

- non-zero Collins effect observed!
  - both Collins FF and transversity sizable

$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_\mathrm{T}}{M_h}\, h_1^q(x,p_\mathrm{T}^2)\,H_1^{\perp q\to h}(z,k_\mathrm{T}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_\mathrm{T}^2)\,D_1^{q\to h}(z,k_\mathrm{T}^2)\right]}$$



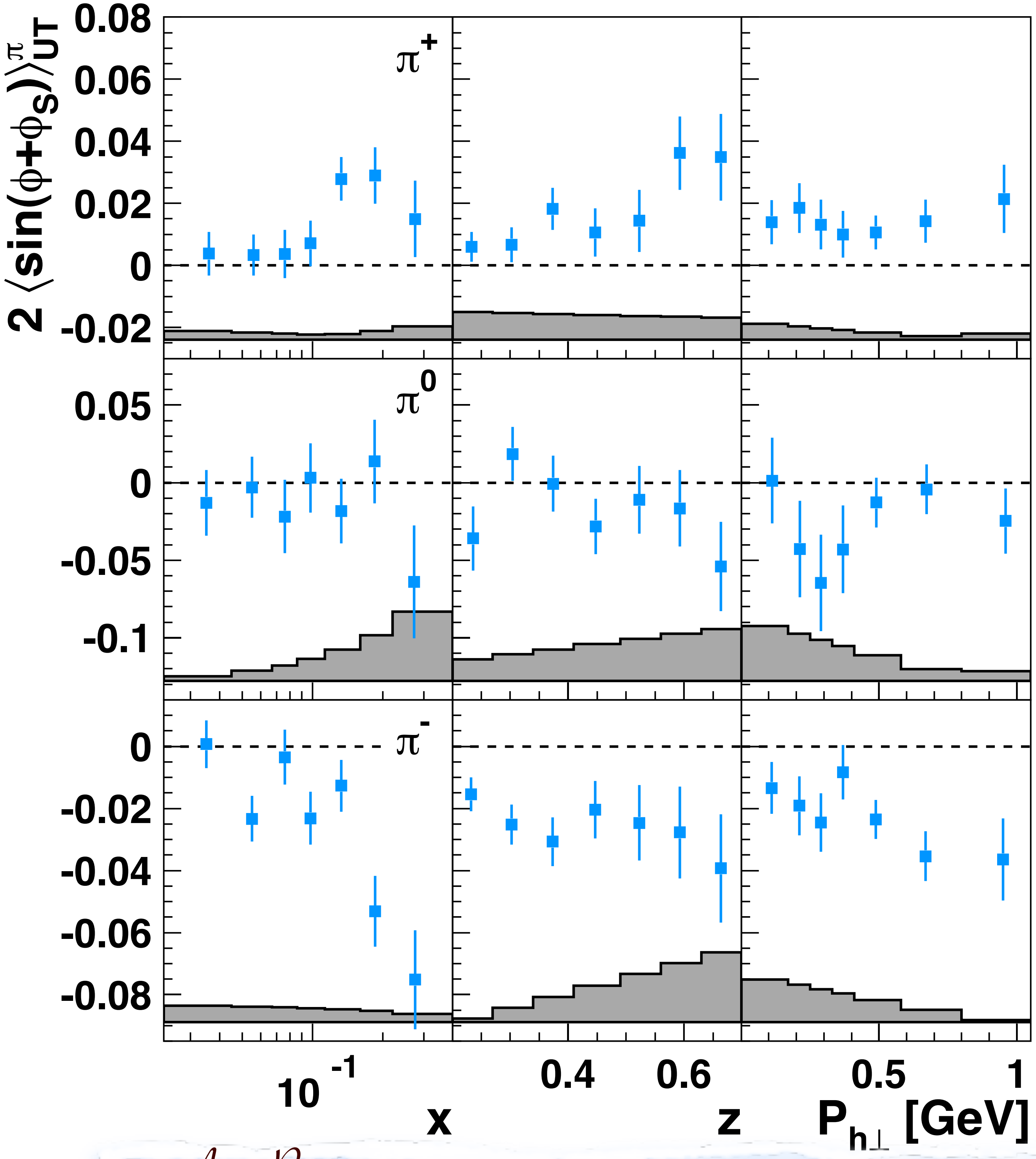
- positive amplitude for **π^+**
- compatible with zero amplitude for **π^0**
- large negative amplitude for **π^-**
- increase in magnitude with x
  - transversity mainly receives contribution from valence quarks
- increase with z
  - in qualitative agreement with BELLE results

Collins amplitudes for pions

Phys. Lett. B 693 (2010) 11-16

- non-zero Collins effect observed!
  - both Collins FF and transversity sizable

$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_{\mathrm{T}}}{M_h}\, h_1^q(x,p_{\mathrm{T}}^2)H_1^{\perp q\to h}(z,k_{\mathrm{T}}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_{\mathrm{T}}^2)D_1^{q\to h}(z,k_{\mathrm{T}}^2)\right]}$$



- positive amplitude for π^+
- compatible with zero amplitude for π^0
- large negative amplitude for π^-
- increase in magnitude with x
  - transversity mainly receives contribution from valence quarks
- increase with z
  - in qualitative agreement with BELLE results
- positive for π^+ and negative for π^-
  - role of disfavored Collins FF:

$$\mathbf{H_1^{\perp,disfav}} \approx -H_1^{\perp,fav}$$

$$u \Rightarrow \pi^+; \qquad d \Rightarrow \pi^-(fav)$$

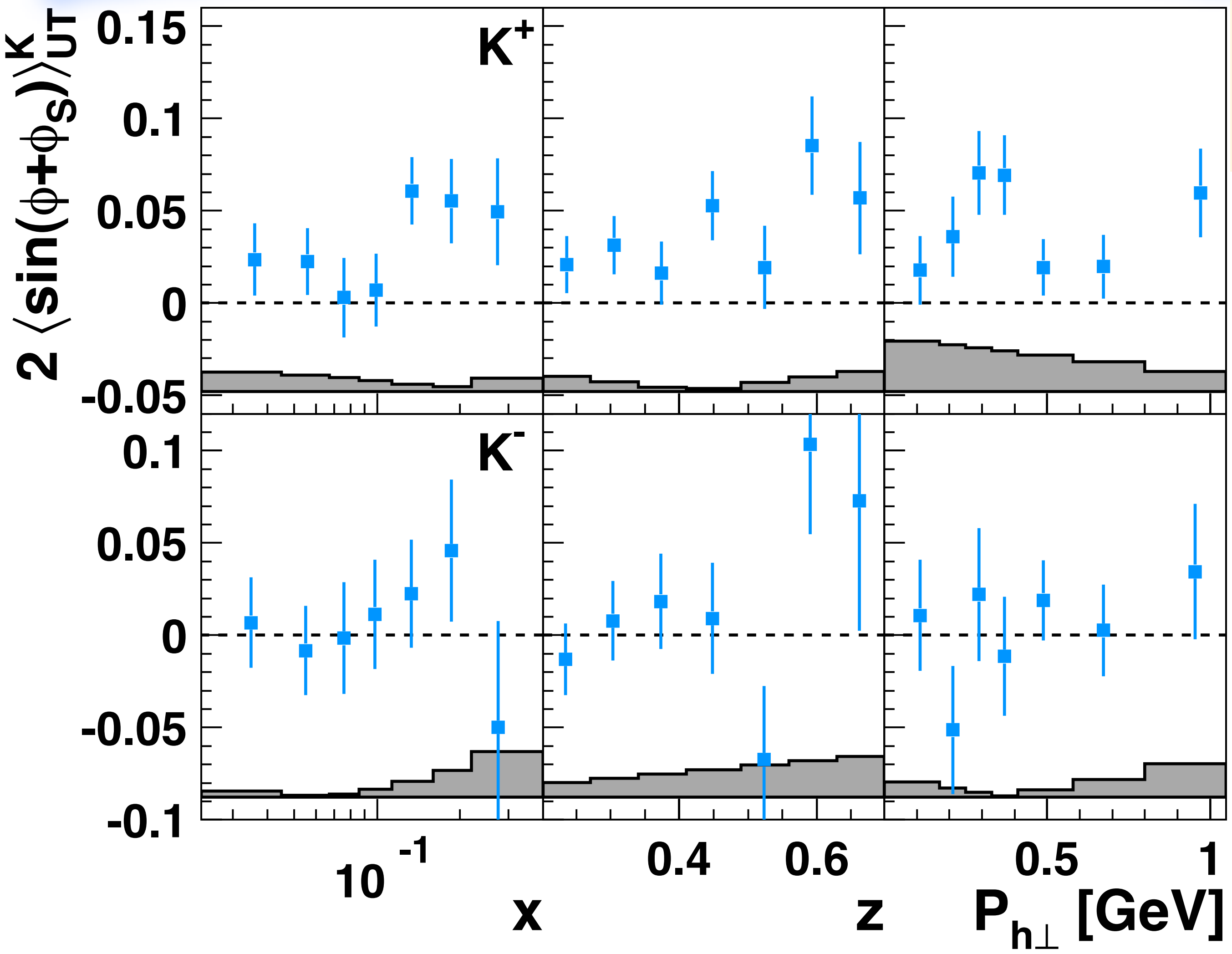
$$u \Rightarrow \pi^-; \qquad d \Rightarrow \pi^+(disfav)$$

$$\mathbf{h_1^u} > 0$$

$$\mathbf{h_1^d} < 0$$

Collins amplitudes for kaons

Phys. Rev. Lett. 103 (2009) 152002



$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_{\mathrm{T}}}{M_h}\, h_1^q(x,p_{\mathrm{T}}^2) H_1^{\perp q\to h}(z,k_{\mathrm{T}}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_{\mathrm{T}}^2) D_1^{q\to h}(z,k_{\mathrm{T}}^2)\right]}$$

K^+

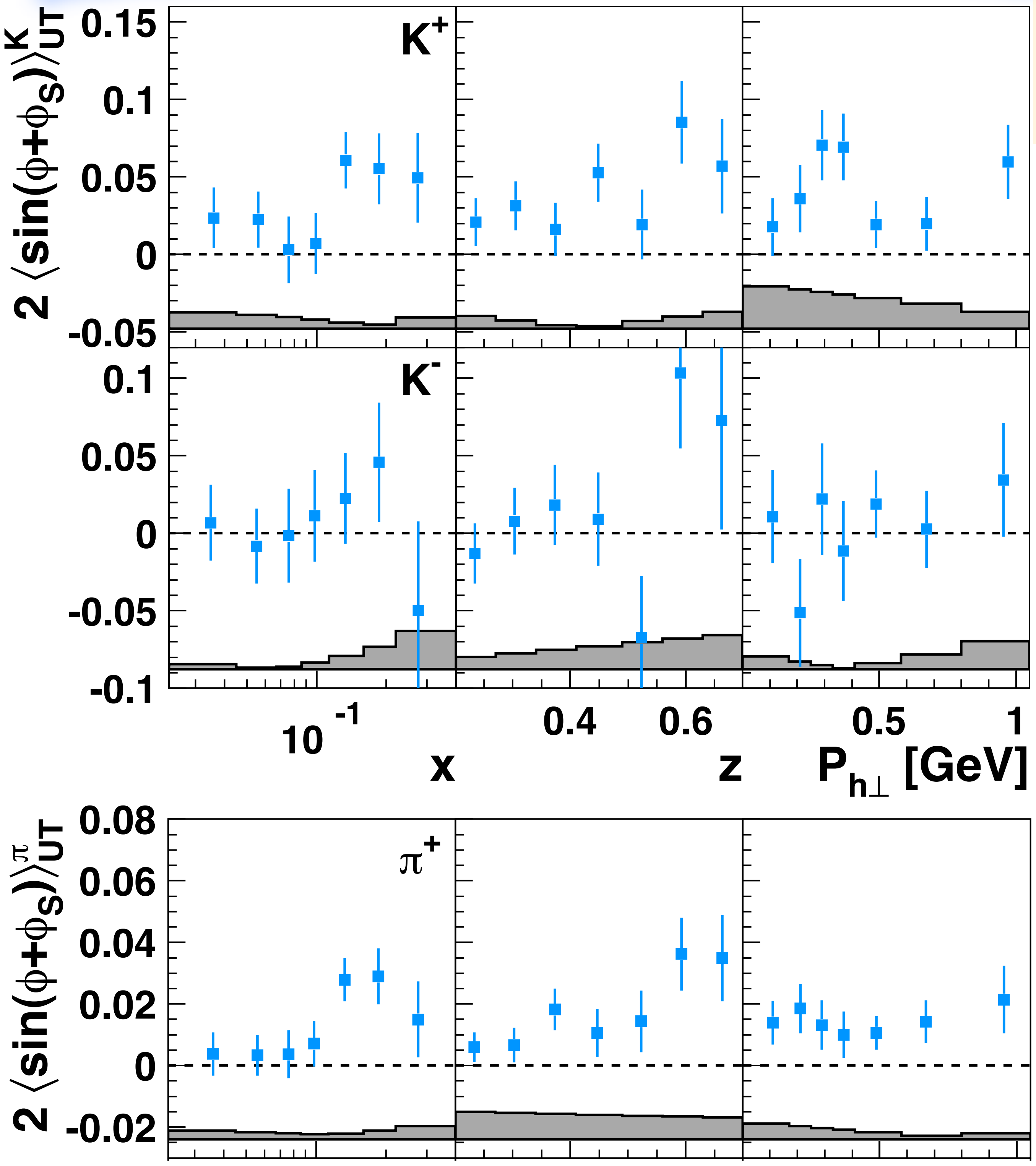
- K^+ amplitudes are similar to $\boldsymbol{\pi}^+$ as expected from the u-quark dominance
- K^+ are larger than $\boldsymbol{\pi}^+$

K^-

- consistent with zero amplitudes
- $\mathbf{K}^-(\bar{\mathbf{u}}\mathbf{s})$ is all see object

Collins amplitudes for kaons

Phys. Rev. Lett. 103 (2009) 152002



$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_{\mathrm{T}}}{M_h}\, h_1^q(x,p_{\mathrm{T}}^2)\, H_1^{\perp q\to h}(z,k_{\mathrm{T}}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_{\mathrm{T}}^2)\, D_1^{q\to h}(z,k_{\mathrm{T}}^2)\right]}$$

K^+

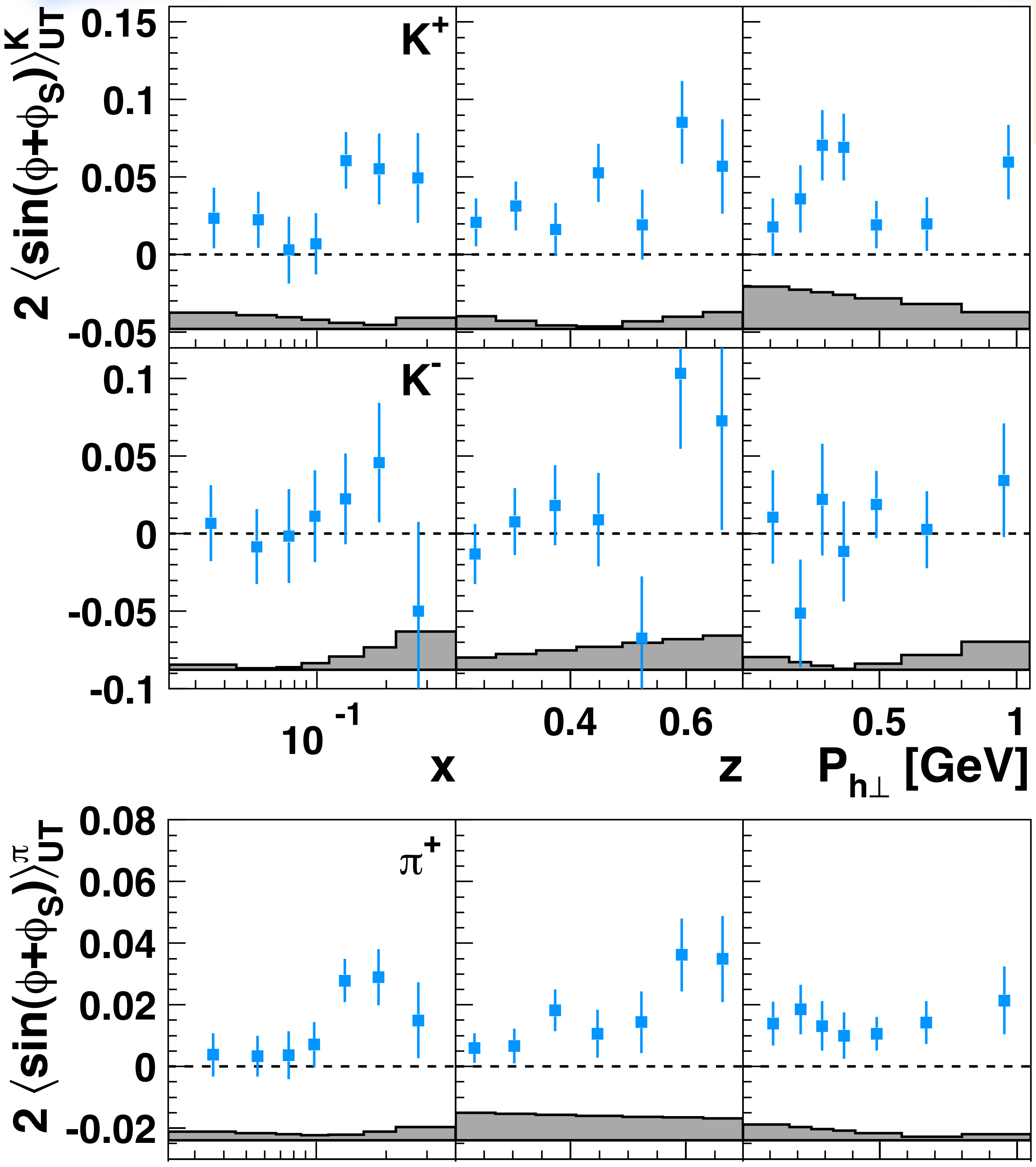
- K^+ amplitudes are similar to $\boldsymbol{\pi}^+$ as expected from the u-quark dominance
- K^+ are larger than $\boldsymbol{\pi}^+$

K^-

- consistent with zero amplitudes
- $\mathbf{K}^-(\bar{\mathbf{u}}\mathbf{s})$ is all see object

Collins amplitudes for kaons

Phys. Rev. Lett. 103 (2009) 152002



$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_{\mathrm{T}}}{M_h}\, h_1^q(x,p_{\mathrm{T}}^2)H_1^{\perp q\to h}(z,k_{\mathrm{T}}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_{\mathrm{T}}^2)D_1^{q\to h}(z,k_{\mathrm{T}}^2)\right]}$$

K^+

- K^+ amplitudes are similar to $\boldsymbol{\pi}^+$ as expected from the u-quark dominance
- K^+ are larger than $\boldsymbol{\pi}^+$

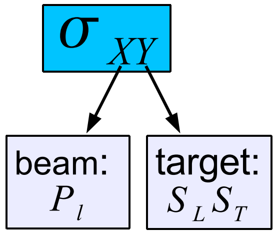
K^-

- consistent with zero amplitudes
- $\mathbf{K}^-(\bar{\mathbf{u}}\mathbf{s})$ is all see object

differences between K^+ and π^+ amplitudes

- role of sea quarks in conjunction with possibly large FF
- various contributions from decay of semi-inclusively produced vector-mesons
- the k_T dependences of the fragmentation functions

Sivers effect

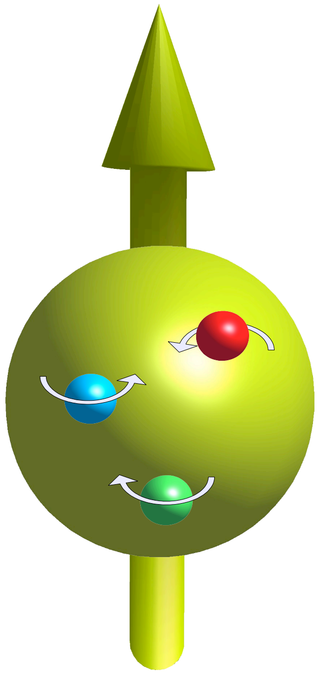

σ_{XY}

beam: P_l

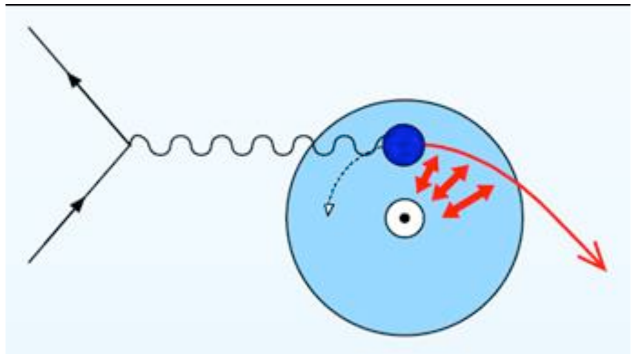
target: $S_L S_T$

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

- Sivers distribution function $f^{\perp,q}_{1T}(x,p^2_T)$ describes the probability to find an unpolarized quark in a transversely polarized nucleon; gives the correlation between parton transverse momentum and transverse spin of the nucleon



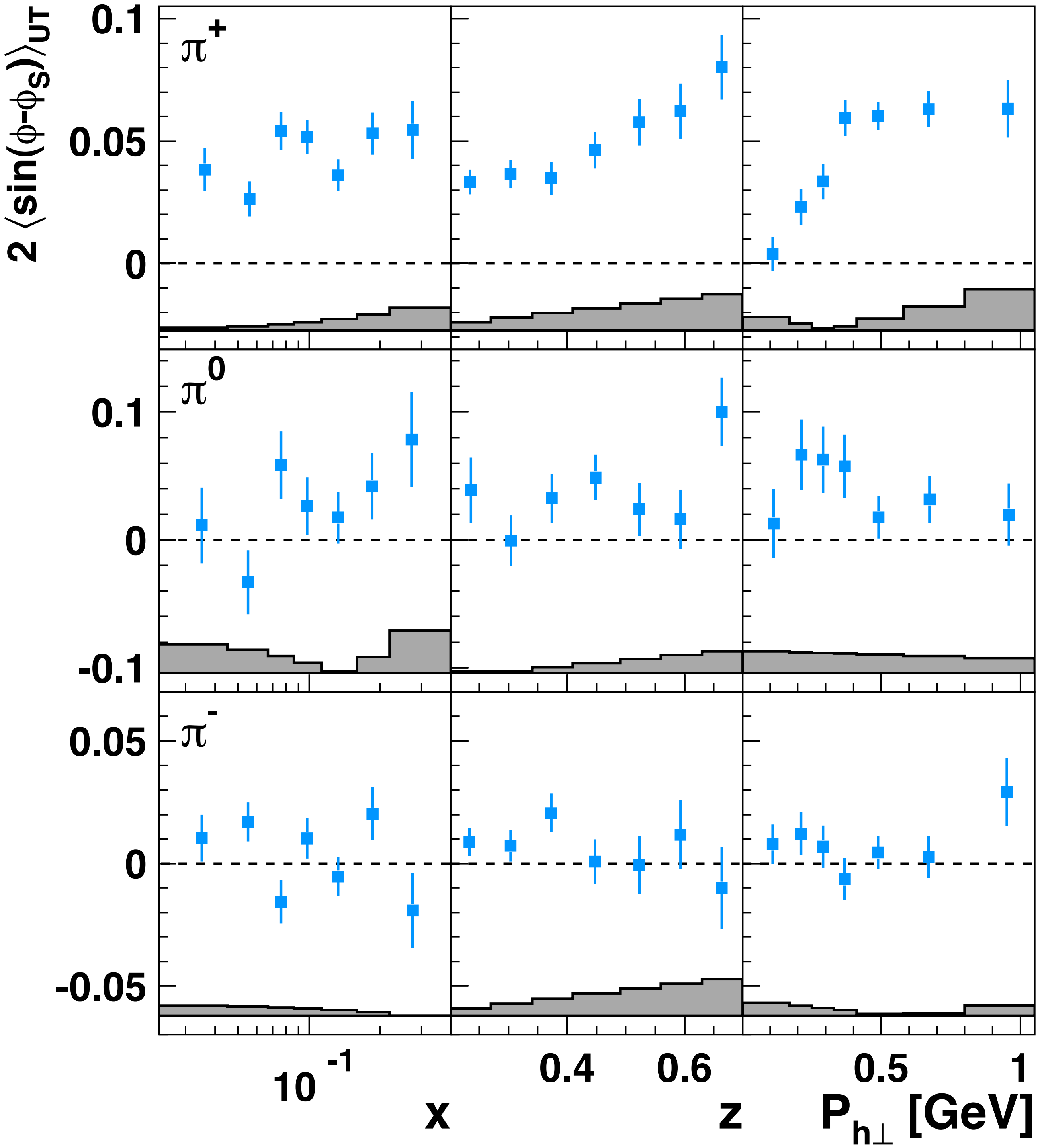
- non-zero Sivers function implies non-zero orbital angular momentum
- correspondence between TMDs and GPDs: Sivers function and GPD E
- due to the final state interactions, Sivers effect generates left-right (azimuthal) asymmetries



Sivers amplitudes for pions

Phys. Rev. Lett. 103 (2009) 152002

$$2\langle\sin(\phi-\phi_s)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2)\otimes_w D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$



π^+

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- dominated by scattering off u-quark:

$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_w D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

- u-quark Sivers DF<0
- non-zero orbital angular momentum

π^0

- slightly positive

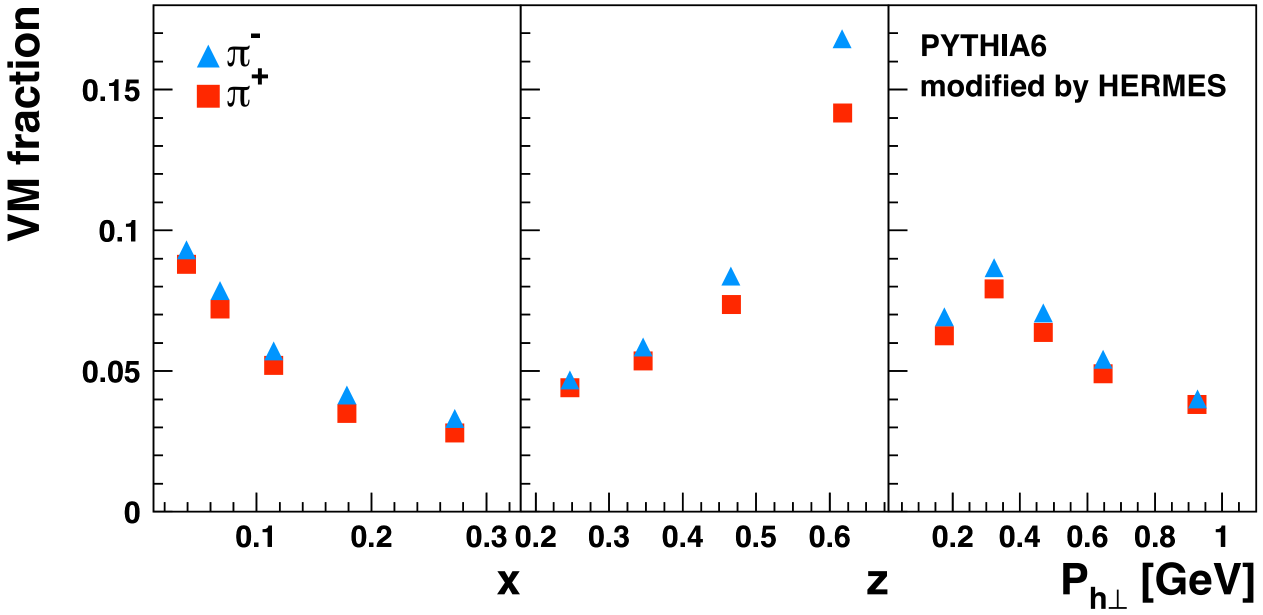
π^-

- consistent with 0
- u- and d-quark cancellation
- d-quark Sivers DF>0

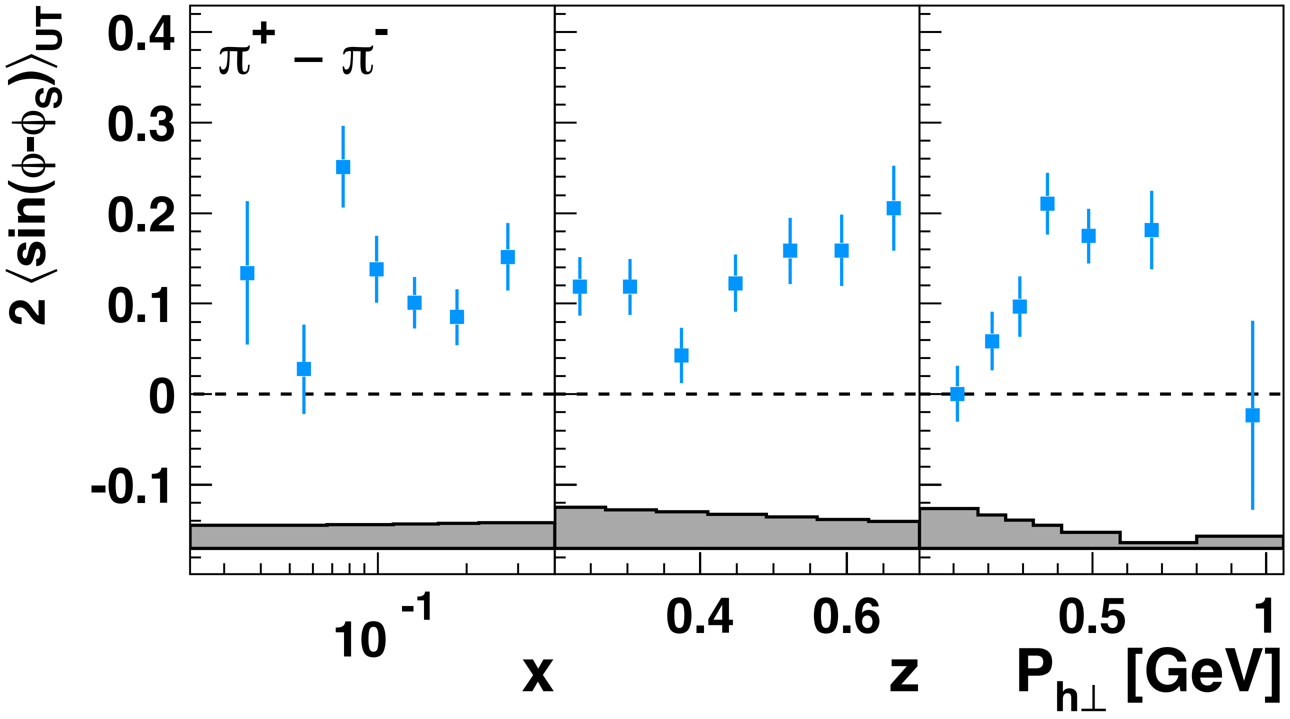
the pion difference asymmetry

$$A_{UT}^{\pi^+-\pi^-} = \frac{1}{\langle |S_T| \rangle} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}$$

☛ non-negligible contribution from exclusive ρ^0 largely cancels out



☛ significantly positive Sivers amplitudes



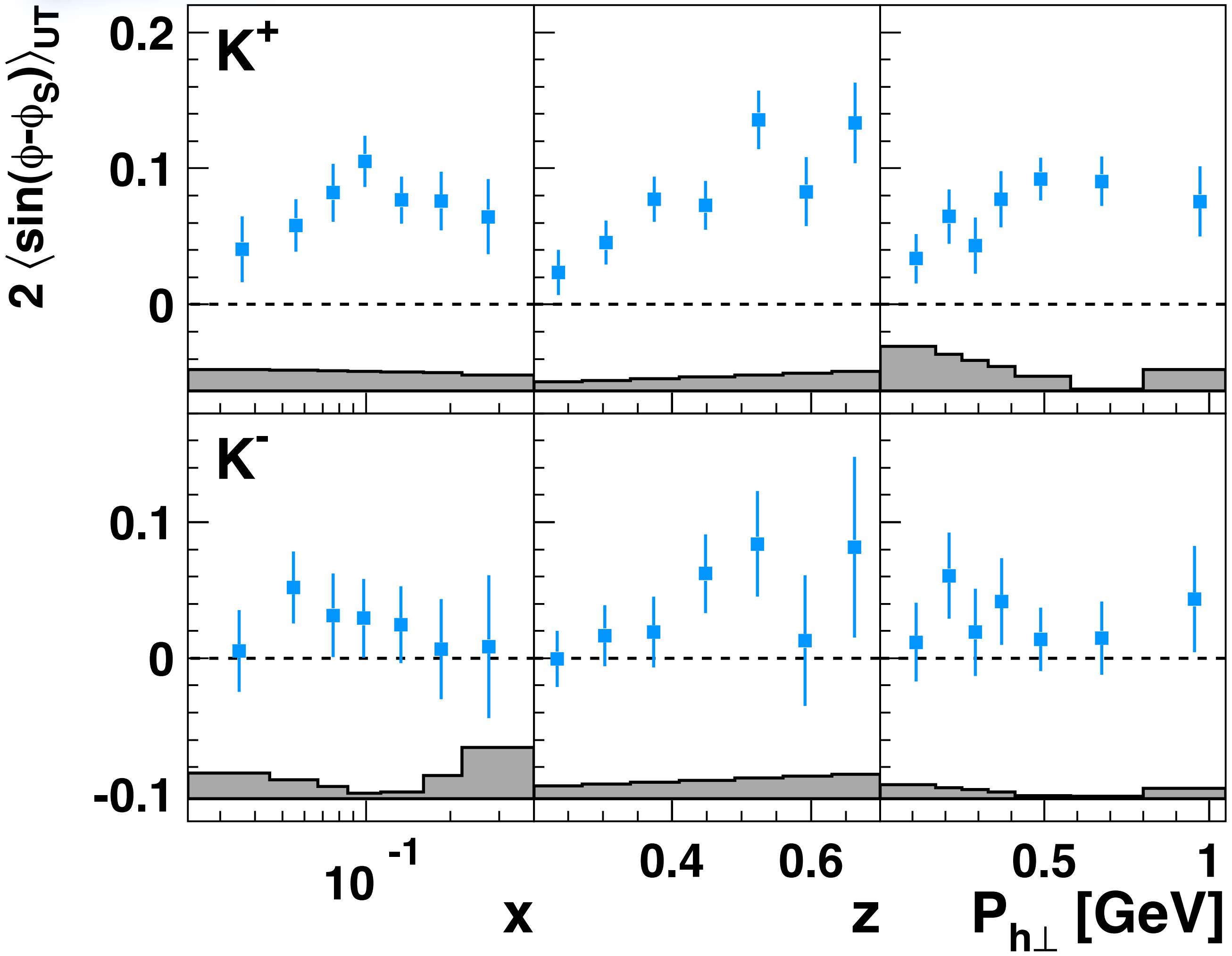
$$\langle \sin(\phi - \phi_\mathbf{s}) \rangle_{\mathbf{UT}}^{\pi^+-\pi^-} \simeq -\frac{\mathbf{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}}{\mathbf{4f_1^{u_v} - f_1^{d_v}}}$$

☛ provides access to Sivers u-valence distribution

☛ either $\mathbf{f_{1T}^{\perp,d_v}} \gg \mathbf{f_{1T}^{\perp,u_v}}$

☛ or $\mathbf{f_{1T}^{\perp,u_v}}$ is large and negative

Sivers amplitudes for kaons



K^+

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$

K^-

- slightly positive

Sivers amplitudes for kaons

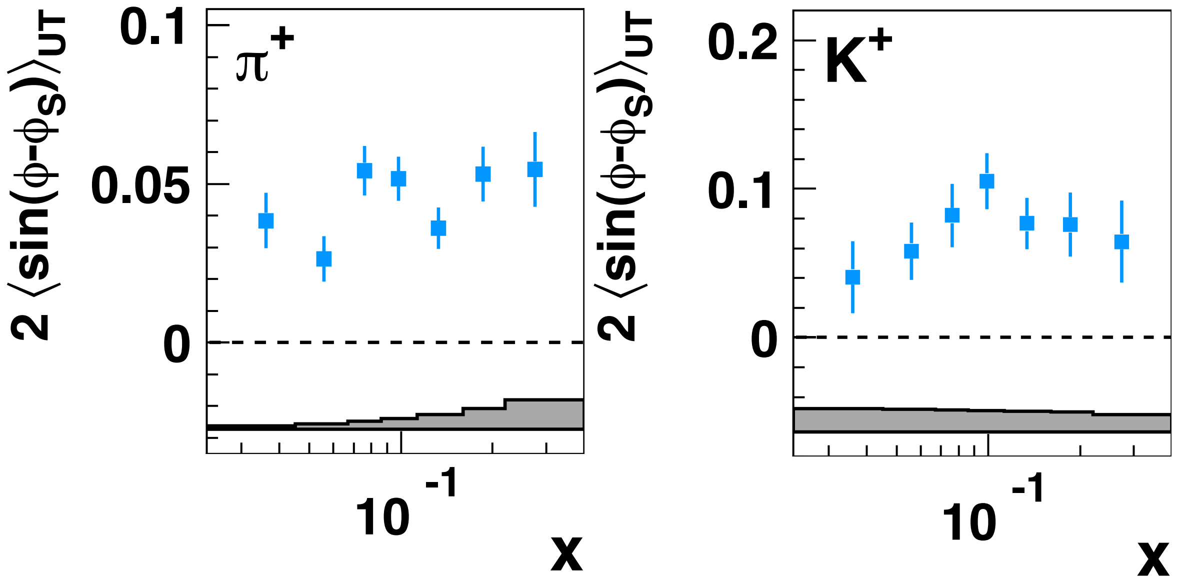
K^+

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$

K^-

- slightly positive

Sivers amplitudes for kaons



K^+

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$

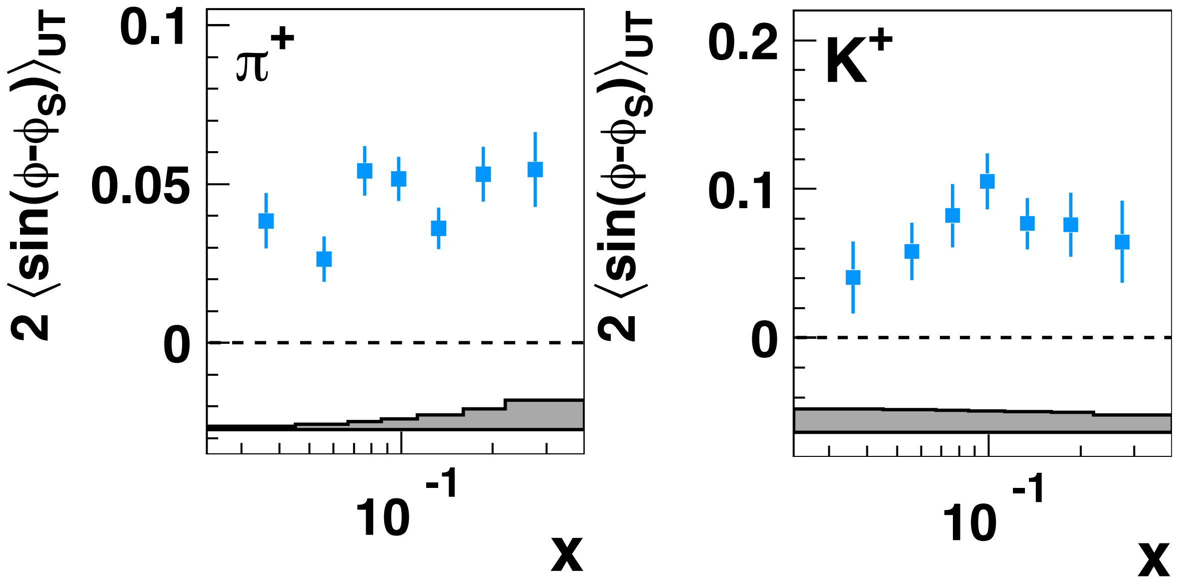
K^-

- slightly positive

- similar to π^+, K^+ dominated by scattering off u-quarks:

$$\propto -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_w D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+/K^+}(z,k_T^2)}$$

Sivers amplitudes for kaons



K^+

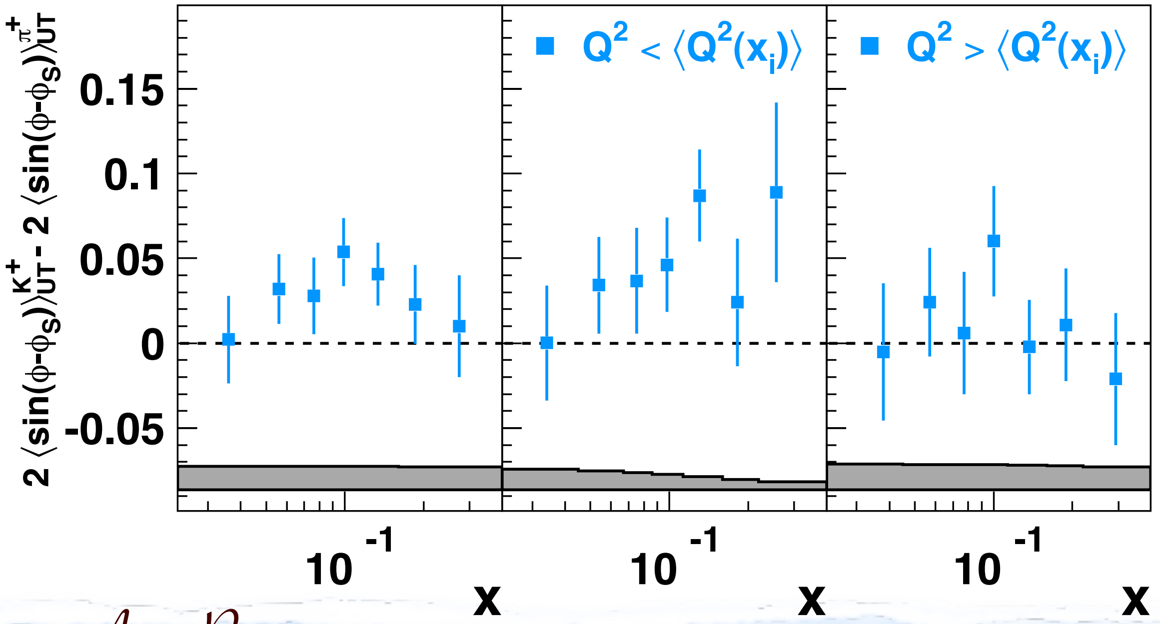
- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$

K^-

- slightly positive

- similar to **π⁺** , **K⁺** dominated by scattering off u-quarks:

$$\propto -\frac{\mathbf{f_{1T}^{\perp,u}(x,p_T^2)\otimes_w D_1^{u\to\pi^+/K^+}(z,k_T^2)}}{\mathbf{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+/K^+}(z,k_T^2)}}$$

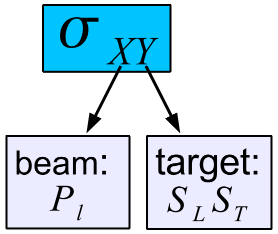


- **K⁺** amplitudes are larger in size than the **π⁺** amplitudes
  - non-trivial role of sea quarks

$$\pi^+ \equiv |\,\mathbf{u\bar{d}}\rangle \qquad \mathbf{K}^+ \equiv |\,\mathbf{u\bar{s}}\rangle$$

  - different **k**$_\mathrm{T}$ dependence of fragmentation functions
  - higher-twist effects

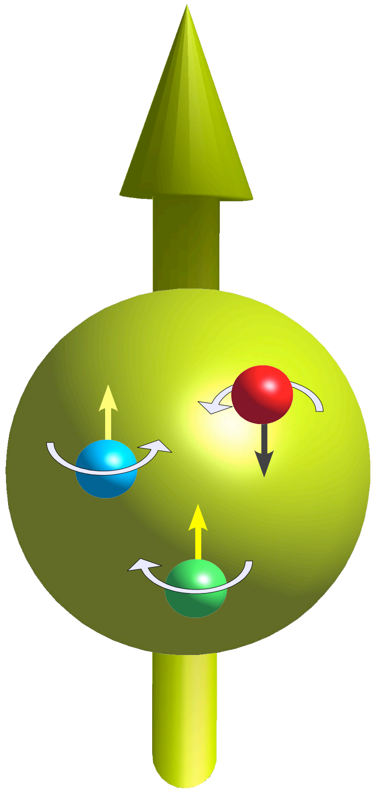
“Pretzelosity”


σ_{XY}

beam: P_l

target: $S_L S_T$

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



☛ “pretzelosity” DF $h_{1T}^{\perp,q}(x,p_T^2)$ gives a measure of the deviation of the nucleon shape from a sphere

☛ correlation between parton transverse momentum and parton transverse polarization in a transversely polarized nucleon

☛ it is expected to be suppressed at small and large x w.r.t. $\mathbf{f_1^q}$, $\mathbf{g_1^q}$, $\mathbf{h_1^q}$

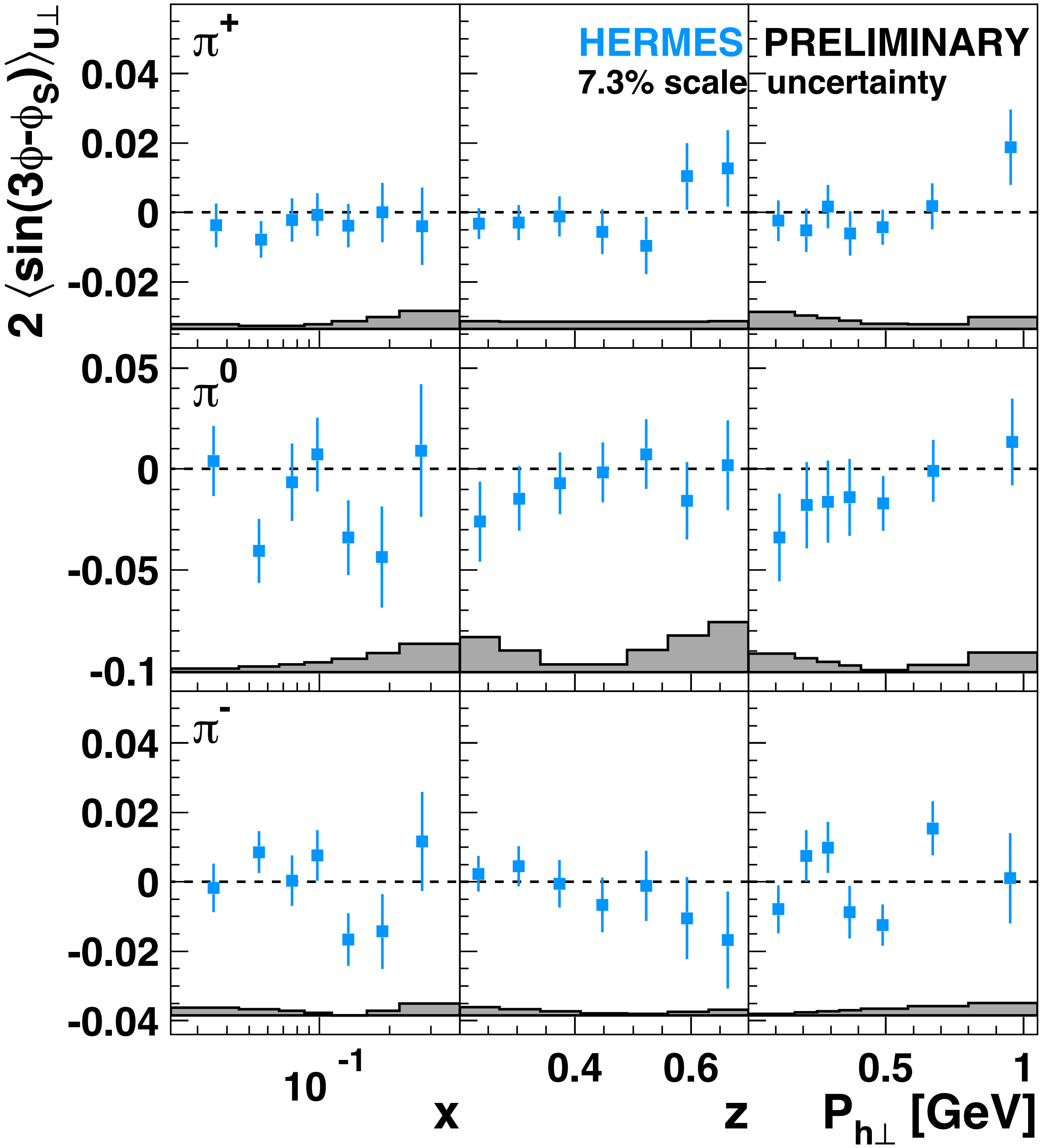
☛ satisfies the positivity condition: $h_{1T}^{\perp,q} \leq \frac{1}{2}(f_1^q + g_1^q)$

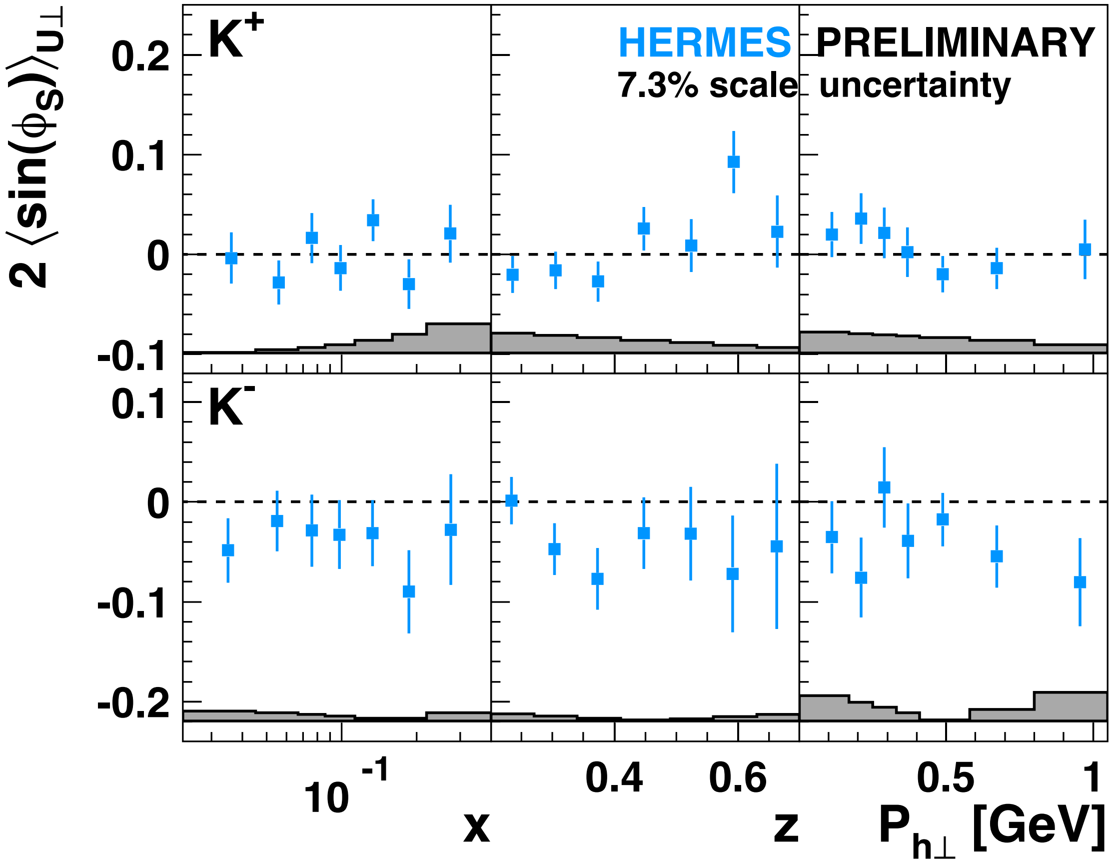
☛ envolve quark and nucleon helicity flips;
is related to chiral-odd GPD $\quad h_{1T}^{(0)\perp,q}(x,p_T^2) = \dfrac{3}{(1-x)^2}\widetilde{H}_T^q(x,0,0)$

☛ gives the measure of ‘relativistic effects’ in the nucleon: $\dfrac{p_T^2}{2M^2}h_{1T}^{\perp\,q}(x,p_T^2) = g_1^q(x,p_T^2) - h_1^q(x,p_T^2)$

$sin(3\phi - \phi_s)$ amplitudes

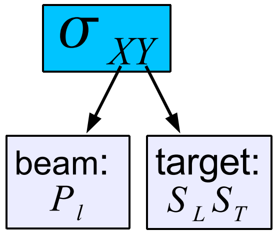
$$2\langle\sin(3\phi-\phi_s)\rangle_{UT} \propto \frac{\sum_q e_q^2\, x\, h_{1T}^{\perp(1),q}(x) \otimes_w H_1^{\perp\,(1/2)\,q}(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$





- ☛ suppressed by two powers of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- ☛ compatible with zero within uncertainties
- ☛ pretzelosity might be non-zero at higher $P_{h\perp}$

“worm-gear”


σ_{XY}

beam: P_l

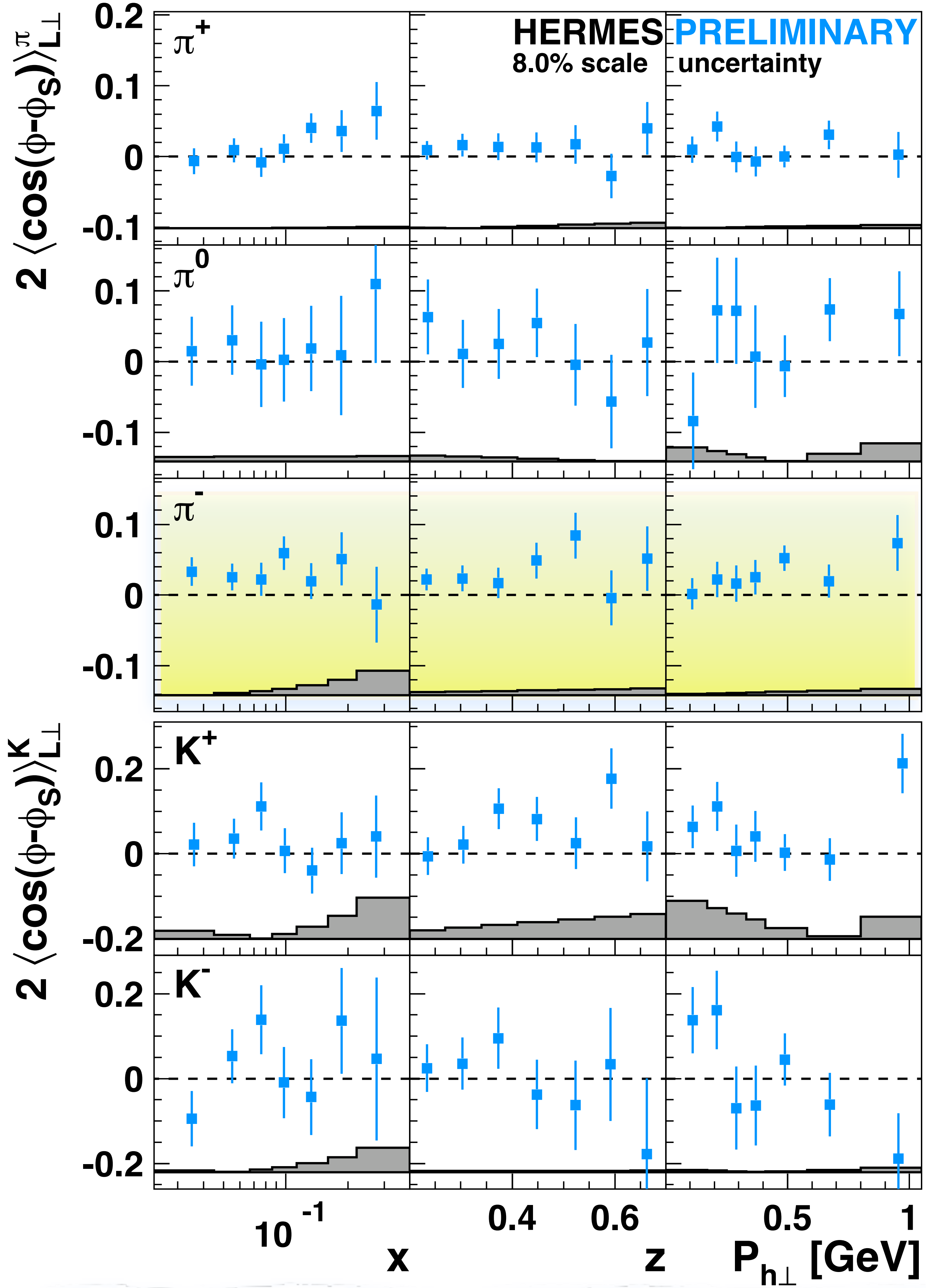
target: $S_L S_T$

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

- worm-gear DF $g^q_{1T}(x,p^2_T)$ and $h^{\perp,\,q}_{1L}(x,p^2_T)$ describes the probability to find a longitudinal/transverse polarized quark in a transversely/longitudinally polarized nucleon
- on a transversely target $h^{\perp,\,q}_{1L}(x,p^2_T)$ accessible in the measurements through $\sin(2\phi+\phi_s)$ Fourier component
- gives correlation between parton transverse momentum and parton longitudinal / transverse polarization in a longitudinal / transversely polarized nucleon
- model dependent relations:

$$h^{\perp,\,q}_{1L}(x,p^2_T) = -g^{\perp,\,q}_{1T}(x,p^2_T)$$

$$
\begin{aligned}
g^{\perp,q}_{1T}(x,p^2_T) &\approx x\int_x^1 \frac{1}{y}\, g^q_1(y,p^2_T)dy \\
h^{\perp,q}_{1L}(x,p^2_T) &\approx -x\int_x^1 \frac{1}{y}\, h^q_1(y,p^2_T)dy
\end{aligned}
$$



the cos(φ - φ$_s$) amplitudes

$$2\langle\cos(\phi-\phi_s)\rangle_{LT} \quad \propto \quad \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{p}_{\mathrm{T}}}{M_h}\, g_{1T}^{\perp,q}(x,p_{\mathrm{T}}^2)D_1^q(z,k_{\mathrm{T}}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_{\mathrm{T}}^2)D_1^q(z,k_{\mathrm{T}}^2)\right]}$$

☛ uncertainties are larger than in single-spin asymmetries scaled by the beam polarization value

π^+

☛ slightly positive

π^0

☛ compatible with zero

π^-

☛ positive

☛ evidence for non-zero worm-gear distribution

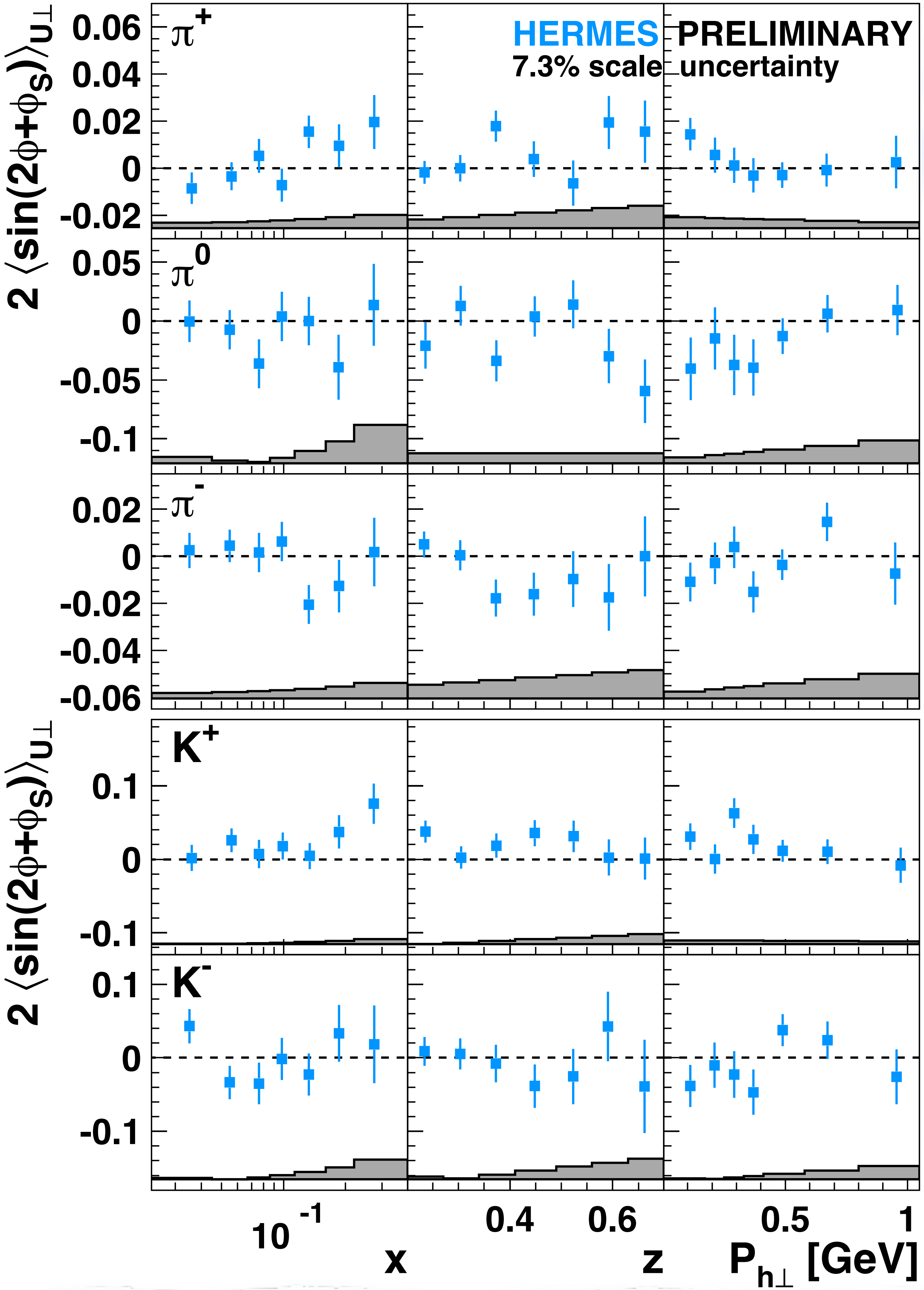
K^+

☛ slightly positive

K^-

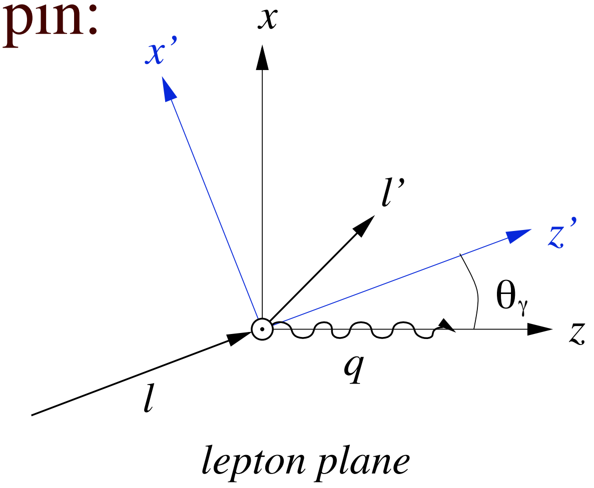
☛ compatible with zero

subleading-twist amplitudes



the subleading-twist $\sin(2\phi+\phi_S)$ amplitudes

- arises solely from longitudinal component of the target spin:

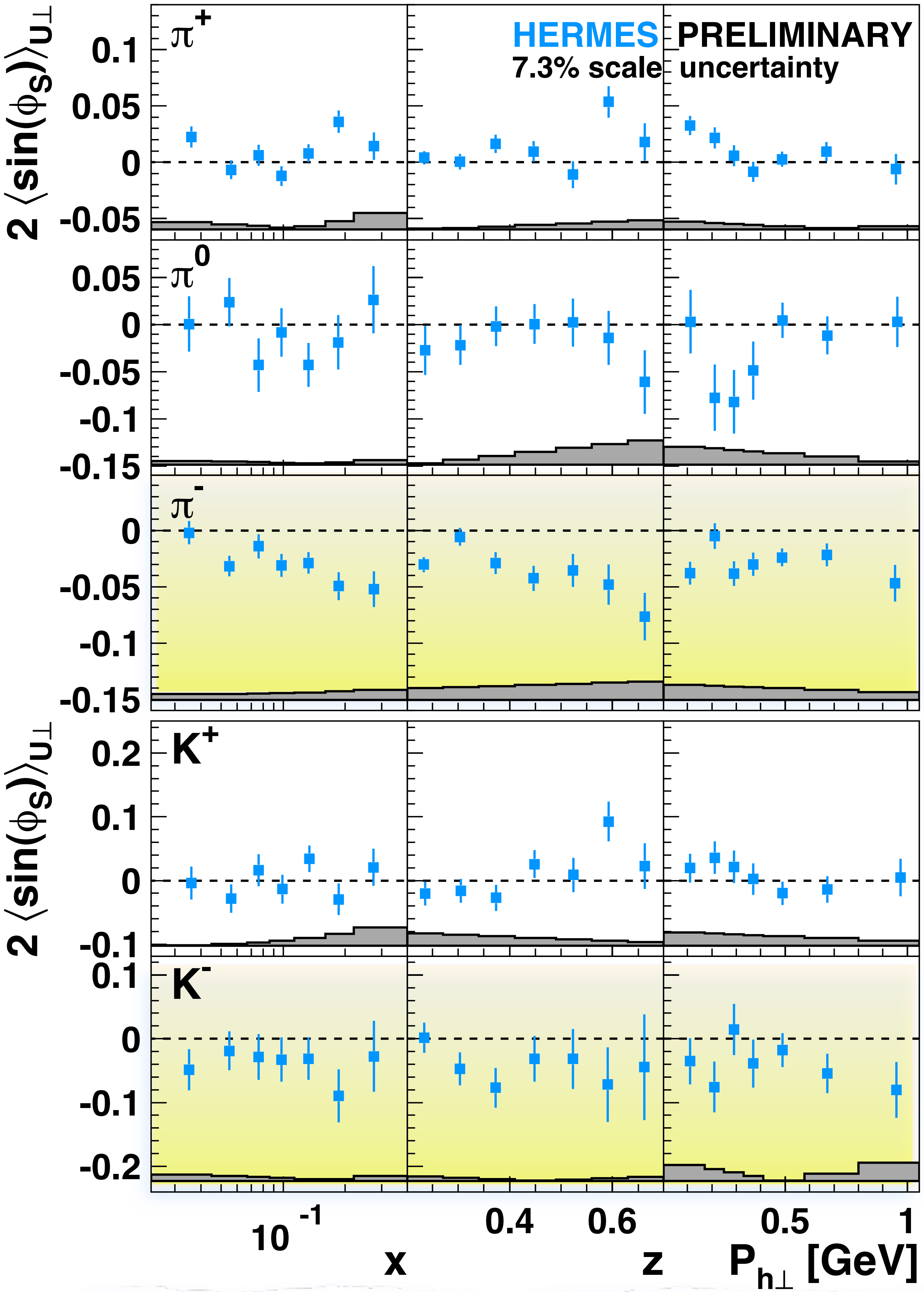


$$P_T A_{U\perp}(\phi,\phi_s) = S_T A_{UT}(\phi,\phi_s) + S_L A_{UL}$$

- longitudinal component of the target spin <15\%
- expected to scale as $\sin\theta_{\gamma^*}\langle\sin(2\phi)_{UL}\rangle$
- related to worm-gear DF $h_{1L}^{\perp,q}$
- $\sin(2\phi+\phi_s)$ amplitude is suppressed by one powers of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- compatible with zero within uncertainties except maybe K^+

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

the subleading-twist $\sin \boldsymbol{\phi}_s$ amplitudes



- survive the integration over $P_{h\perp}$

$$F_{UT}^{\sin\phi_S}(x,z,Q^2) = -x \sum_a e_a^2 \, \frac{2M_h}{Q} \, h_1^a(x) \, \frac{\tilde{H}^a(z)}{z}$$

- in one-photon approximation

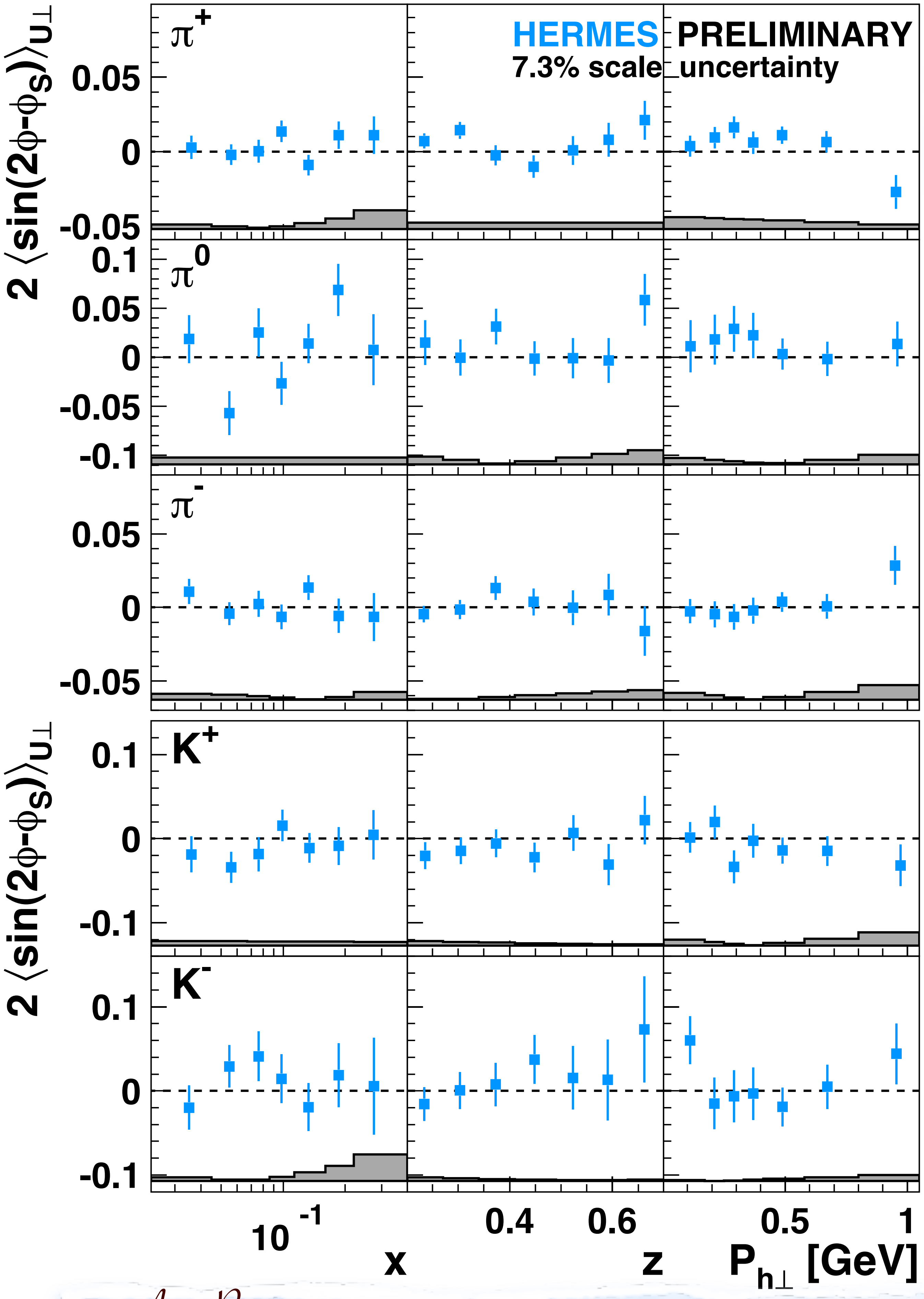
$$\sum_z \int dz \, z \, F_{UT}^{\sin\phi_s}(x,z,Q^2) = 0$$

- receives various contributions

$$\propto \quad x f_T D_1 - \tfrac{M_h}{M} h_1 \frac{\widetilde{H}}{z}$$

$$-W_1(p_T,k_T) \left(\quad x h_T H_1^\perp + \tfrac{M_h}{M} g_{1T} \frac{\widetilde{G}^\perp}{z} \quad - \quad x h_T^\perp H_1^\perp + \tfrac{M_h}{M} f_{1T}^\perp \frac{\widetilde{D}^\perp}{z} \right)$$

- non-zero signal observed for π^- and K^-



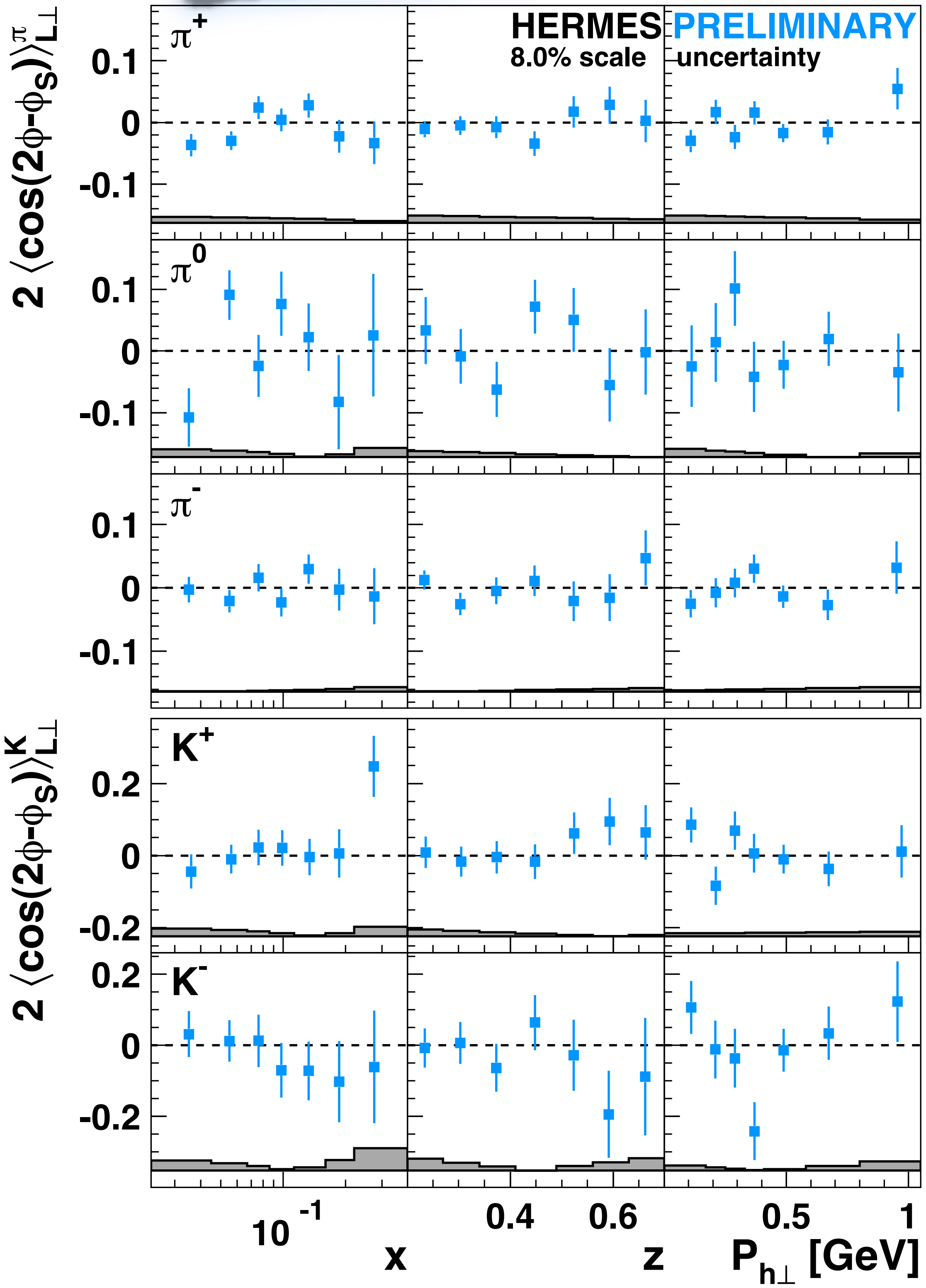
the subleading-twist $\sin(2\phi-\phi_s)$ amplitudes

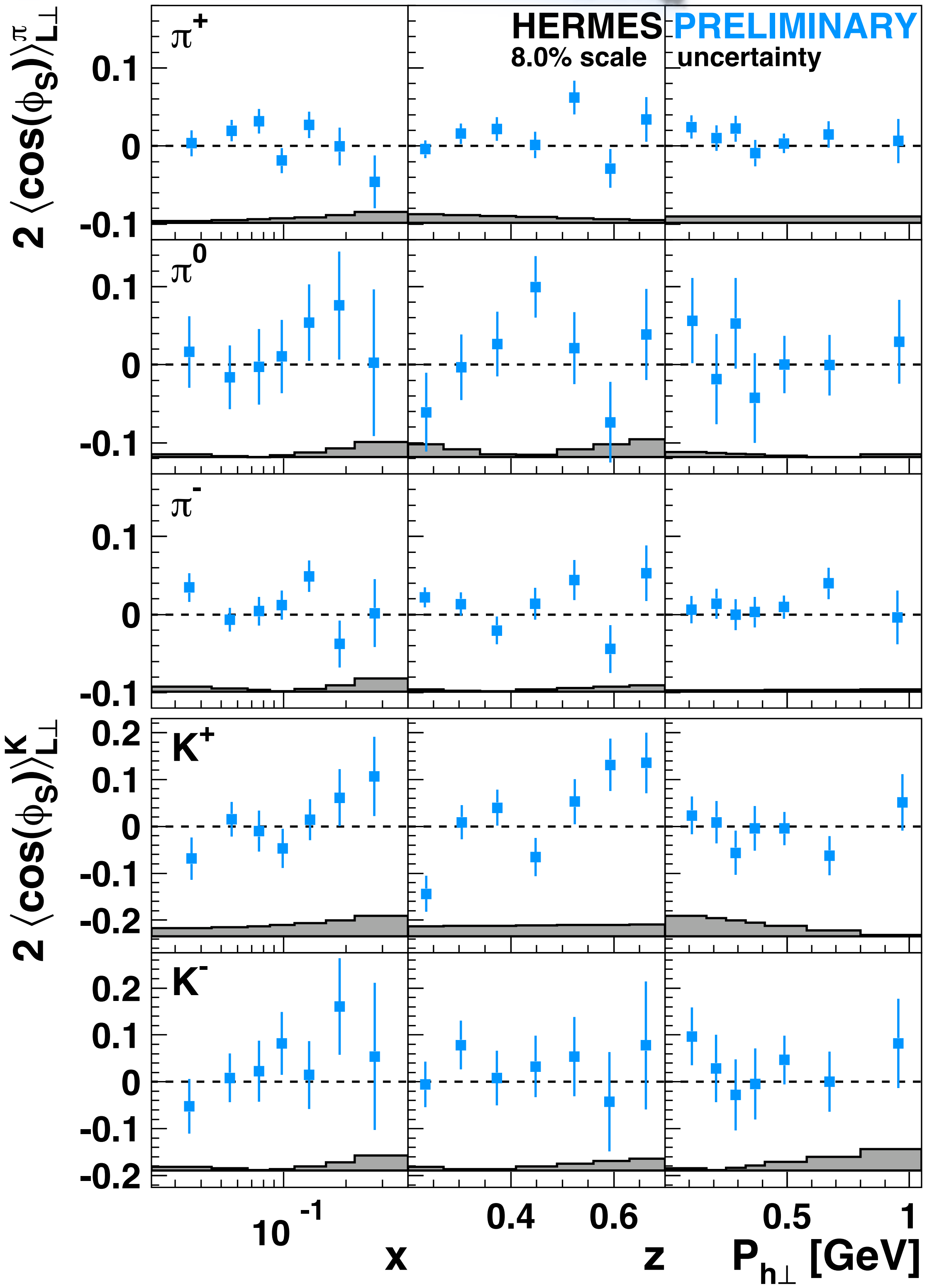
$$\propto W_1(p_T,k_T,P_{h\perp})\left(xf_T^\perp D_1-\frac{M_h}{M}h_{1T}^\perp\frac{\widetilde{H}}{z}\right)$$

$$-W_2(p_T,k_T,P_{h\perp})\left(xh_TH_1^\perp+\frac{M_h}{M}g_{1T}\frac{\widetilde{G}^\perp}{z}+xh_T^\perp H_1^\perp-\frac{M_h}{M}f_{1T}^\perp\frac{\widetilde{D}^\perp}{z}\right)$$

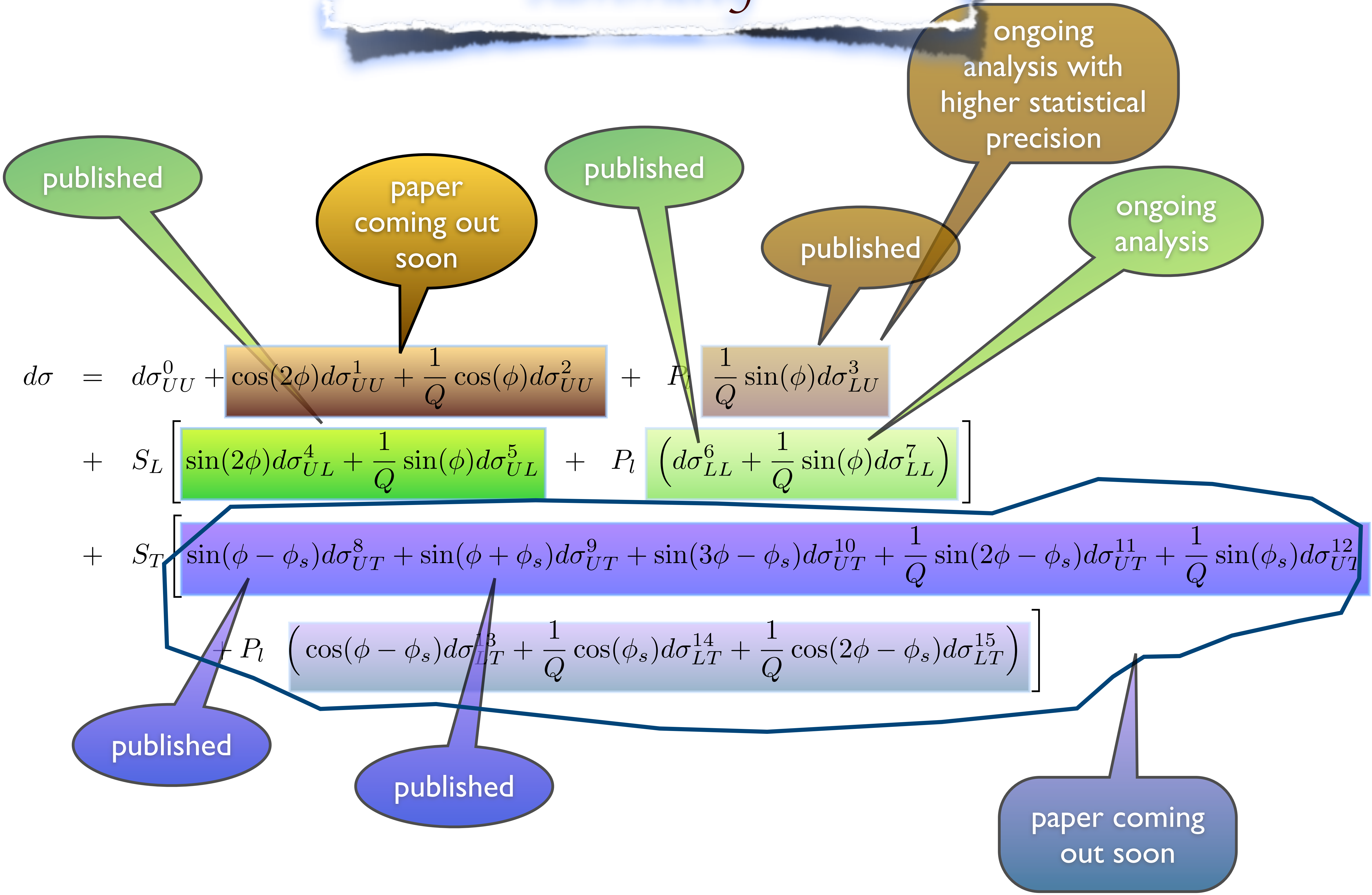
- ☛ suppressed by two power of $P_{h\perp}$ and an additional factor 2M/Q compared to Collins and Sivers amplitudes
- ☛ compatible with zero within uncertainties

compatible with zero subleading-twist $\cos\phi_s$ and $\cos(2\phi - \phi_s)$ amplitudes





summary

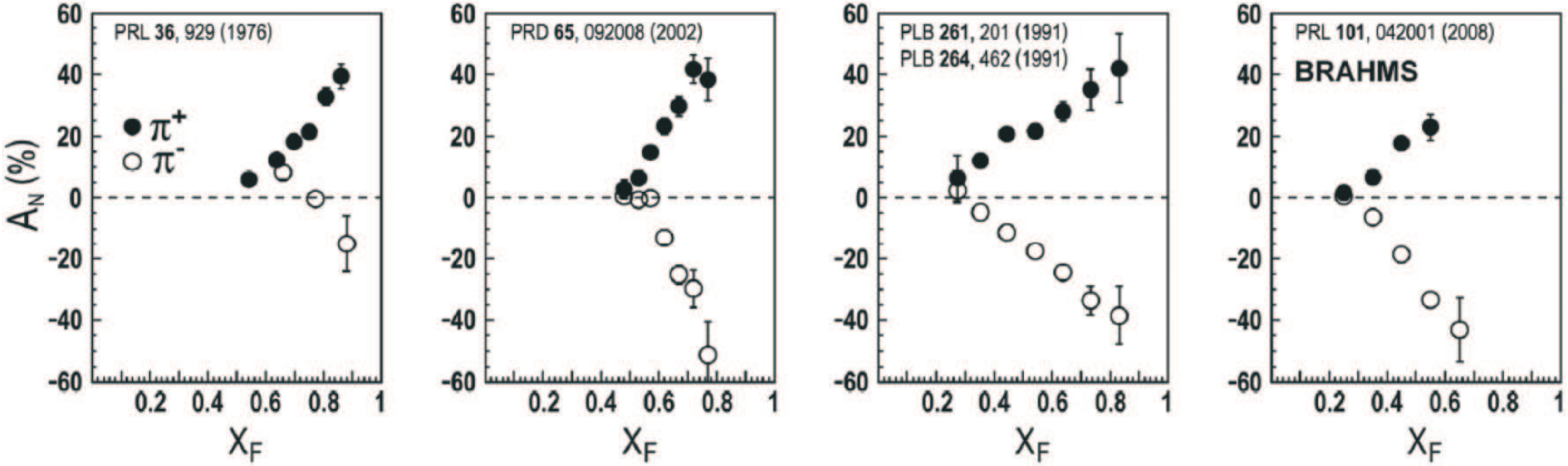


$$
\begin{aligned}
d\sigma \;=\; & d\sigma^0_{UU} + \cos(2\phi) d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi) d\sigma^2_{UU} \;+\; P_l \frac{1}{Q}\sin(\phi) d\sigma^3_{LU} \\
+ \; & S_L \left[\sin(2\phi) d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi) d\sigma^5_{UL} \;+\; P_l \left(d\sigma^6_{LL} + \frac{1}{Q}\sin(\phi)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

TSA in inclusive hadron production in $p^{\uparrow}p$

measurements of $A_N = \frac{N_R - N_L}{N_R + N_L}$ in $p^{\uparrow}p \to \pi X$

	ANL (1976)	BNL (2002)	FNAL (1991)	RHIC (2008)
$\sqrt{s} =$	4.9 GeV	6.6 GeV	19.4 GeV	62.4 GeV



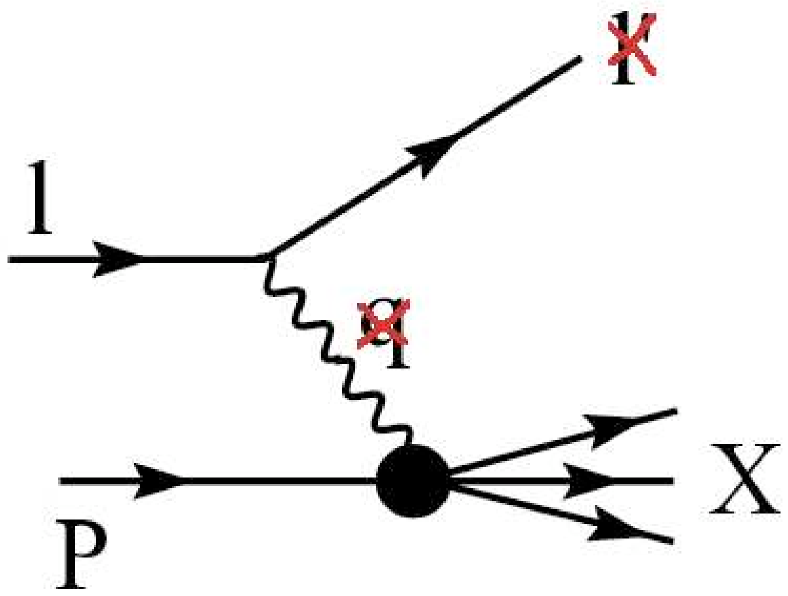
interpretations:

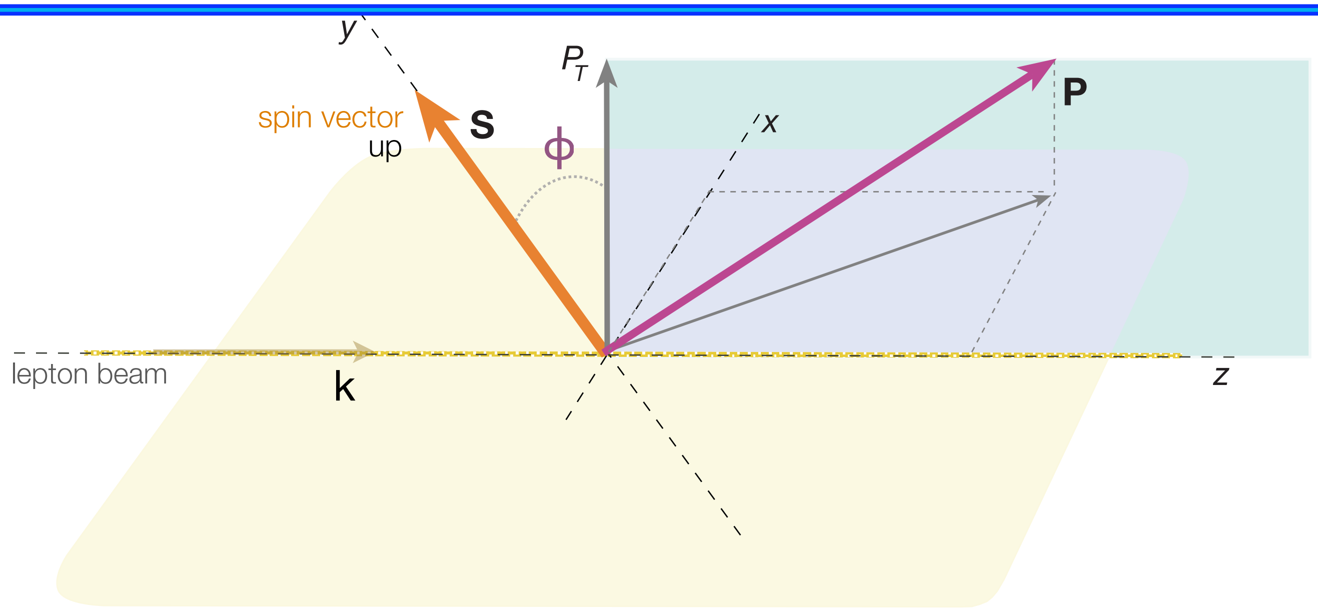
- TMDs (Sivers effect)
- twist-3 qg correlators

suggest:

- increase of A_N with increase of x_F
- decrease of A_N with increase of p_T at fixed x_F
- $A_N \to 0$ at high p_T

inclusive hadron production





spin dependent part of the cross section

$$\sigma = \sigma_{UU} + \sigma_{UT}$$

$$\propto \vec{S} \cdot (\vec{k} \times \vec{P}) \sim \sin\phi$$

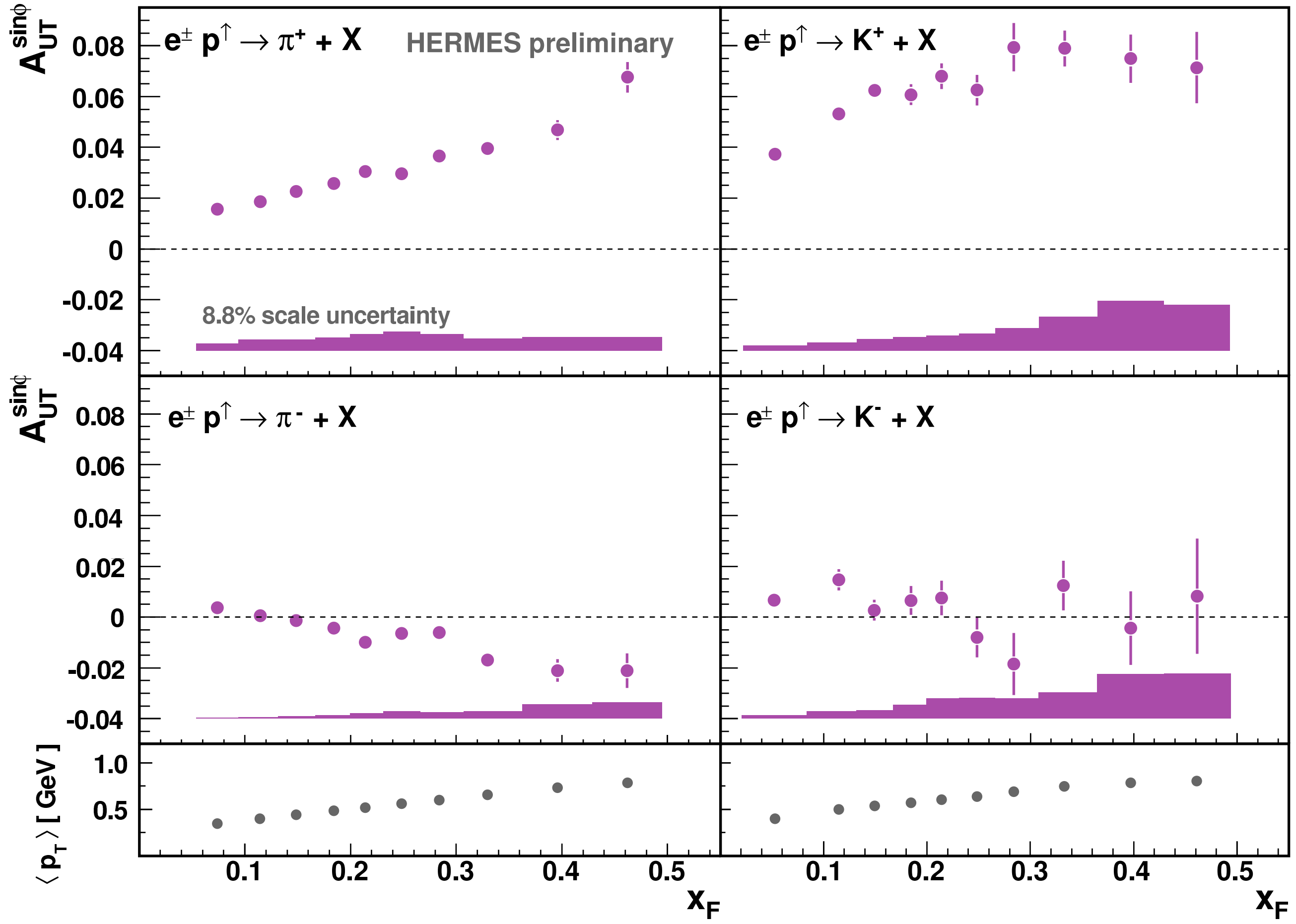
no scattered lepton detection

- DIS variables: Q^2, x
- inclusive hadron production: x_F, P_T

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = A_{UT}^{\sin\phi} \sin\phi$$

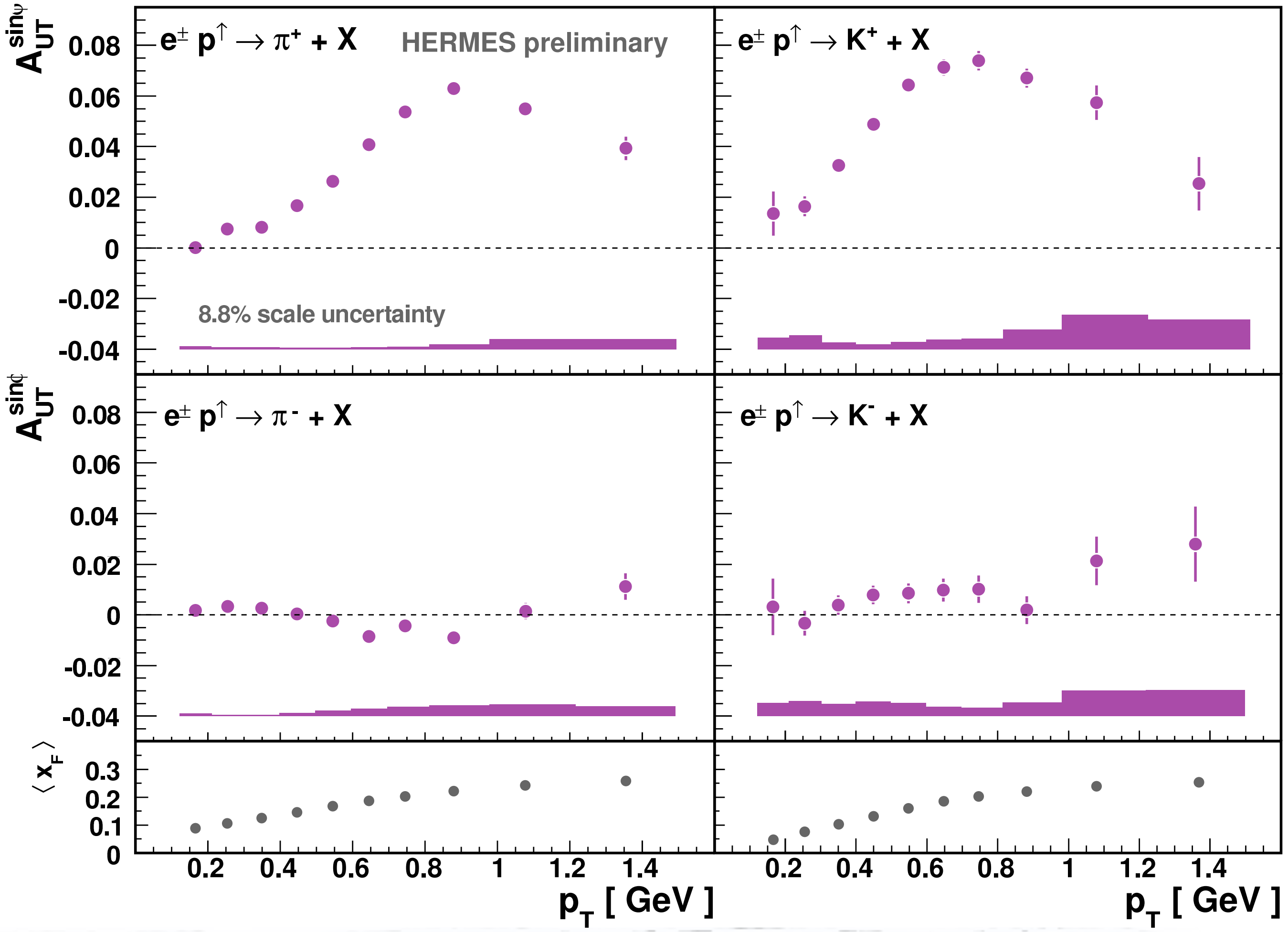
$$A_N = \frac{\int d\phi \, \sigma_{UT} \, \sin\phi}{\int d\phi \, \sigma_{UU}} = -\frac{2}{\pi} A_{UT}^{\sin\phi}$$

$A_{UT}^{\sin\phi}$ % p_T & x_F



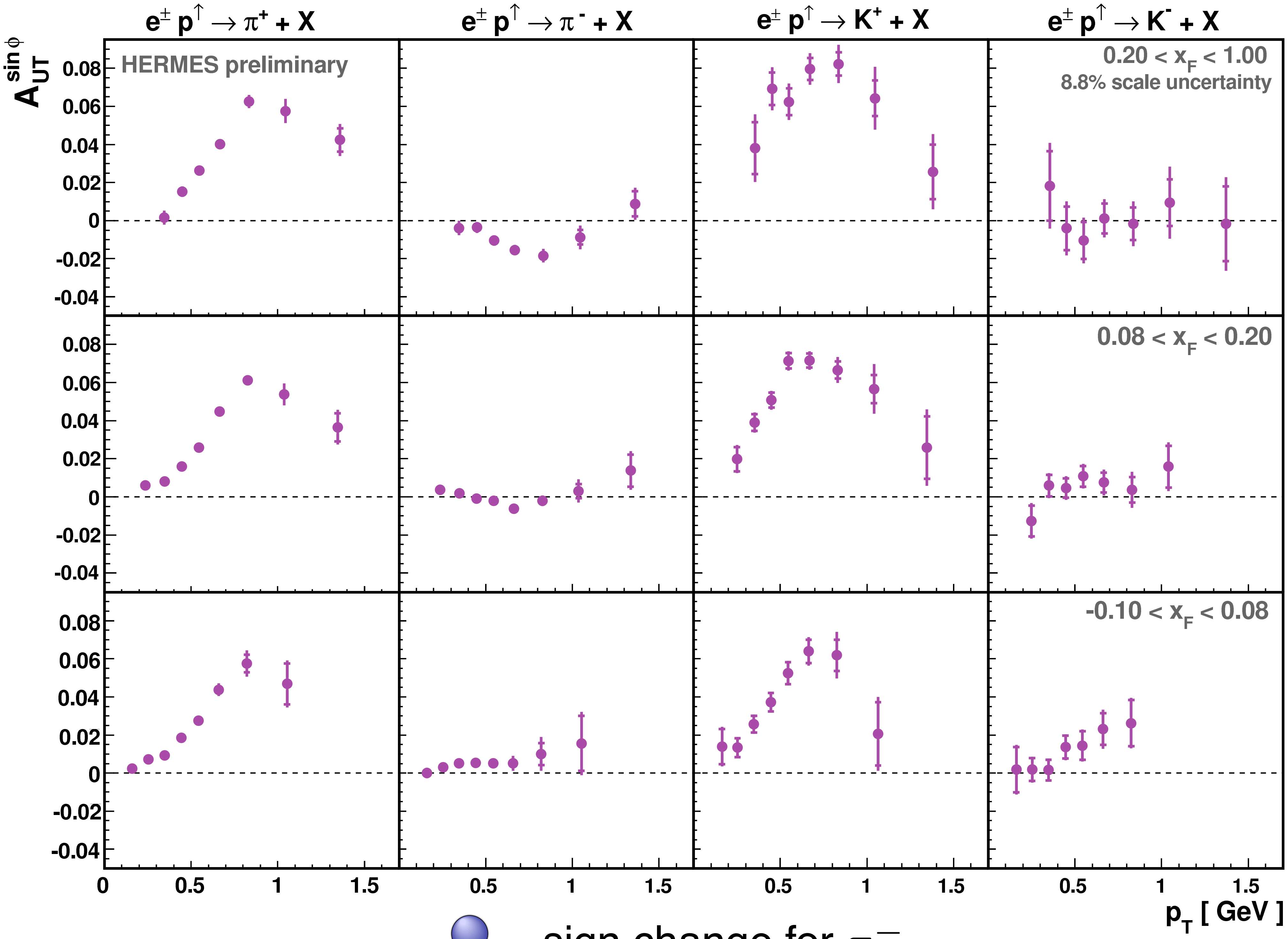
- π^+, K^+:
  positive
- π^-:
  slightly negative
- K^-:
  compatible with zero

π^+ and K^+ asymmetries decrease at high P_T



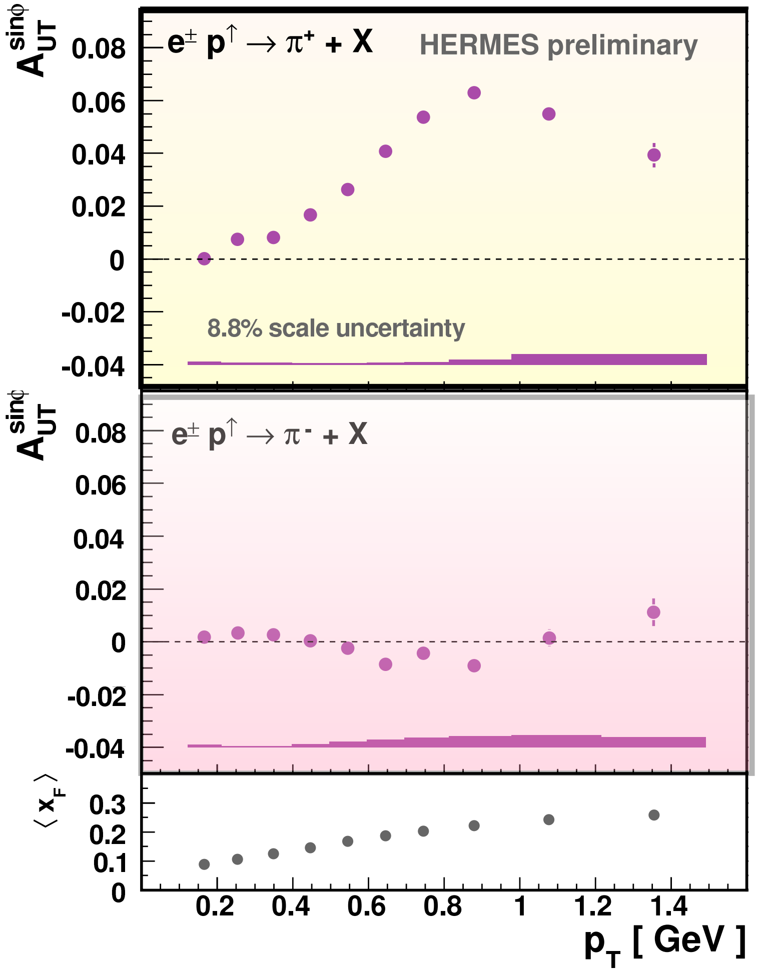
- π^+, K^+:
  positive
- π^-, K^-:
  compatible with zero

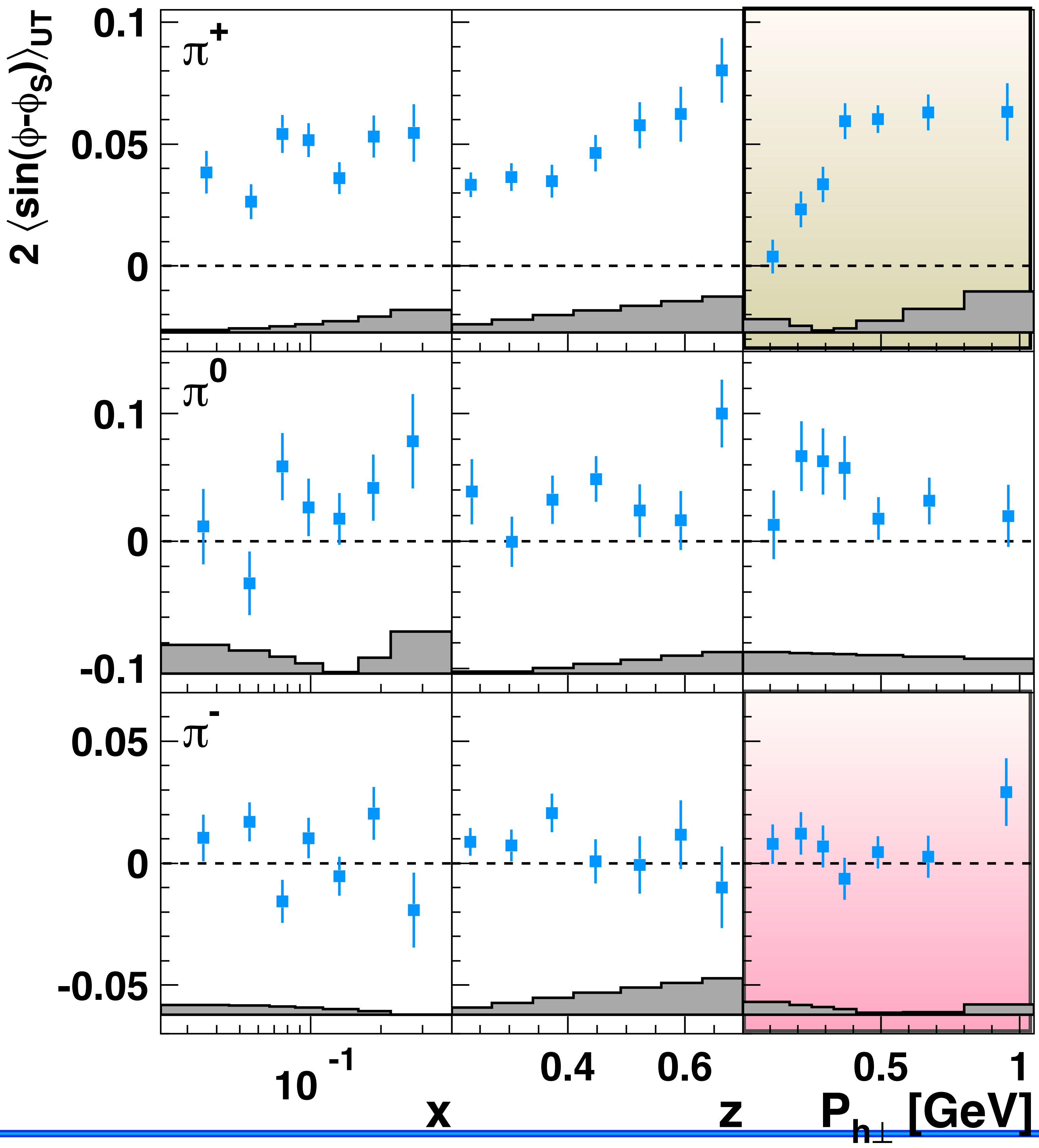
$A_{UT}^{\sin\phi}$ % p_T & $\mathrm{x_F}$



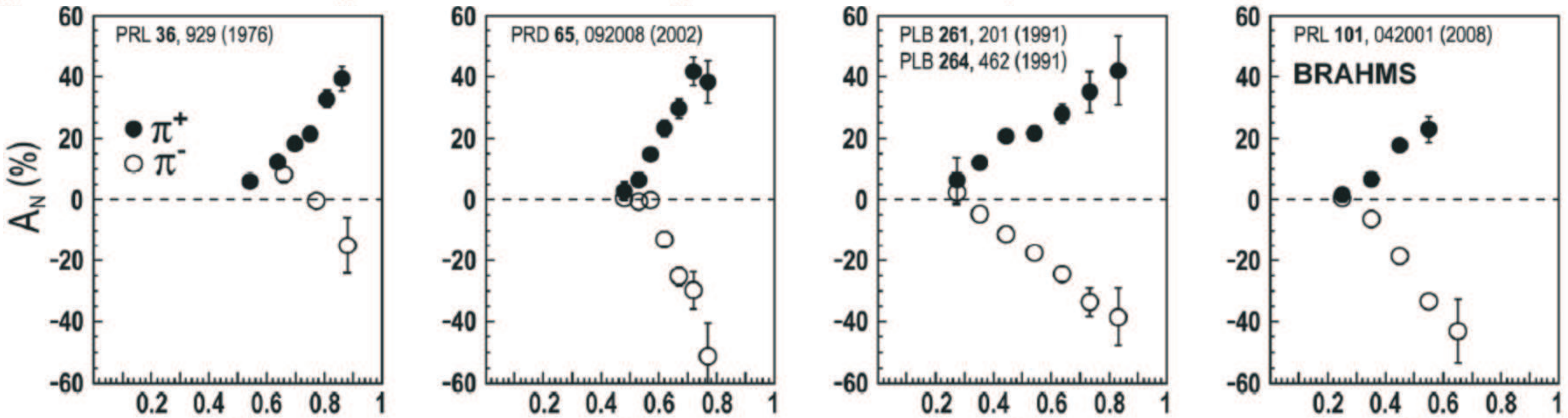
- sign change for π^-
- positive K^- for $\mathrm{x_F} \approxeq 0$

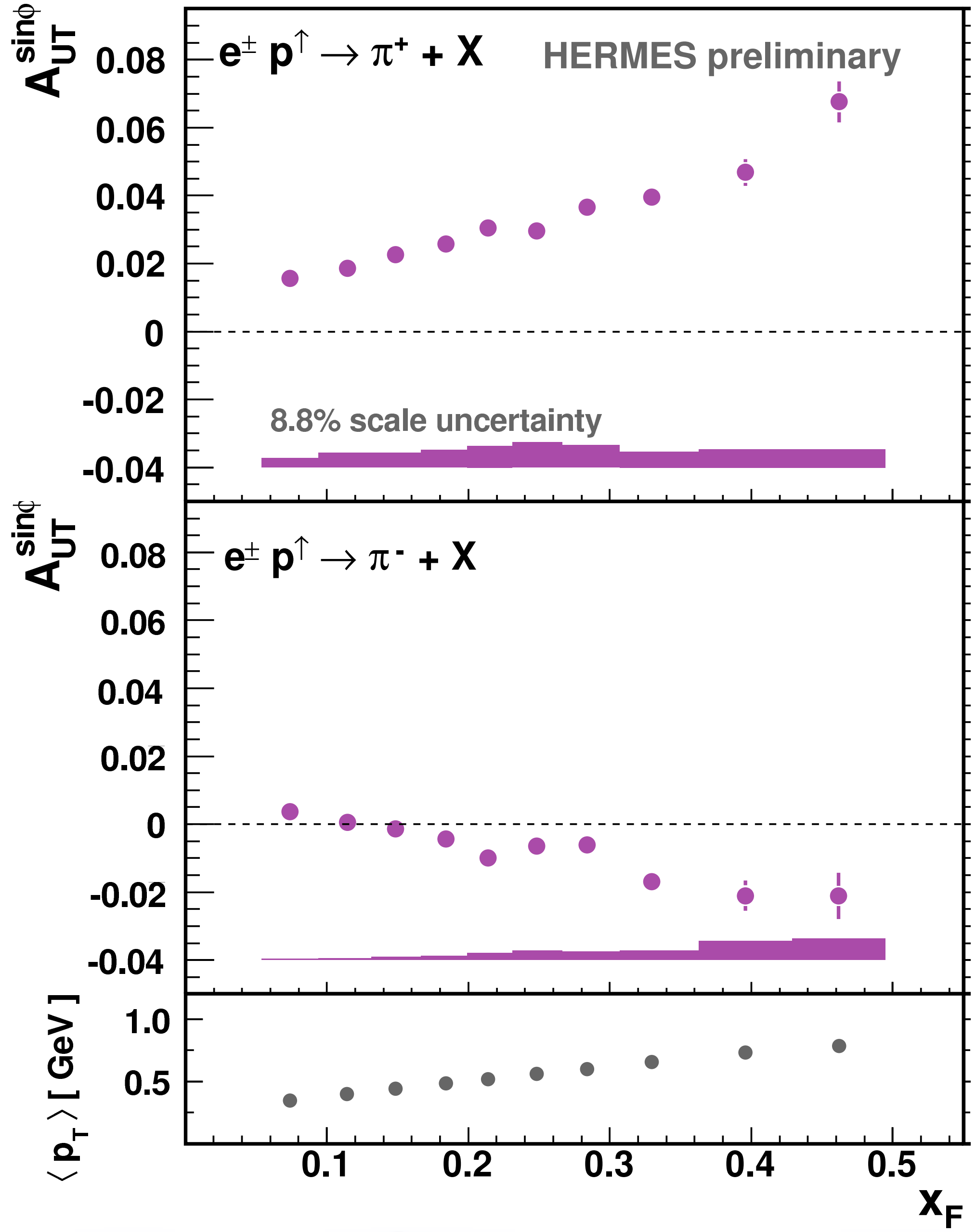
comparison to SIDIS measurements





comparison to previous measurements



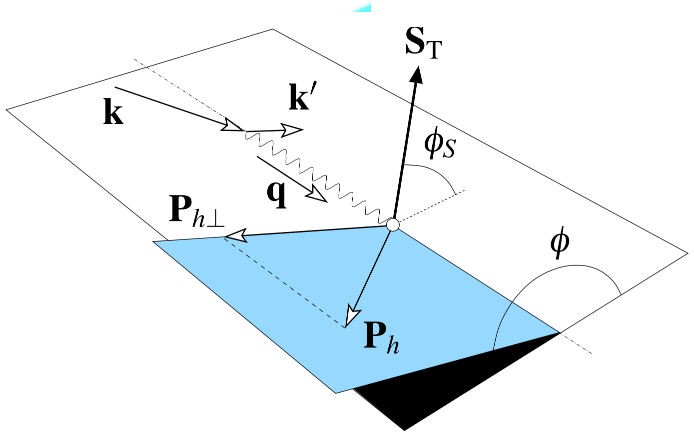


u-quark dominance in $ep^{\uparrow}$ may explain the smaller size of π^{-} asymmetry

A_{UT}^{1h}

A_{LL}

A_N



TMD

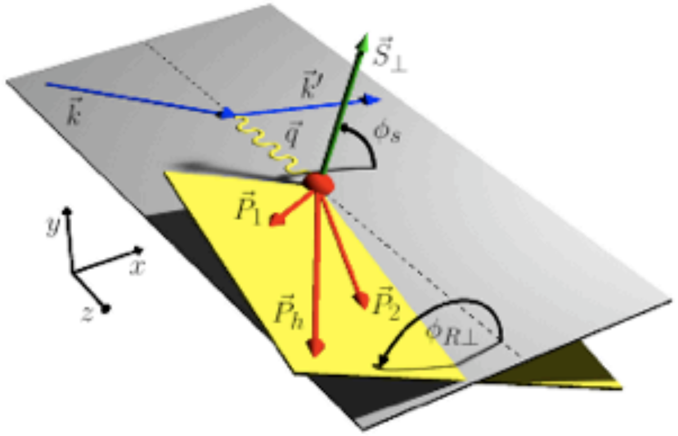
A_{LU}

A_{UU}

A_{LT}

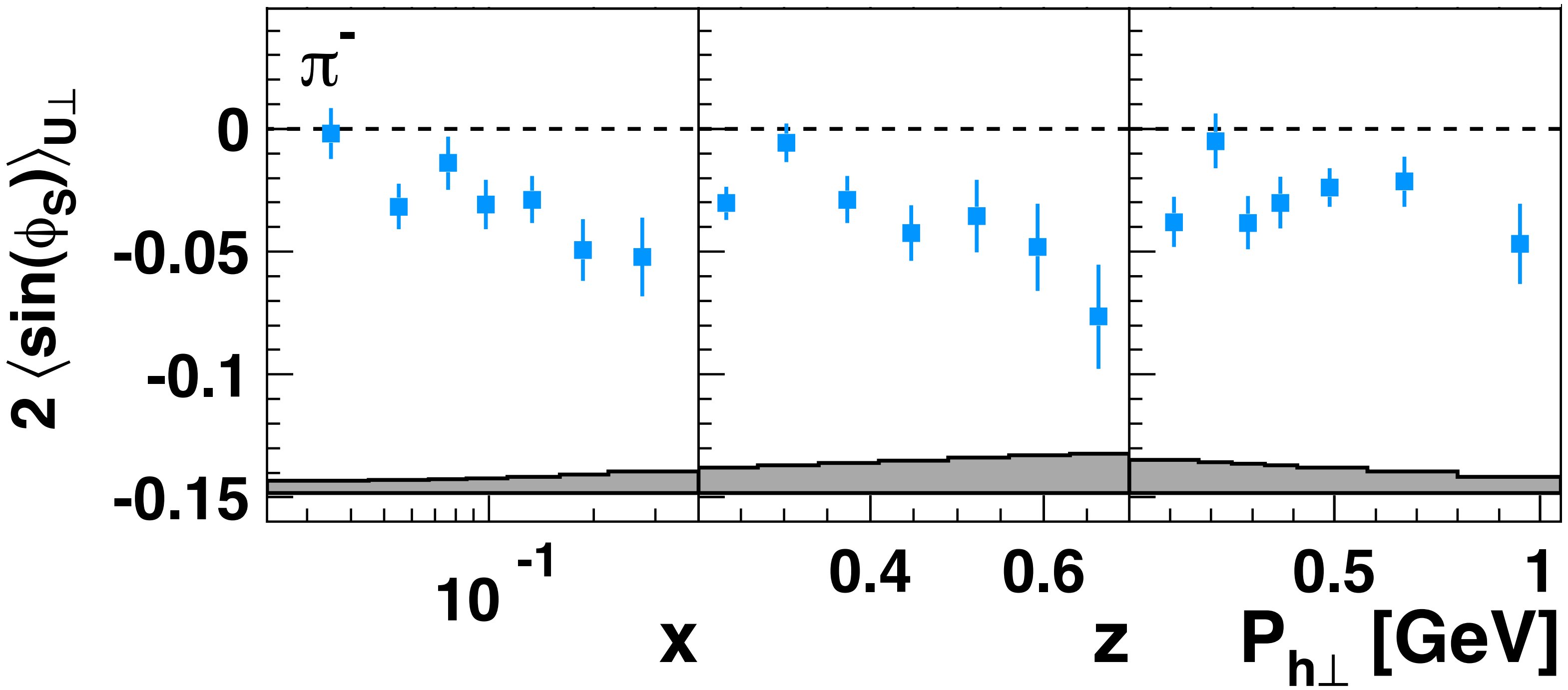
A_{UL}

A_{UT}^{2h}



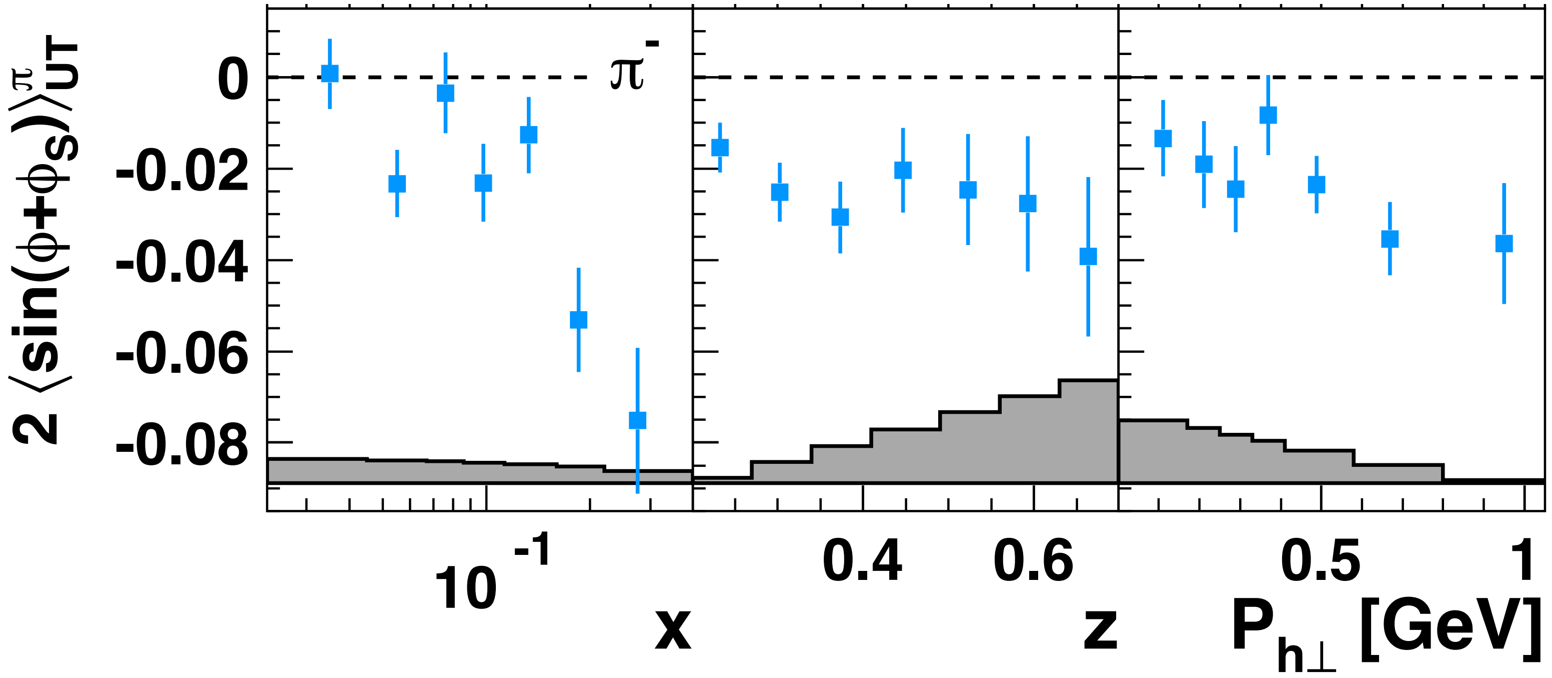
backup slides

the subleading-twist sin ϕ_s amplitudes



π^- sin ϕ_s amplitude and Collins amplitude

☛ similarities in size and the shape



☛ might be due to correlations between amplitudes

☛ might be explained also by physics