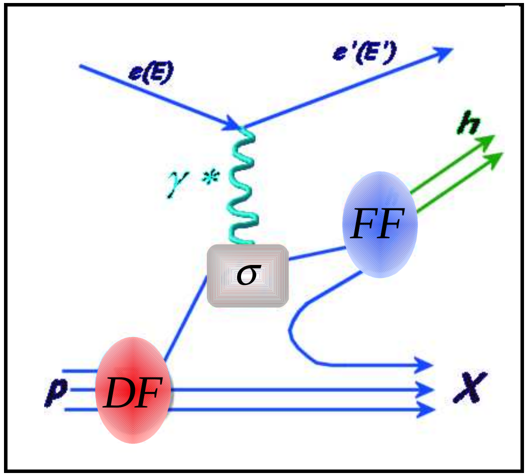
TMDs at HERMES

Workshop on TMDs
Trento, Italy, 2010

Ami Rostomyan

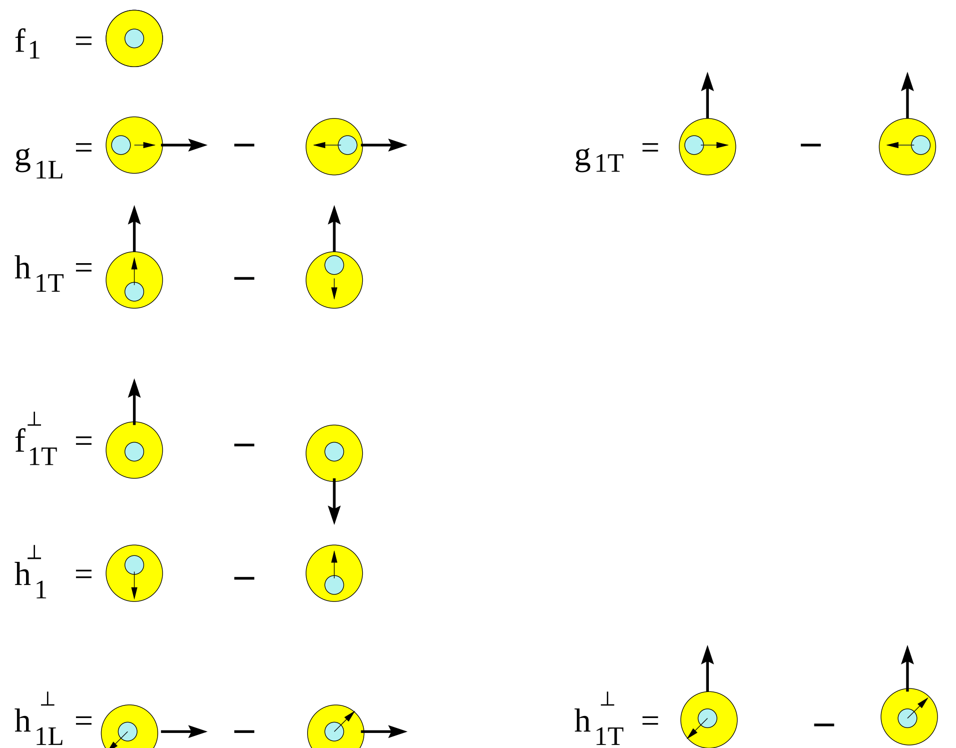
(on behalf of the HERMES collaboration)

quark structure of the nucleon

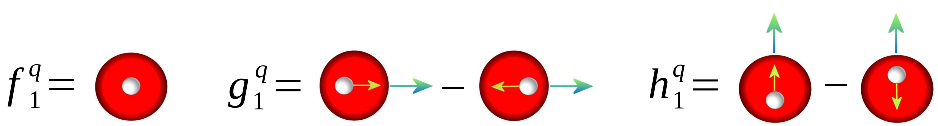


$$\sigma^{ep\to ehX} \propto \sum_q DF(x) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z)$$

transverse-momentum-dependent distribution functions



at leading-twist

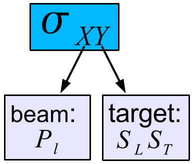


unpolarized quarks and nucleons

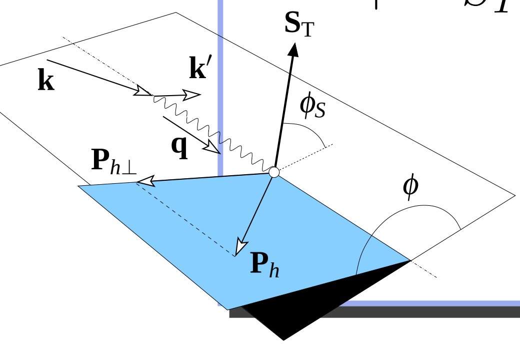
longitudinally polarized quarks and nucleons

transversely polarized quarks and nucleons

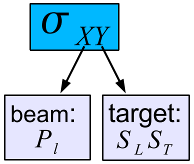
1-hadron production x-section $(ep \to ehX)$



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



1-hadron production x-section $(ep \longrightarrow ehX)$



$$
\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}\sin(\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]
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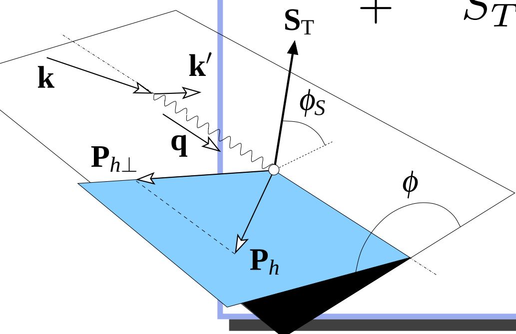


disentangling the contributions:

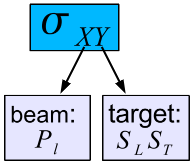
- experiments with beam and target polarization states (U, L, T)
- fit the cross section asymmetry for opposite spin states

$$A_{UT}(\phi,\phi_s) \;=\; \frac{1}{\langle |S_T| \rangle} \frac{\sigma^{\uparrow}(\phi,\phi_s) - \sigma^{\downarrow}(\phi,\phi_s)}{\sigma^{\uparrow}(\phi,\phi_s) + \sigma^{\downarrow}(\phi,\phi_s)}$$

- extract the relevant Fourier amplitudes based on their azimuthal dependences

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

“Boer-Mulders” and “Cahn” effects



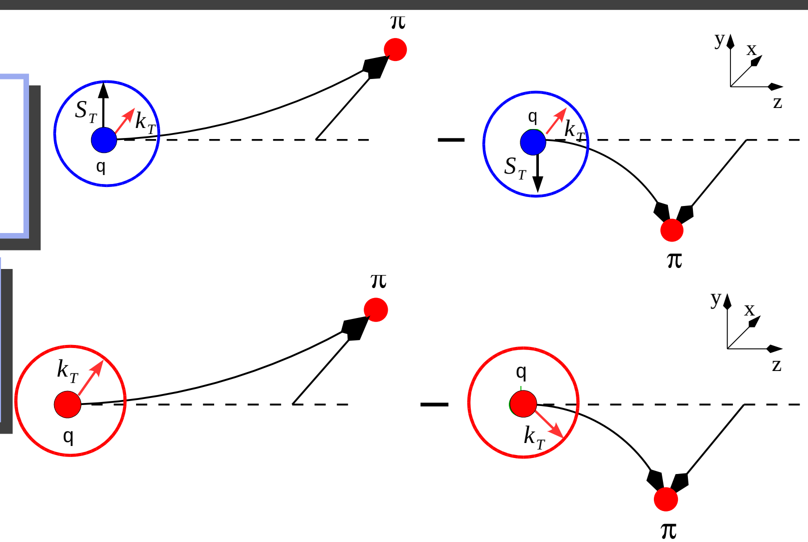
$$d\sigma = d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} + P_l\frac{1}{Q}\sin(\phi)d\sigma^3_{LU}$$
$$+ S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} + P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\sin(\phi)d\sigma^7_{LL}\right)\right]$$

an intrinsic quark transverse motion gives origin to an azimuthal asymmetry in the hadron production direction

- the“Boer-Mulders effect” (DF $h_1^\perp(x, p_T^2)$) originates from the correlation between quark spins and their own orbital angular momentum in an unpolarized nucleon
- the “Cahn effect” is generated by the non-zero intrinsic transverse motion of quarks

$$F_{UU}^{\cos 2\phi} = C\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_T) - (\vec{k}_T\cdot\vec{p}_T)}{MM_h}h_1^\perp H_1^\perp\right]$$

$$F_{UU}^{\cos\phi} = \frac{2M}{Q}C\left[-\frac{\hat{h}\cdot\vec{p}_T}{M_h}xh_1^\perp H_1^\perp - \frac{\hat{h}\cdot\vec{k}_T}{M}xf_1D_1\right]$$



extraction of $\cos$-terms

- twist-2:

  $$A^{\cos(2\phi)} \propto h_1^{\perp q} H_1^{\perp q}$$

- twist-3:

  $$A^{\cos(\phi)} \propto h_1^{\perp q} H_1^{\perp q} - f_1^q D_1^q$$

- extraction is challenging
- $\cos(\phi)$ and $\cos(2\phi)$ azimuthal modulations are possible due to
  - detector geometrical acceptance
  - QED effects
- analysis based on a multidimensional unfolding of data to correct for acceptance, detector smearing and higher order QED effects
- the dependence of a moment on a single variable is obtained by projection of the differential result onto that variable

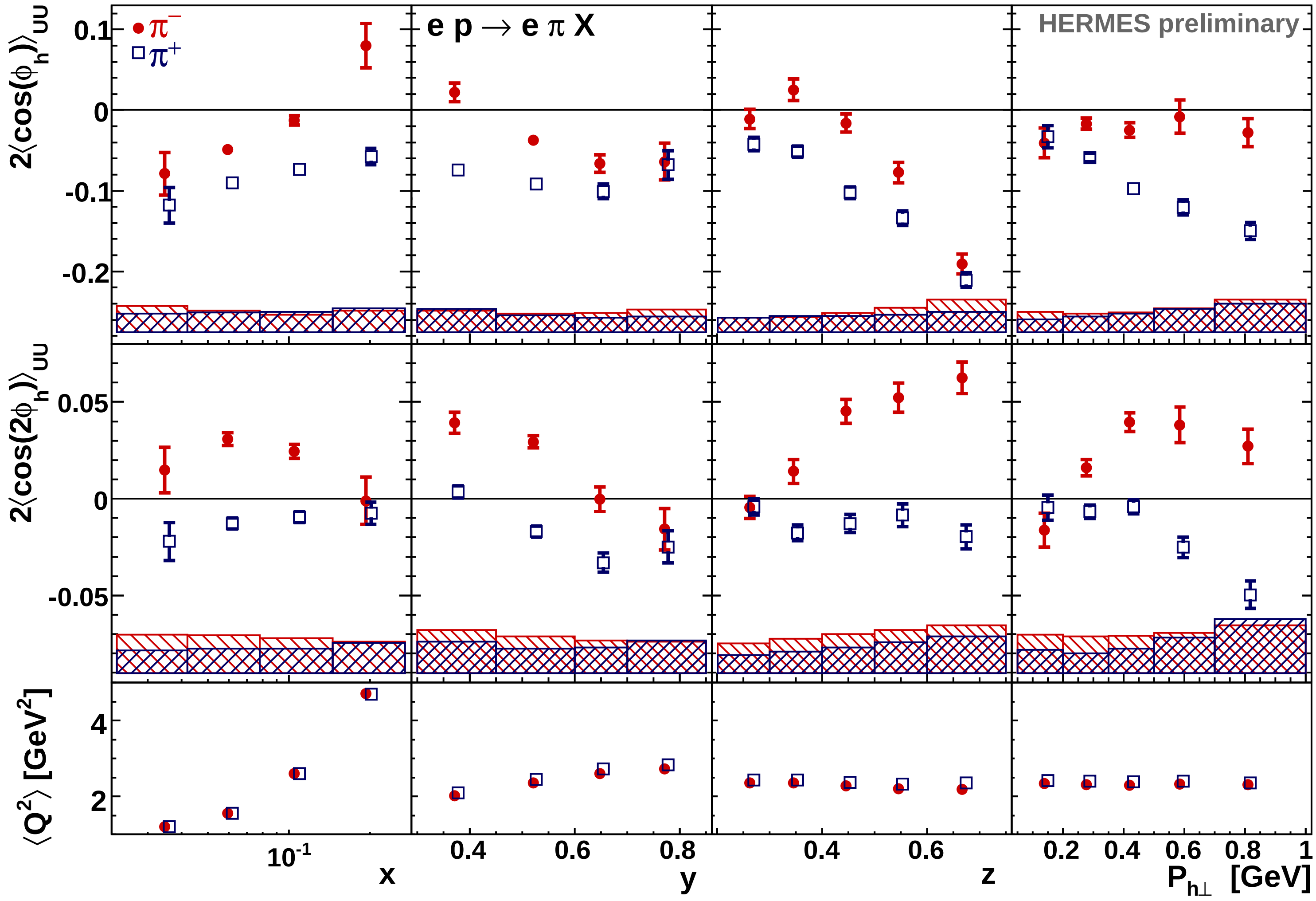
probability that an event generated with a certain kinematics is measured with a different kinematics

$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

$$n_{BORN} = S^{-1}\left[n_{EXP} - n_{Bg}\right]$$

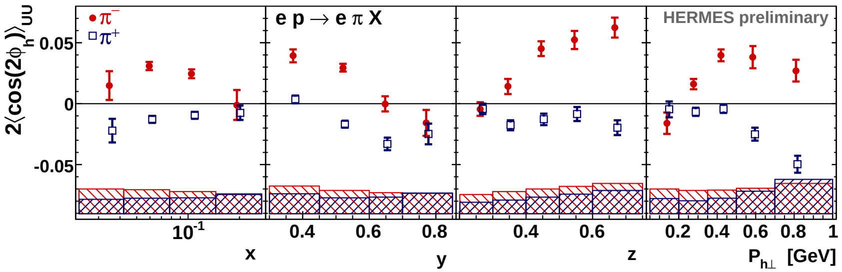
includes the events smeared into the acceptance

results



- negative $\cos(\phi)$ amplitudes for both π^+ and π^-
- positive $\cos(2\phi)$ amplitude for π^- and slightly negative for π^+
- similar results for D target

theoretical model predictions



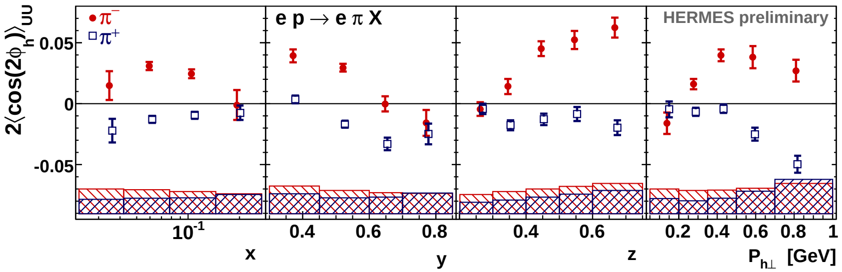
- twist-2:

$$A^{\cos(2\phi)} \propto h_1^{\perp q} H_1^{\perp q}$$

$$H_1^{\perp, u\to\pi^+} \approx -H_1^{\perp, u\to\pi^-}$$

- twist-4 (Cahn):
  noncollinear kinematics at order k_T^2/Q^2
- perturbative gluon radiation

theoretical model predictions



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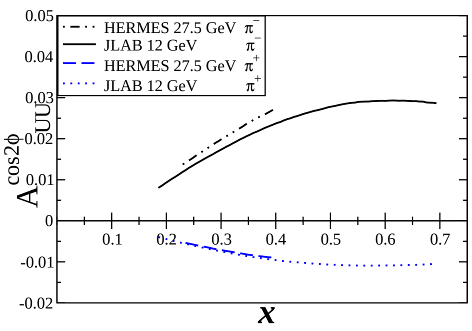
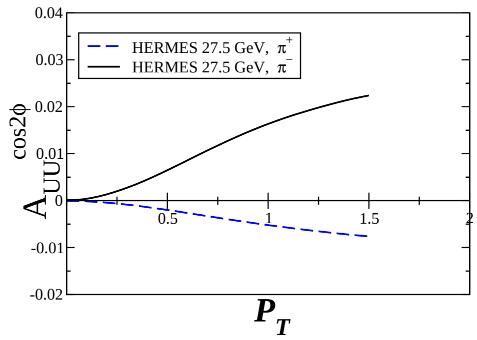
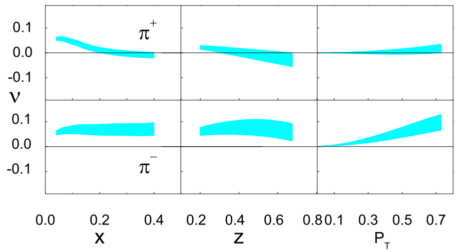


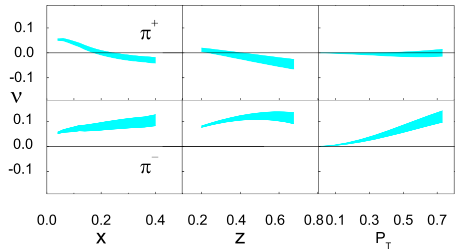


-Gamberg, Goldstein, Schlegel

Phys. Rev. D77:094016, (2008) -

$$h_1^{\perp, u} \;\&\; h_1^{\perp, d} < 0$$



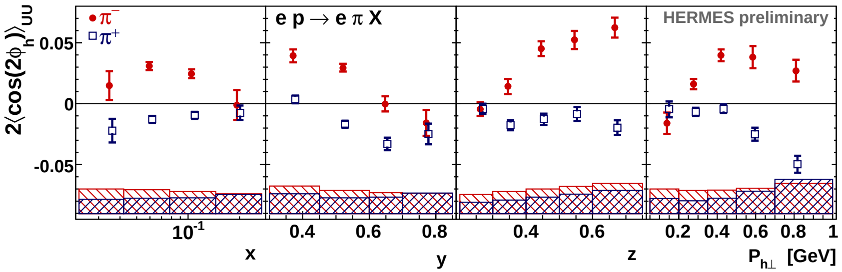


- $h_1^{\perp, u} \& \; h_1^{\perp, d}$ have same sign
- $h_1^{\perp, u} \& \; h_1^{\perp, d}$ have different signs

-Zhang et al.

Phys. Rev. D78:034035, (2008) -

theoretical model predictions



- twist-2:

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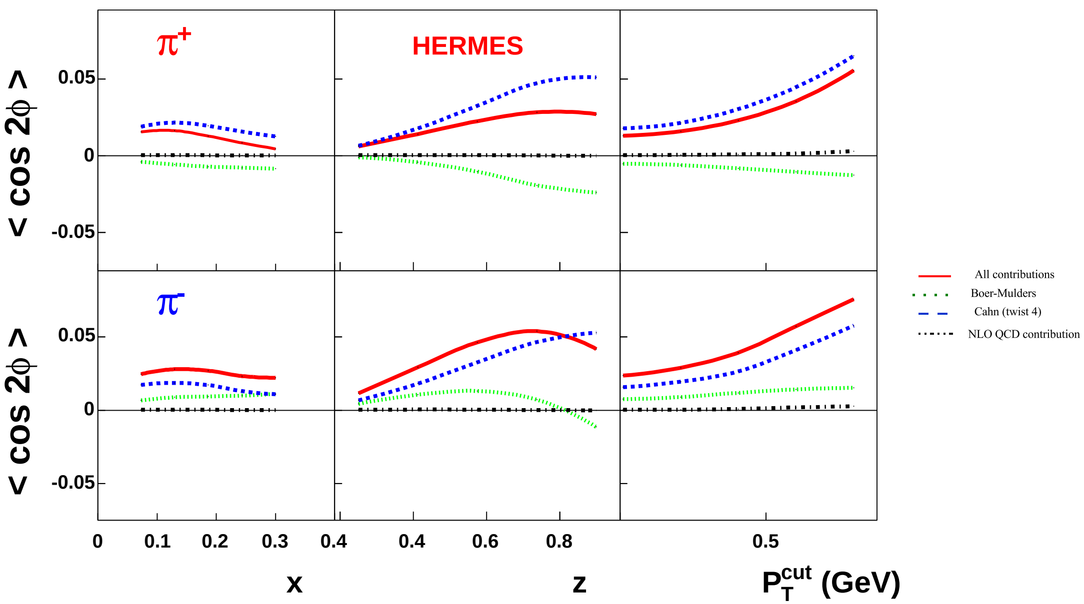
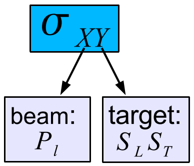


-Barone et al. Phys.Rev. D78:045022, (2008) -

- Boer-Mulders contributions to π^+ and π^- are opposite in sign
  - negative signs for $h_1^{\perp,u}$ and $h_1^{\perp,d}$
- Cahn contribution (>0) is the same for π^+ and π^-
- gluon emission is negligible at HERMES kinematics

asymmetry is larger for π^- than for π^+

"Collins-effect "



$$
\begin{aligned}
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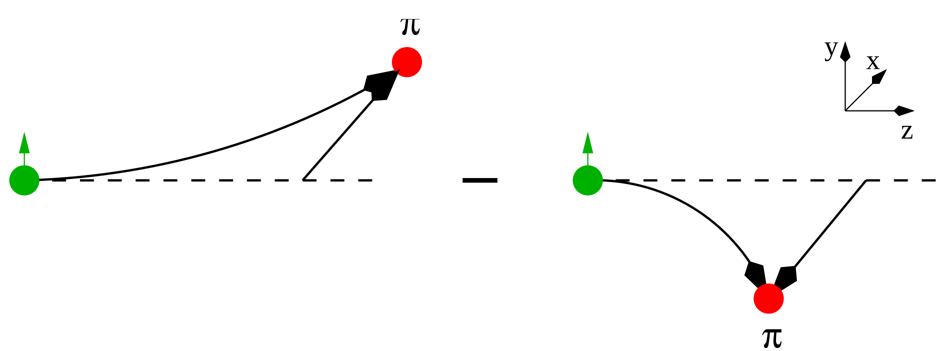
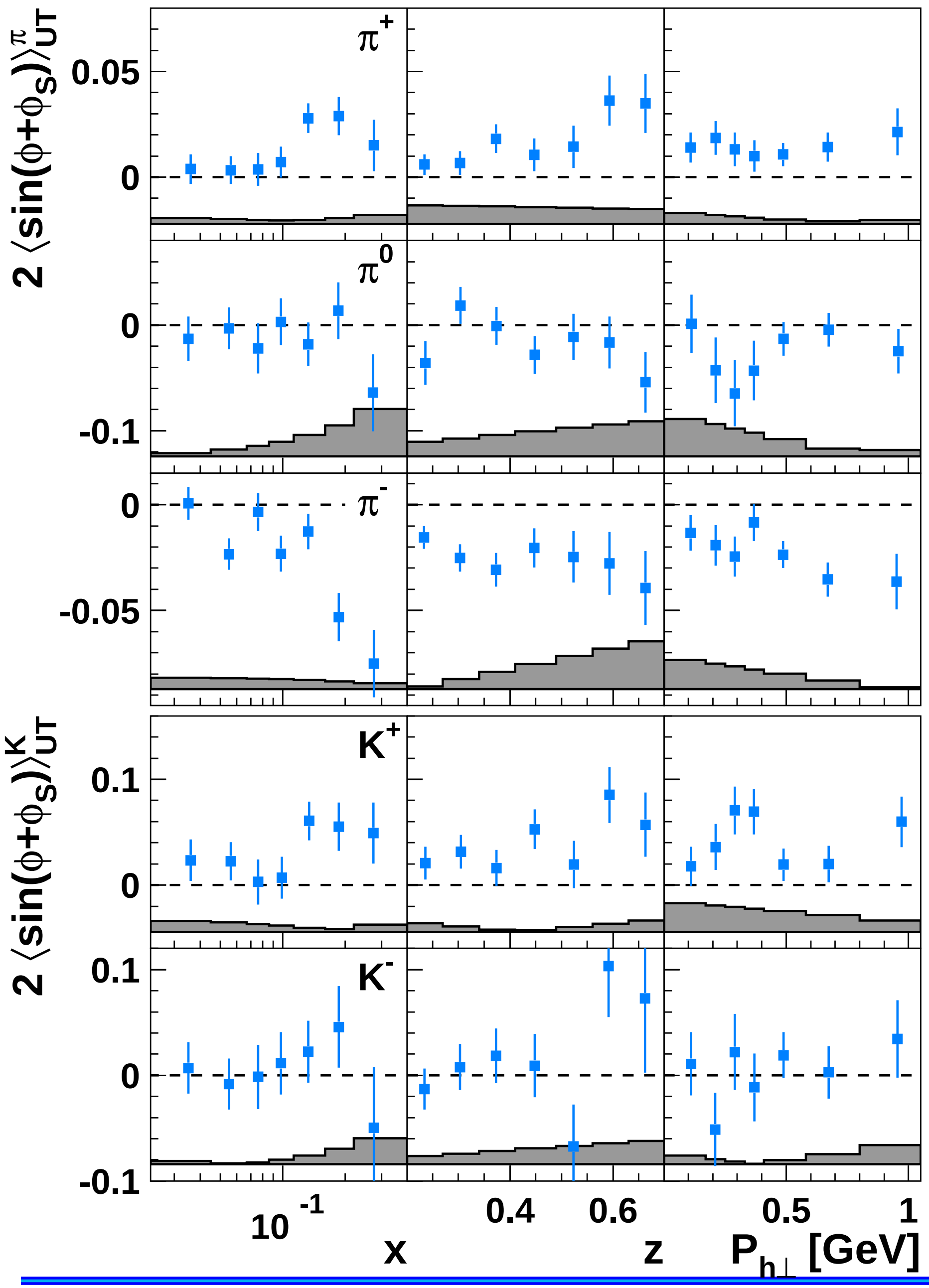
+\;& S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} \;+\; P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\sin(\phi)d\sigma^7_{LL}\right)\right] \\
+\;& S_T\left[\sin(\phi-\phi_s)d\sigma^8_{UT} + \sin(\phi+\phi_s)d\sigma^9_{UT} + \sin(3\phi-\phi_s)d\sigma^{10}_{UT} + \right.
\end{aligned}
$$

- "Collins-effect " accounts for the correlation between the transverse spin of the fragmenting quark and the transverse momentum of the produced unpolarized hadron
- sensitive to quark transverse spin
- generates left-right (azimuthal) asymmetries in the direction of the outgoing hadrons



Collins amplitudes



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

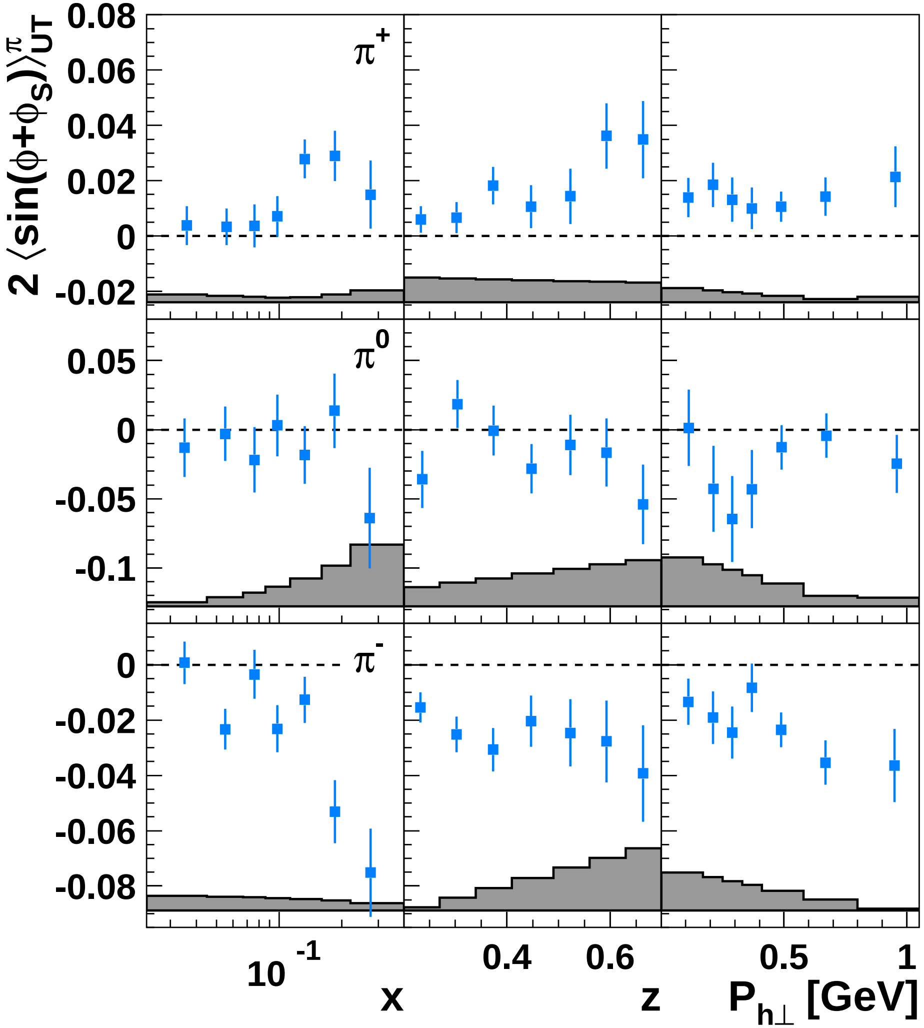
final results!!!

non-zero Collins effect observed!

- both Collins FF and transversity sizeable
- 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

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



- positive amplitude for π^+
- compatible with zero amplitude for π^0
- negative amplitude for π^-
- unexpected large π^- asymmetry
  - role of disfavored Collins FF:

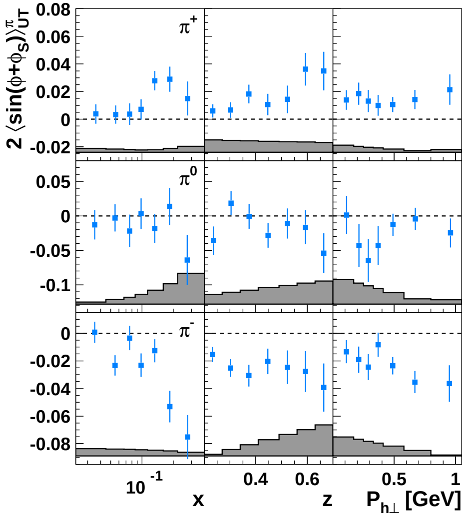
$$H_1^{\perp,disfav} \approx -H_1^{\perp,fav}$$

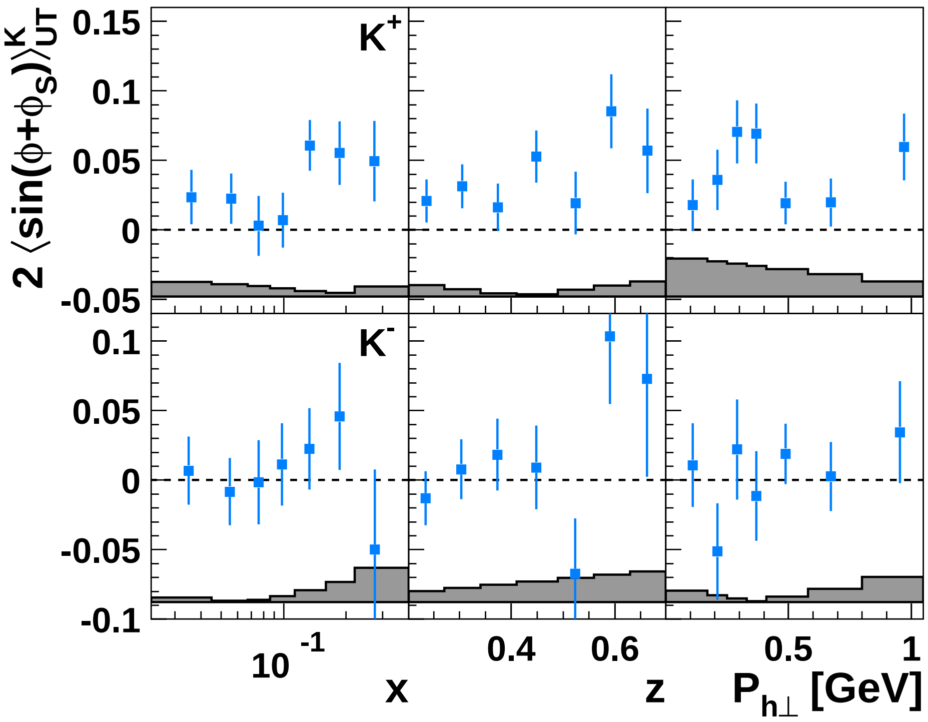
$$u \Rightarrow \pi^+; \qquad d \Rightarrow \pi^-(fav)$$

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

- positive for π^+ and negative for π^-
  - $h_1^u > 0$
  - $h_1^d < 0$

Collins amplitudes for kaons





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

K^+

- K^+ amplitudes are similar to π^+ as expected from u-quark dominance
- K^+ are larger than π^+

K^-

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

differences between amplitudes of π and K

- 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

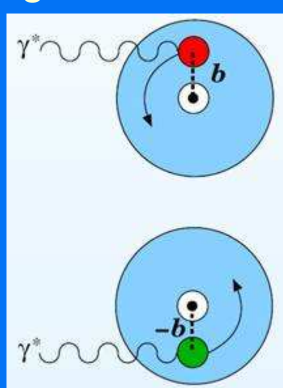
"Sivers-effect "

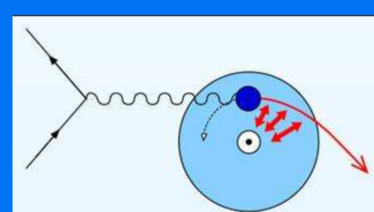
σ_{XY}

beam: P_l | target: $S_L S_T$

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

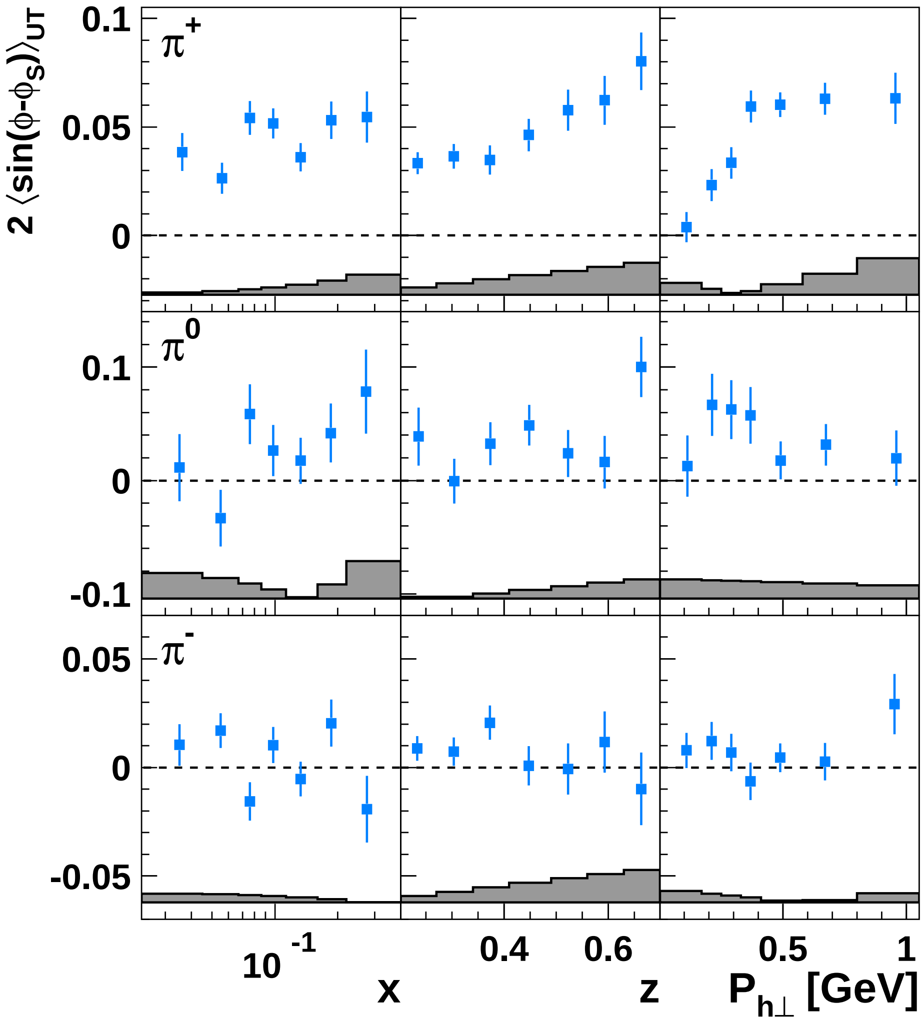
- Sivers distribution function $f_{1T}^{\perp q}(x, p_T^2)$ gives the probability to find an unpolarized quark with transverse momentum in a transversely polarized nucleon
- correlation between parton transverse momentum and transverse spin of the nucleon
- non-zero Sivers function implies non-zero orbital angular momentum
- generates left-right (azimuthal) asymmetries in the direction of the outgoing hadrons





Sivers amplitudes for pions

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



π^+

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- dominated by u-quark scattering:
  $\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_w D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$
- u-quark Sivers $DF < 0$
- $L_z^u > 0$ *-M.Burkardt (2002)-*

π^0

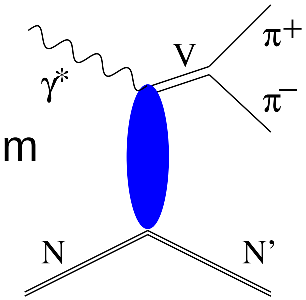
- slightly positive

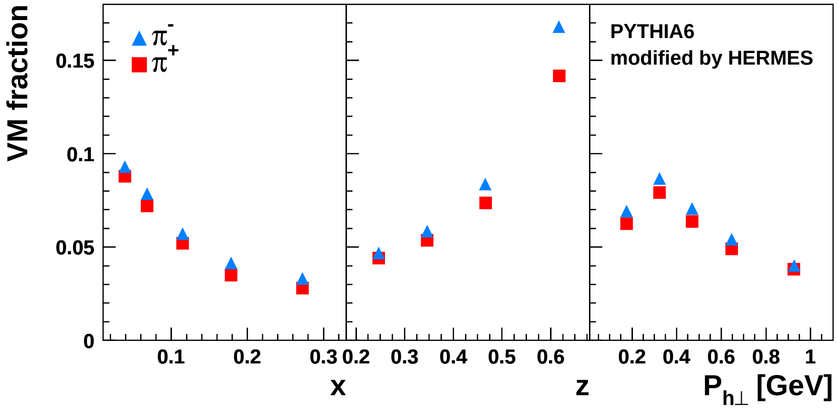
π^-

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

the pion-difference asymmetry

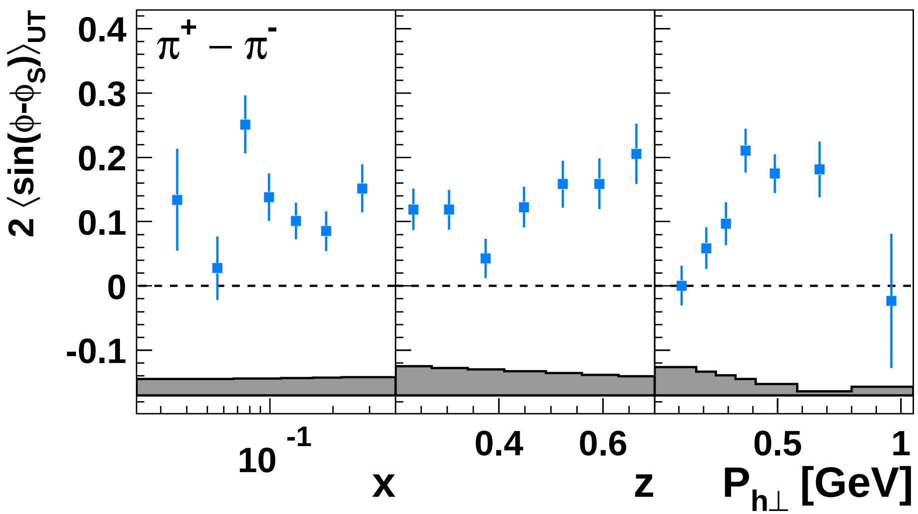
non-negligible contribution from





contribution from exclusive ρ^0 largely cancels out in

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

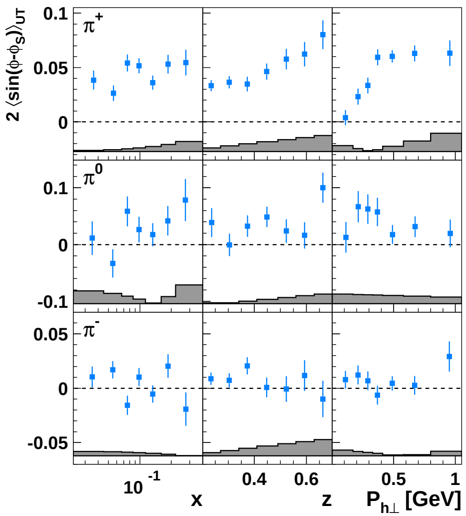


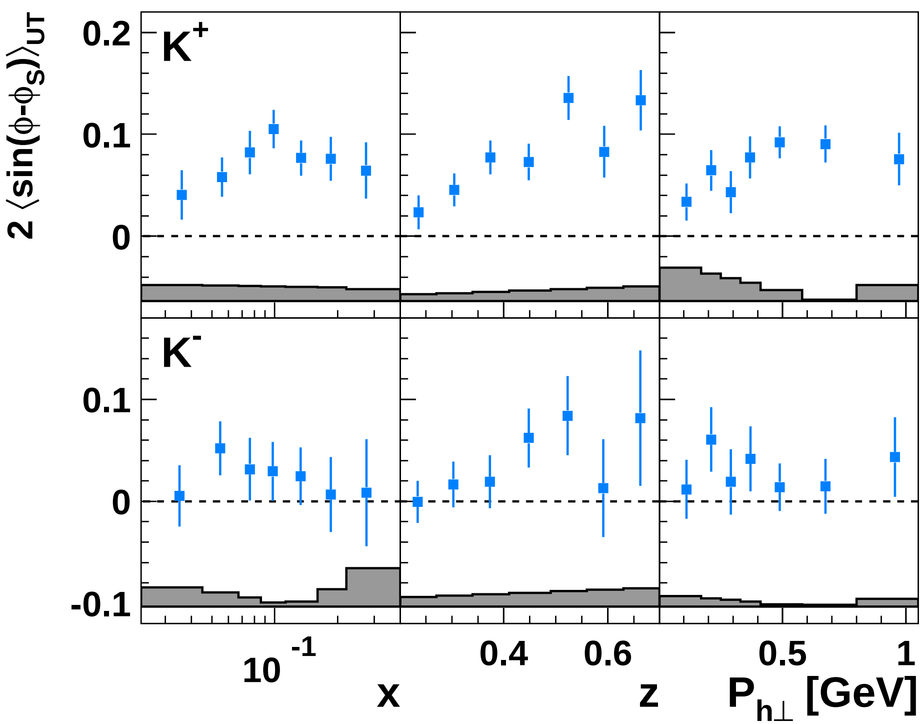
$$\langle \sin(\phi - \phi_s) \rangle_{UT}^{\pi^+-\pi^-} \simeq - \frac{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

- either $f_{1T}^{\perp,d_v} \gg f_{1T}^{\perp,u_v}$
- or $f_{1T}^{\perp,u_v}$ is large and < 0
- provides access to Sivers u-valence distribution

- significantly positive Sivers amplitudes are obtained

Sivers amplitudes for kaons





K^+

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

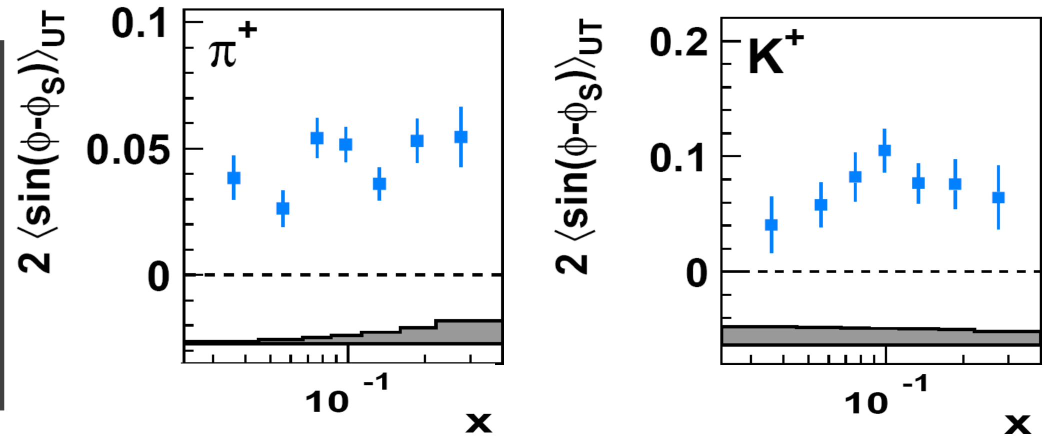
K^-

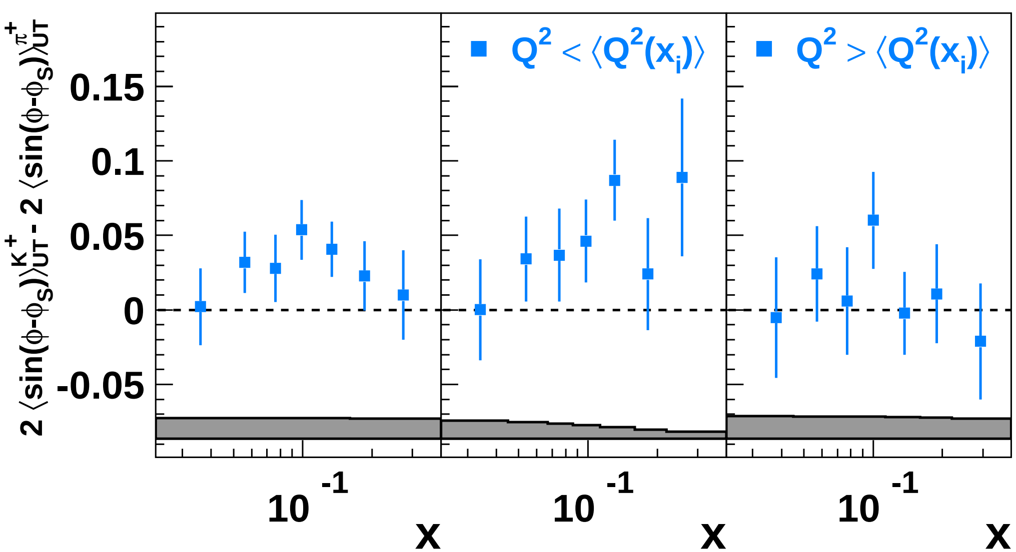
- slightly positive

The Sivers π^+/K^+ challenge

- π^+/K^+ production dominated by scattering off u-quarks:

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





- $\pi^+ \equiv |u\bar{d}\rangle$, $K^+ \equiv |u\bar{s}\rangle \Rightarrow$ non trivial role of sea quarks
- in numerator $D_1^u(z,k_T^2)$ in convolution integrals over k_T and p_T
  - can lead to additional z-dependences
  - can lead to a difference in size of π^+, K^+ amplitudes
- higher-twist contribution for kaons
  - separate each x-bin in two Q^2 bins
  - only in low-Q^2 region significant (90% c.l.) deviation

extraction of transversity and Sivers function

$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

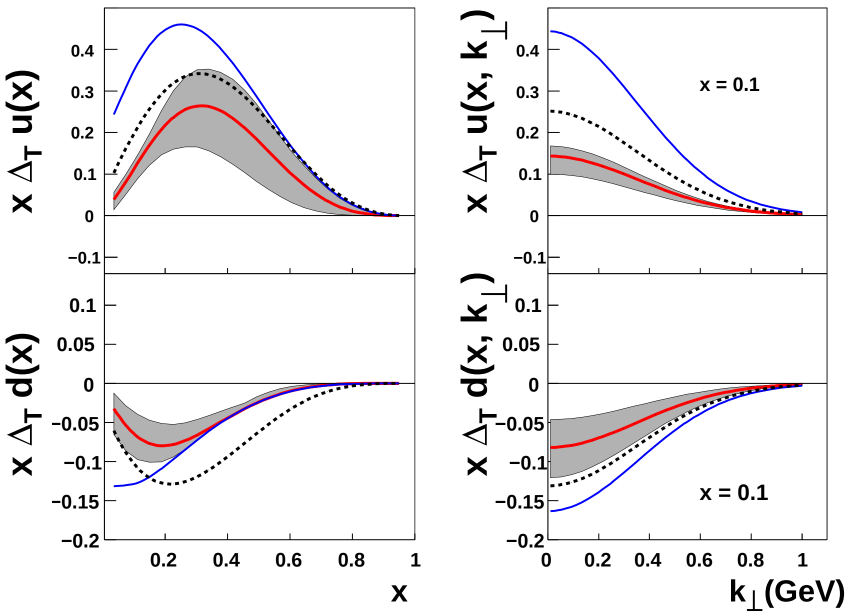
$lp \to l'hX$ $ld \to l'hX$ $e^+e^- \to h_1 h_2 X$

$$A_{UT}^{\sin(\phi-\phi_S)} \propto f_{1,T}^{\perp}(x) \otimes D_1^q(z)$$

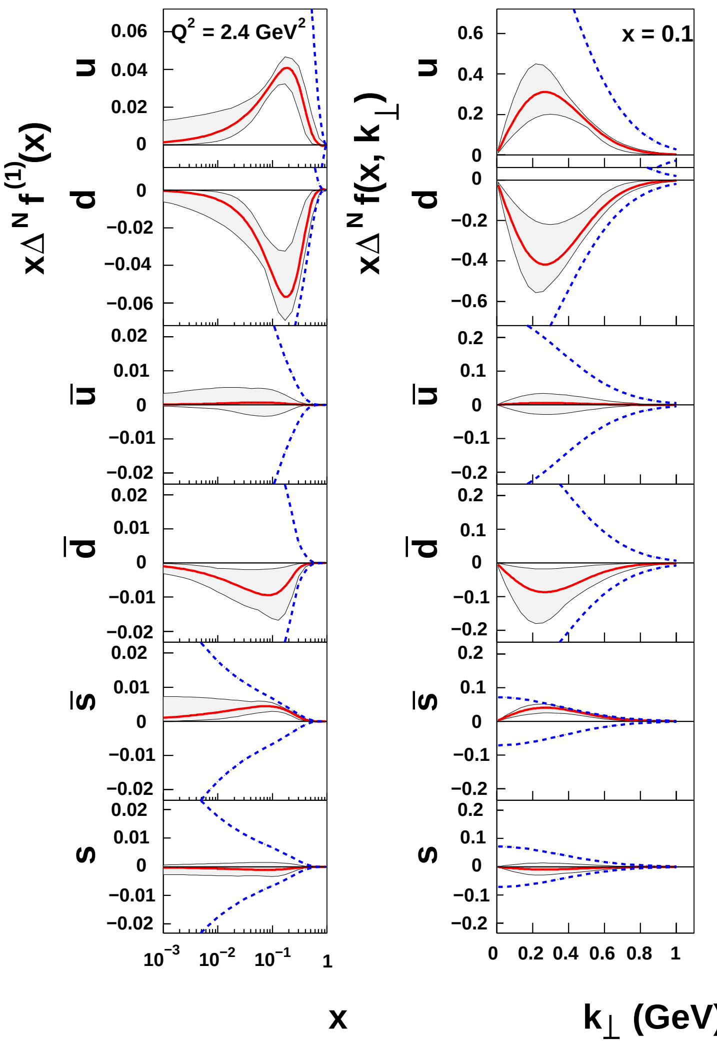
Known

$lp \to l'hX$

$ld \to l'hX$

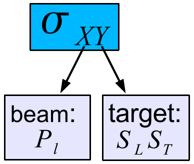


-Anselmino et al. Phys. Rev. D 75 (2007)-



-Anselmino et al. Eur.Phys.J.A39 (2009)-

"Pretzelosity"

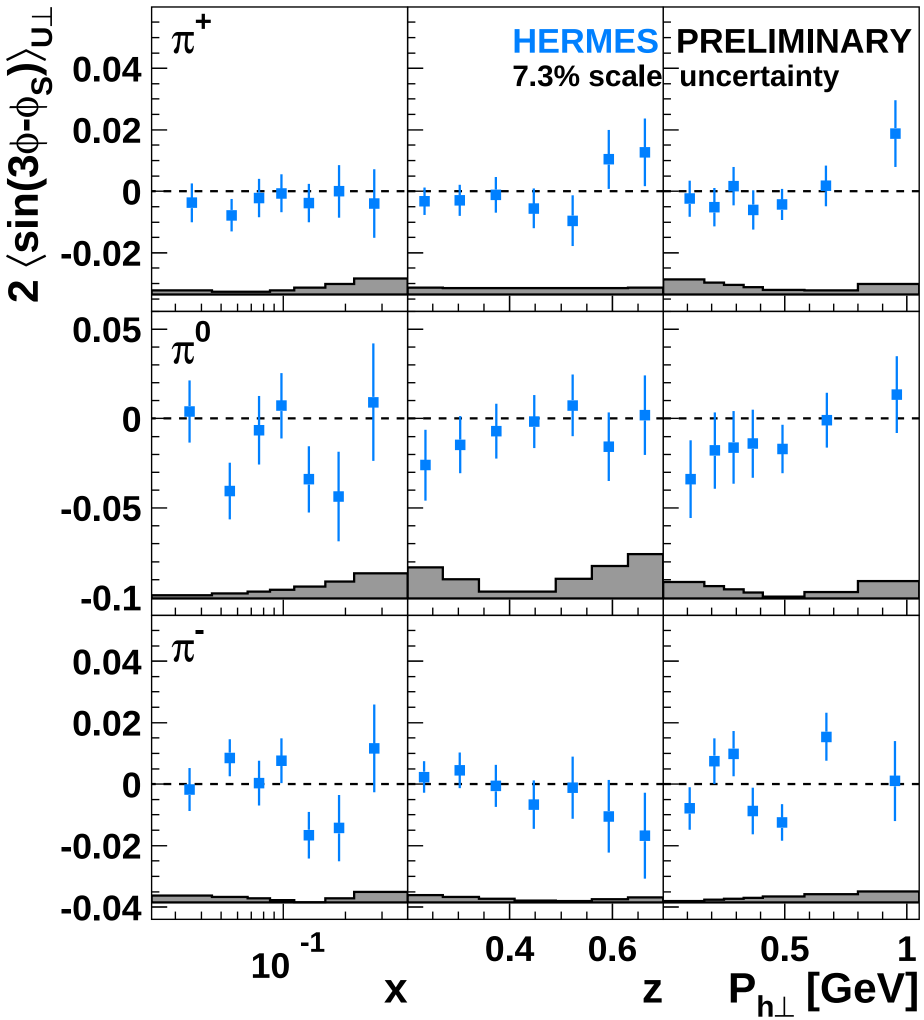


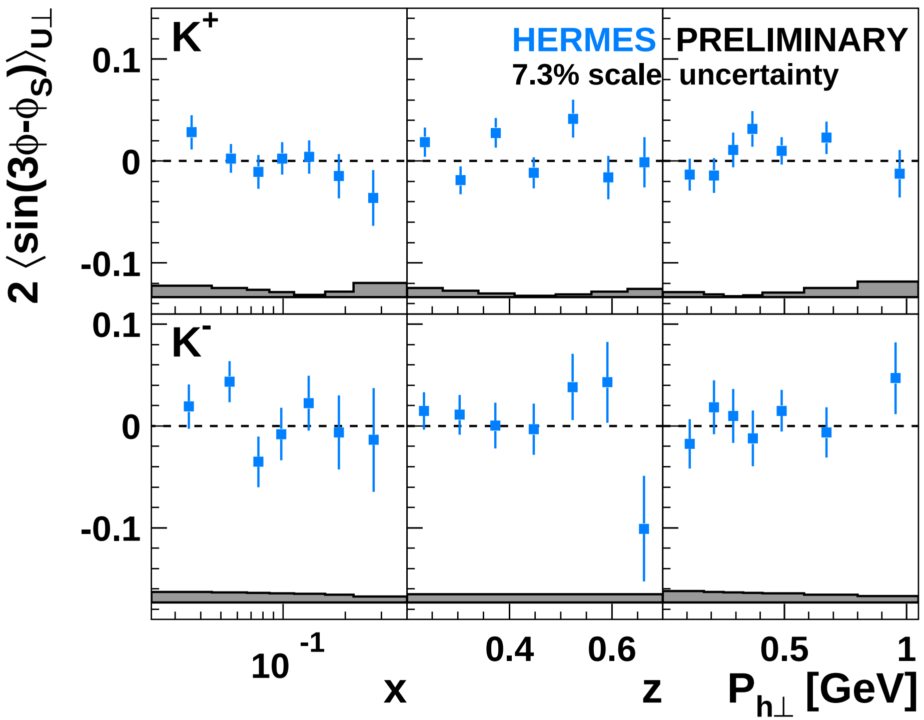
$$
\begin{aligned}
d\sigma \quad = \quad & d\sigma^0_{UU} + \cos(2\phi) d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi) d\sigma^2_{UU} \quad + \quad P_l \frac{1}{Q}\sin(\phi) d\sigma^3_{LU} \\
+ \quad & S_L \Big[\sin(2\phi) d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi) d\sigma^5_{UL} \quad + \quad P_l \Big(d\sigma^6_{LL}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

- "pretzelosity"DF $h_{1T}^{\perp,q}(x)$ 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 w.r.t. f_1^q, g_1^q, h_1^q

the $\sin(3\phi - \phi_s)$ *Fourier component*

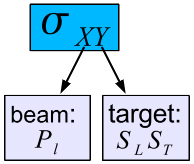
$$\mathbf{h_{1T}^{\perp,q}(x) \otimes H_1^{\perp,q}(z)}$$





- suppressed by two powers of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- compatible with zero within uncertainties
- $h_{1T}^{\perp,q}(x)$ might be non-zero at higher $P_{h\perp}$

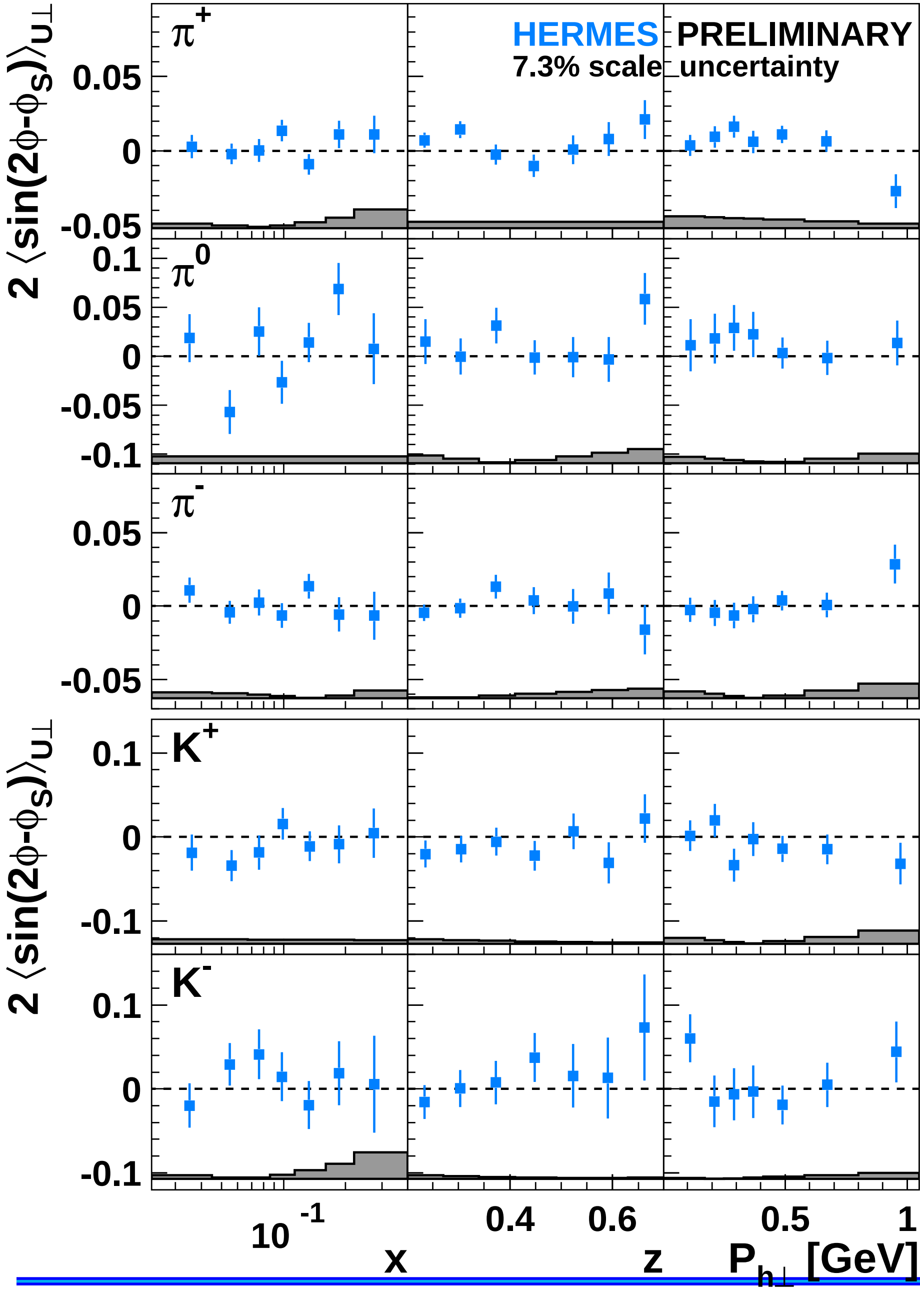
worm-gear distribution function $g_{1T}^{q}(x, p_T^2)$



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

- worm-gear DF $g_{1T}^{q}(x, p_T^2)$ gives correlation between parton transverse momentum and parton longitudinal polarization in a transversely polarized nucleon

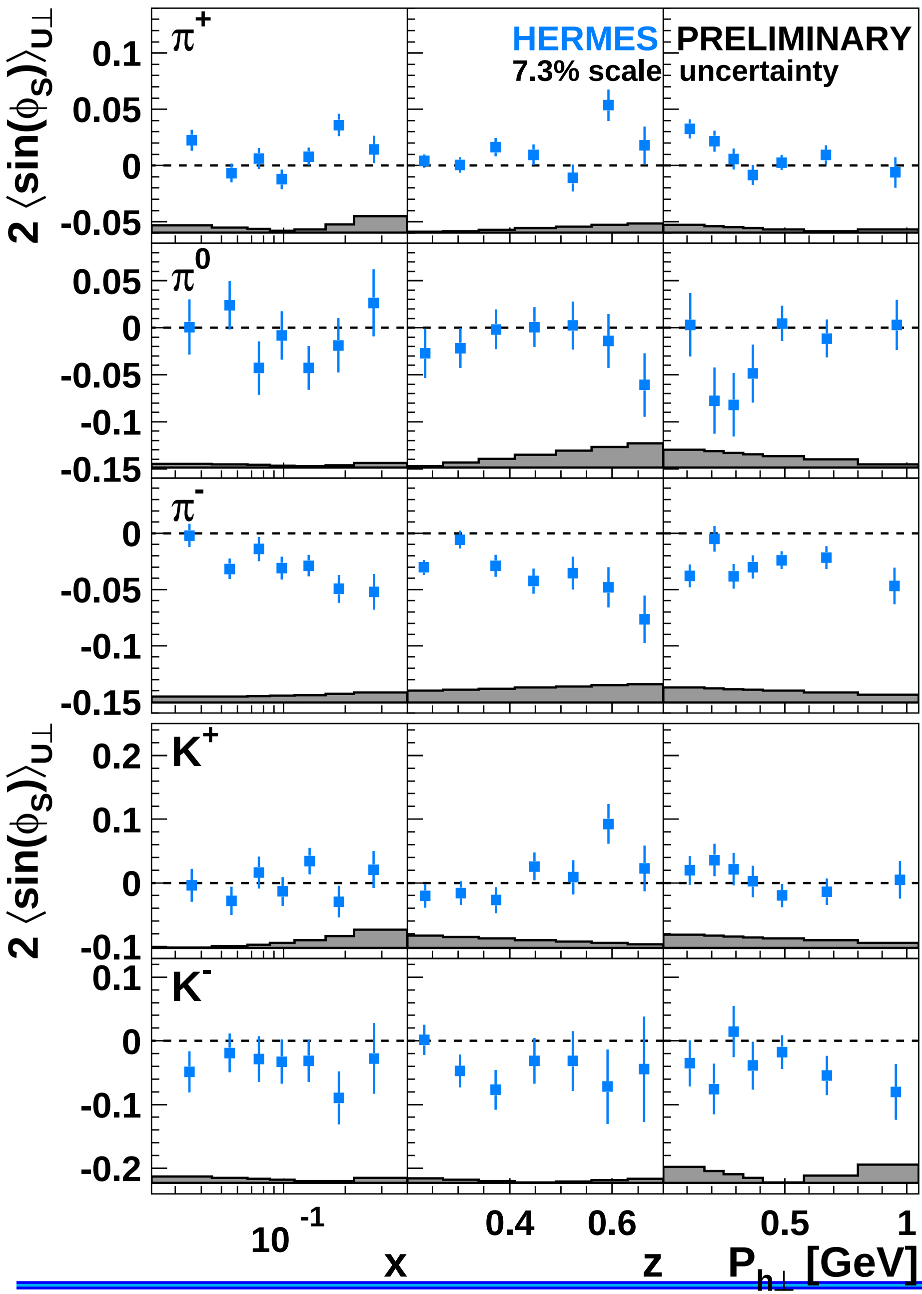
the twist-3 $\sin(2\phi - \phi_s)$ *Fourier component*



$$\propto W_1(p_T, k_T, P_{h\perp})\Big(x f_T^{\perp} D_1 - \frac{M_h}{M} h_{1T}^{\perp} \frac{\widetilde{H}}{z} \Big)$$
$$- W_2(p_T, k_T, P_{h\perp})\Big(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \frac{\widetilde{G}^{\perp}}{z} +$$
$$x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp} \frac{\widetilde{D}^{\perp}}{z} \Big)$$

- $\sin(2\phi - \phi_s)$ - related to pretzelosity, worm-gear, Sivers, etc.
- suppressed by one power of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- compatible with zero within uncertainties

the twist-3 $\sin(\phi_s)$ *Fourier component*



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

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

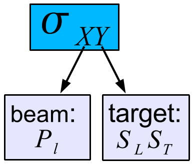
$$x h_T^{\perp} H_1^{\perp} + \frac{M_h}{M} f_{1T}^{\perp} \frac{\widetilde{D}^{\perp}}{z} \quad \Big)$$

- $\sin\phi_s$ - related to pretzelosity, worm-gear, Sivers, etc.
- in one-photon approximation:

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

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

worm-gear distribution function $h_{1L}^{q}(x, p_T^2)$

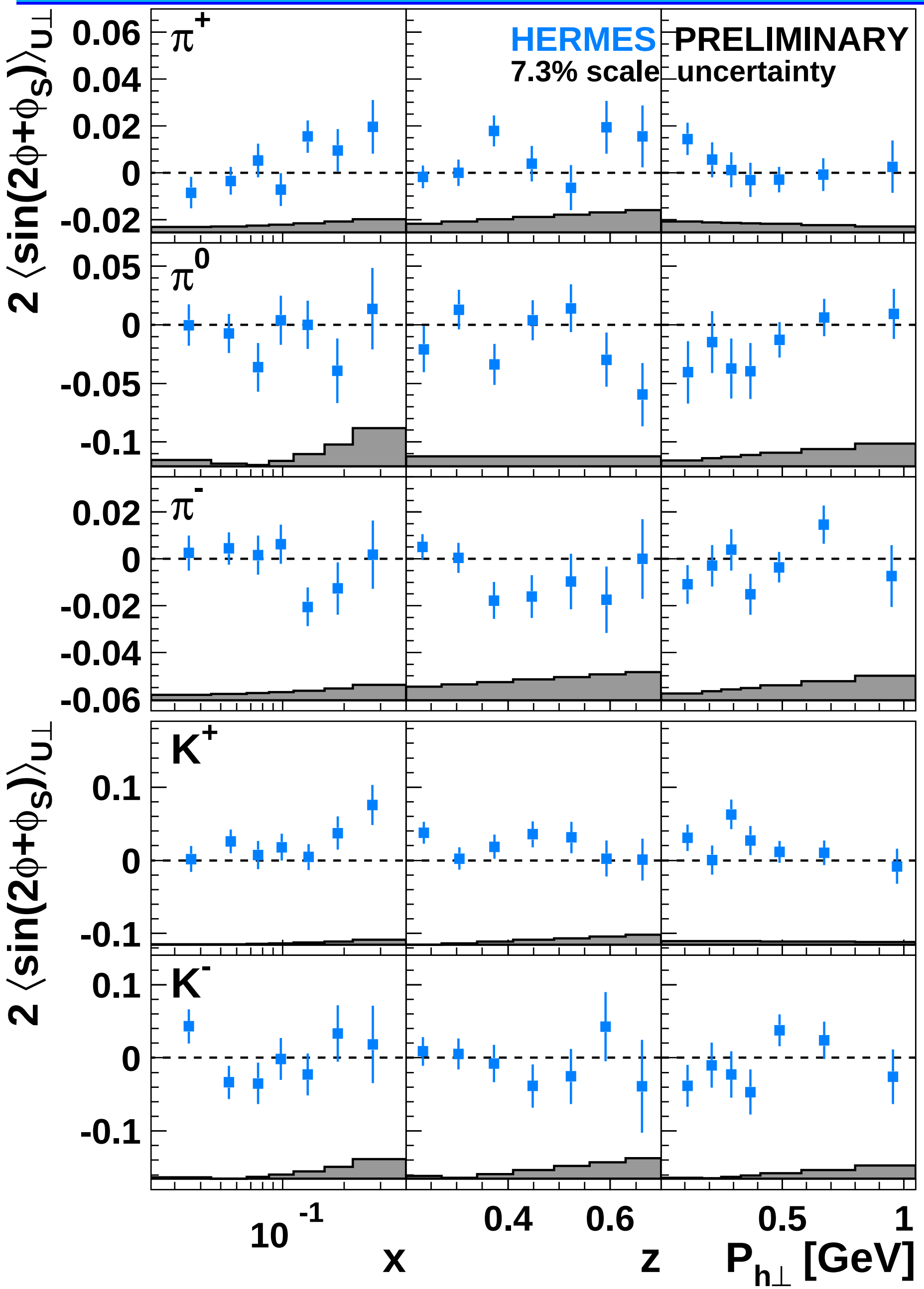


$$
\begin{aligned}
d\sigma \;=\;& d\sigma_{UU}^{0} + \cos(2\phi)d\sigma_{UU}^{1} + \frac{1}{Q}\cos(\phi)d\sigma_{UU}^{2} \;+\; P_l \frac{1}{Q}\sin(\phi)d\sigma_{LU}^{3} \\
+\;& S_L\Big[\sin(2\phi)d\sigma_{UL}^{4} + \frac{1}{Q}\sin(\phi)d\sigma_{UL}^{5} \;+\; P_l\Big(d\sigma_{LL}^{6} + \frac{1}{Q}\sin(\phi)d\sigma_{LL}^{7}\Big)\Big]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

- worm-gear DF $h_{1L}^{q}(x, p_T^2)$ gives correlation between parton transverse momentum and parton transverse polarization in a longitudinally polarized nucleon
- accessible in UT measurements through $\sin(2\phi+\phi_s)$ Fourier component
- arises solely from longitudinal component of the target spin:

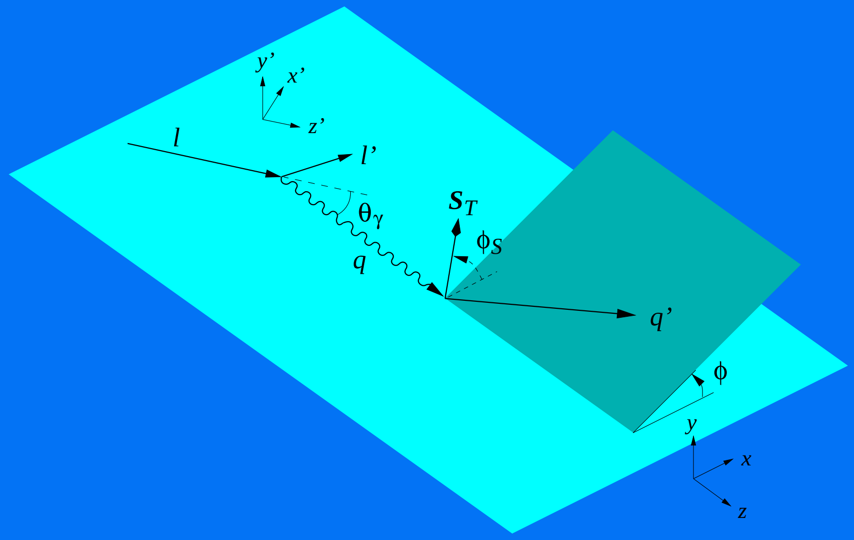
$$P_T A_{U\perp}(\phi, \phi_s) = S_T A_{UT}(\phi, \phi_s) + S_L A_{UL}(\phi)$$

The twist-3 $\sin(2\phi + \phi_s)$ Fourier component



$$\mathbf{h_{1L}^{\perp,q}(x, p_T^2) \otimes H_1^{\perp,q}(z)}$$

- suppressed by one powers of $P_{h\perp}$ compared to Collins and Sivers amplitudes
- expected to scale as $\sin\theta_{\gamma^*}\langle\sin(2\phi)_{UL}\rangle$

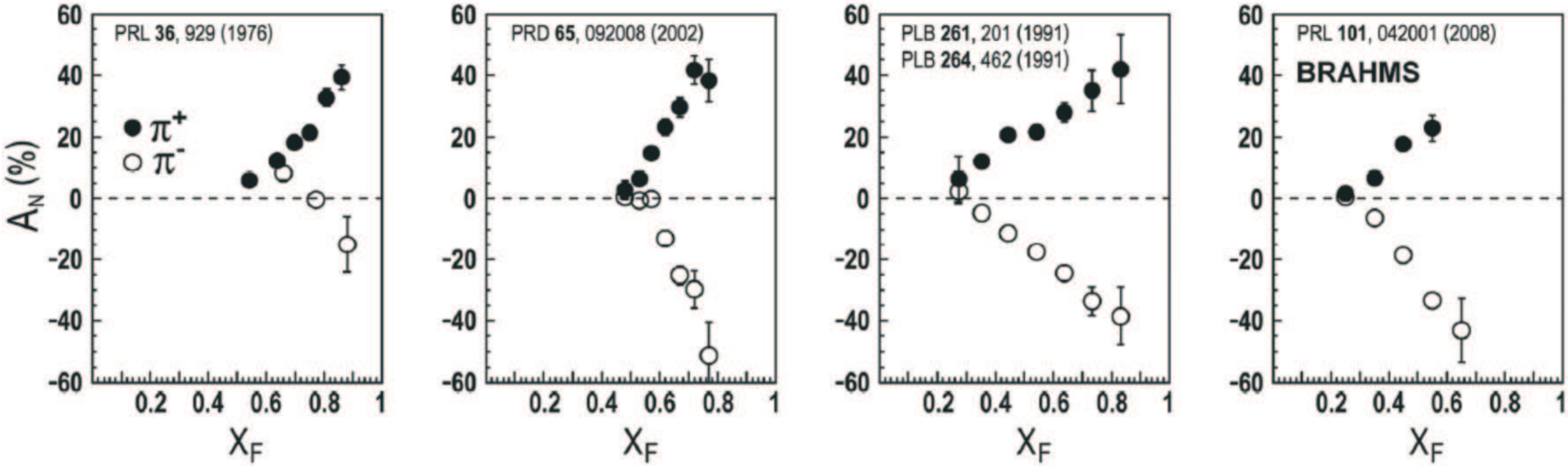


- longitudinal component of the target spin $\leq 15\%$
- compatible with zero within uncertainties except maybe K^+

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

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

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



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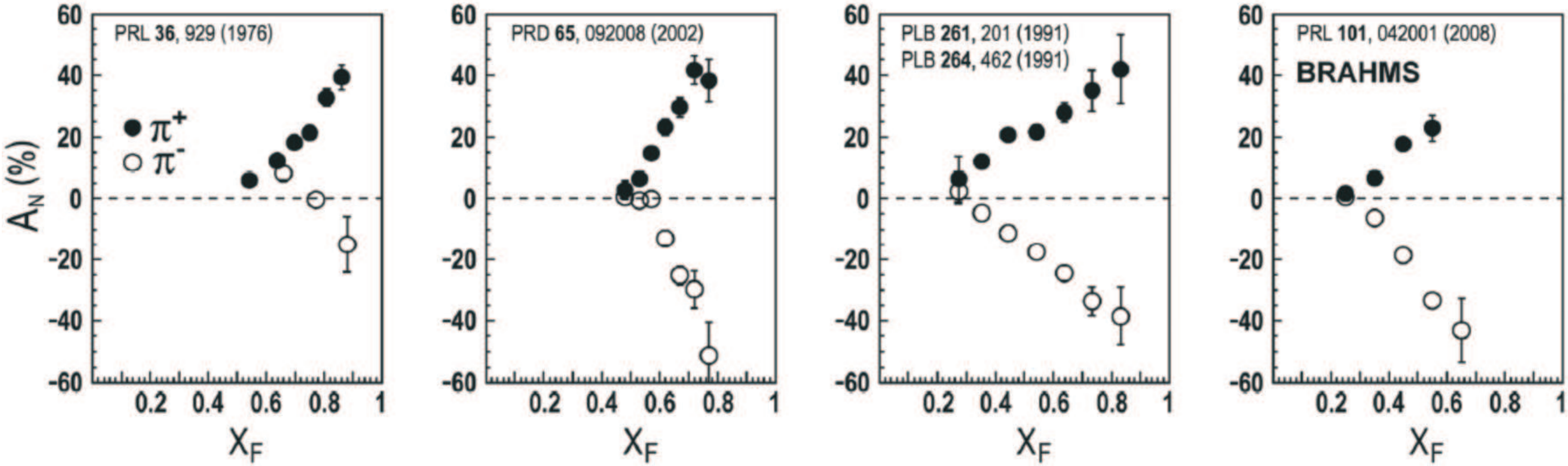

interpretations:

- 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

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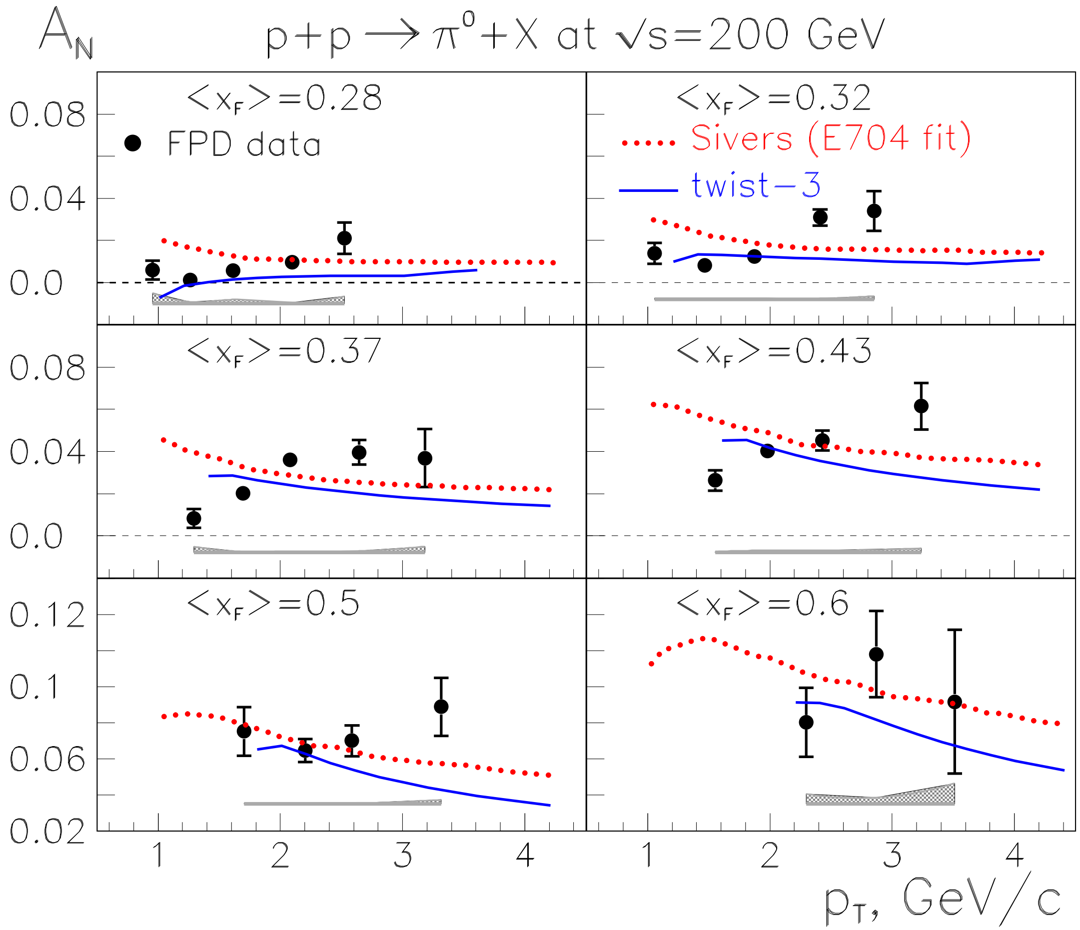
-STAR collab, PRL 101, 222001 (2008) -



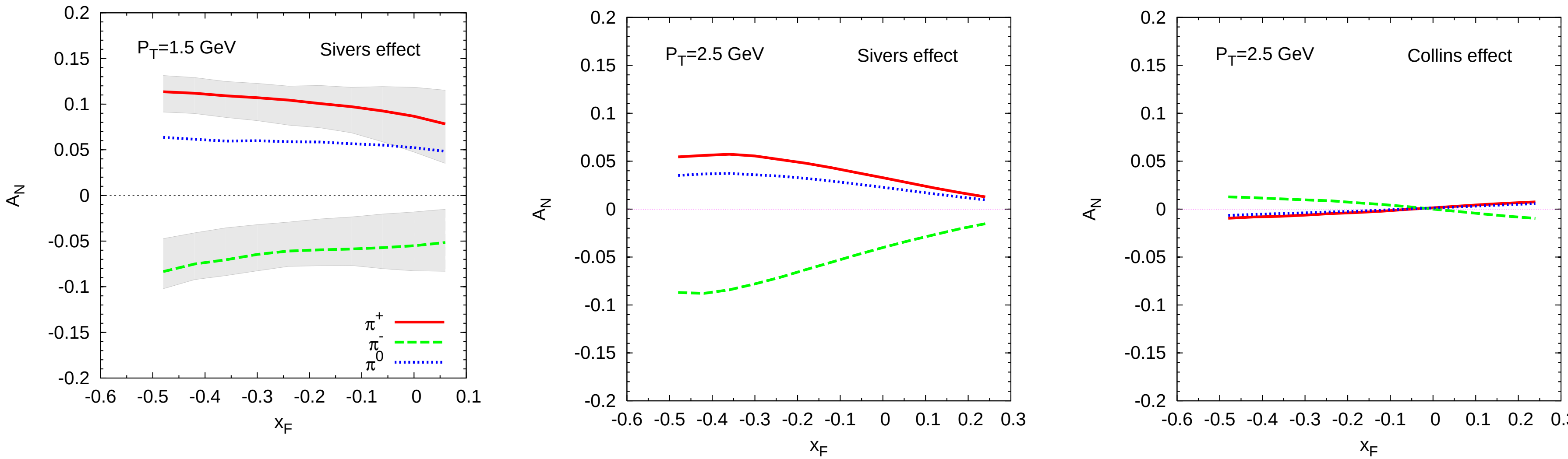
better test of models needed!

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

up to date: all data coming from pp-scattering

$$A_N = \frac{N_R - N_L}{N_R + N_L}$$ can be also measured in $ep \to \pi X$

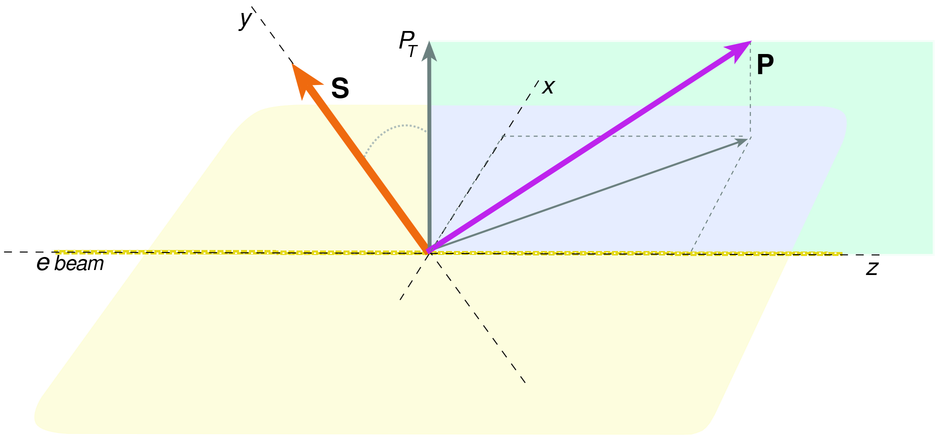
-Anselmino et al. (2009)-

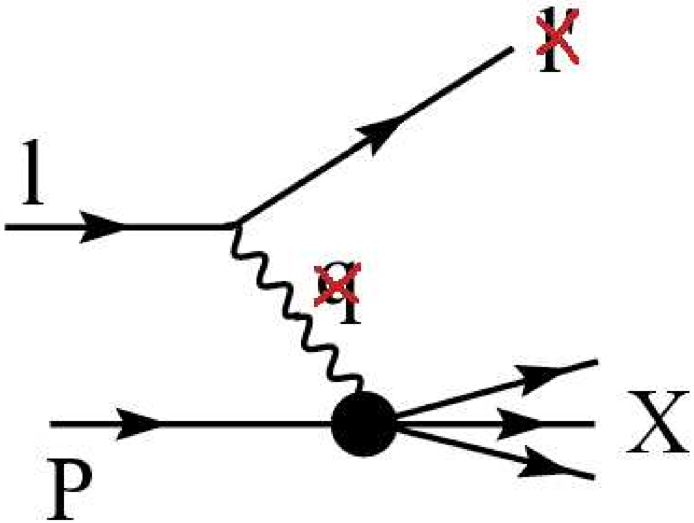


inclusive hadron production

no scattered lepton detection

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

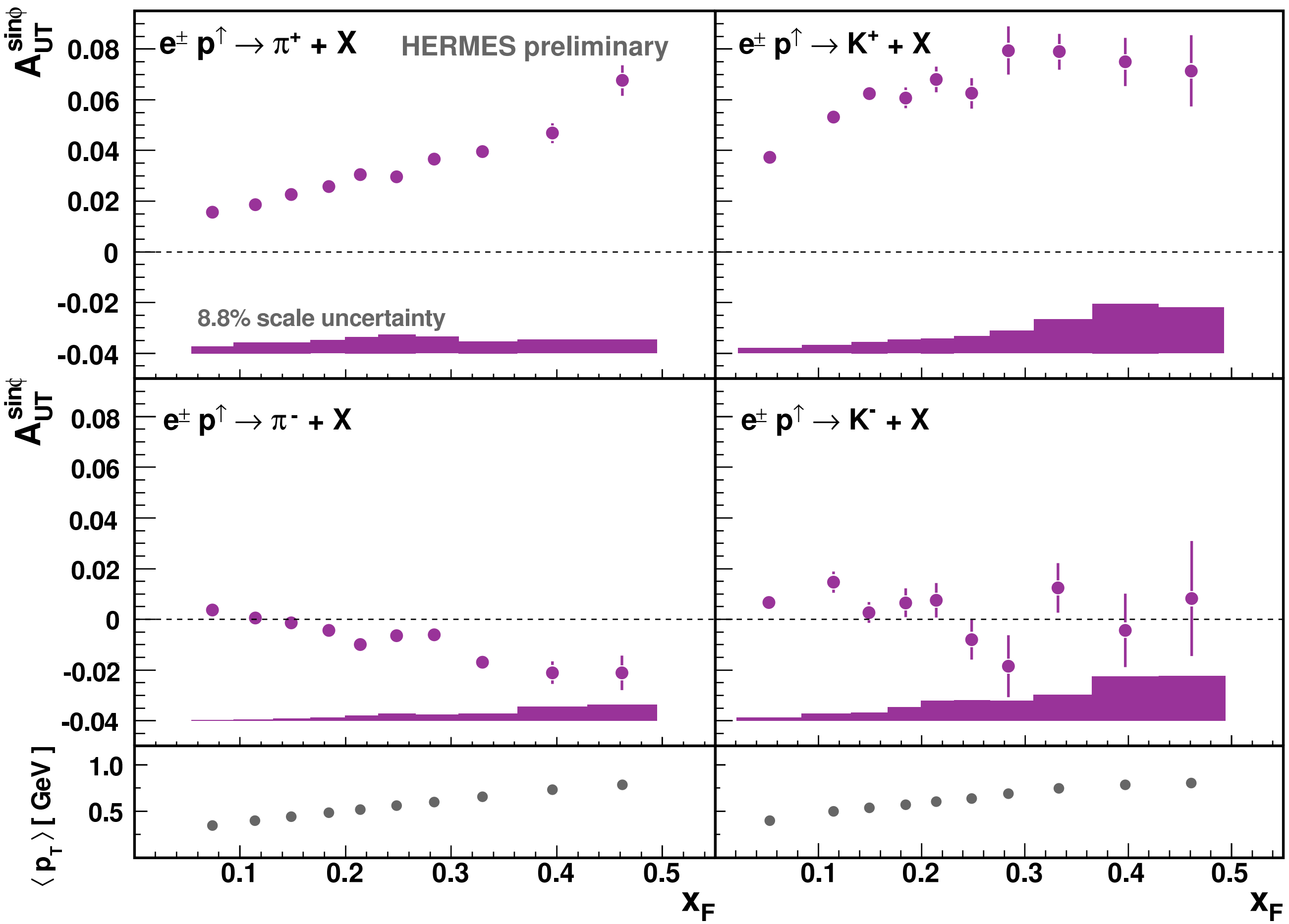




$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = A_{UT}^{\sin\phi} \sin\phi$$

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

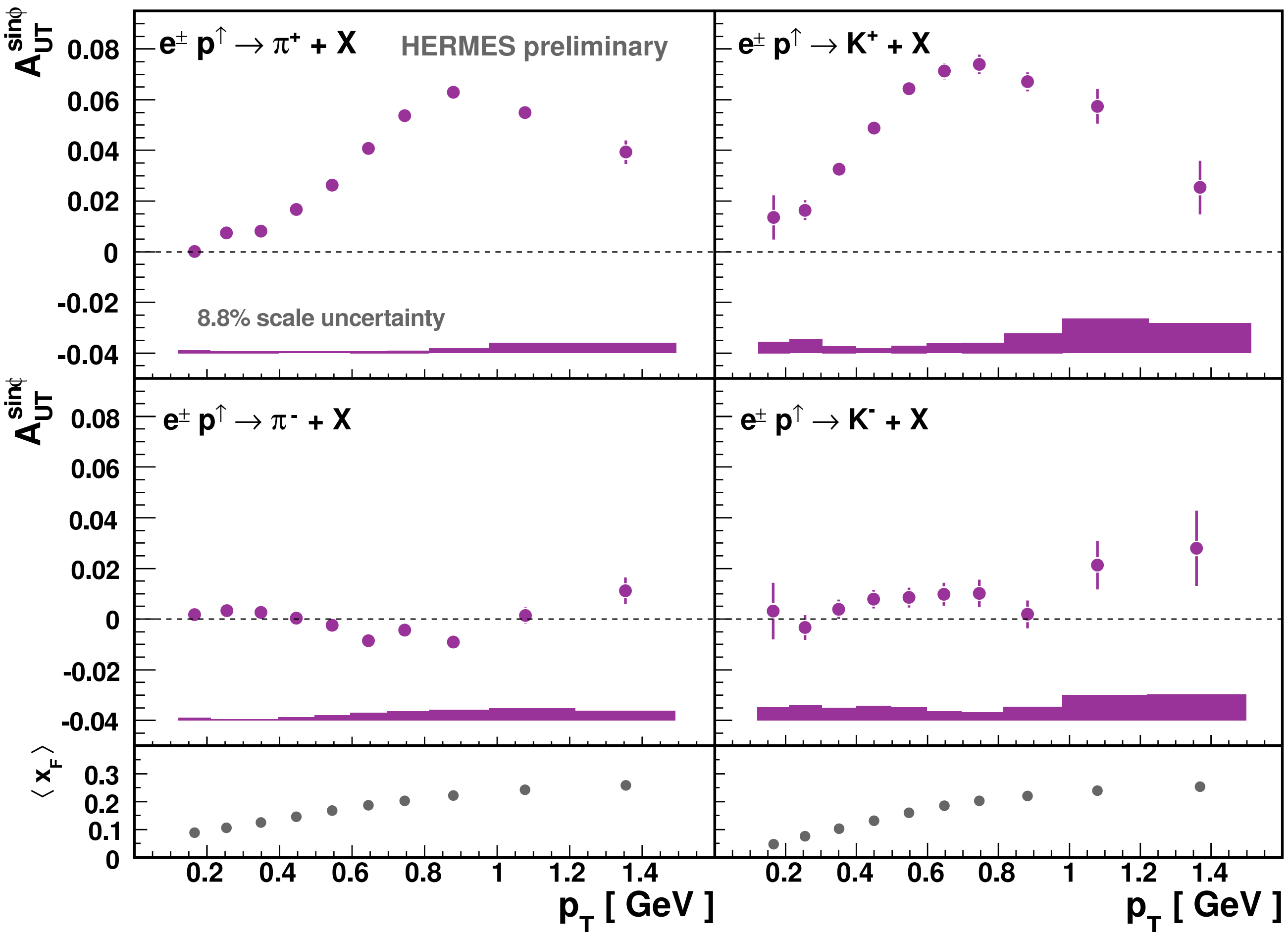
$A_{UT}^{\sin\phi}$ % x_F



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

A_N much smaller than in $pp^{\uparrow}$

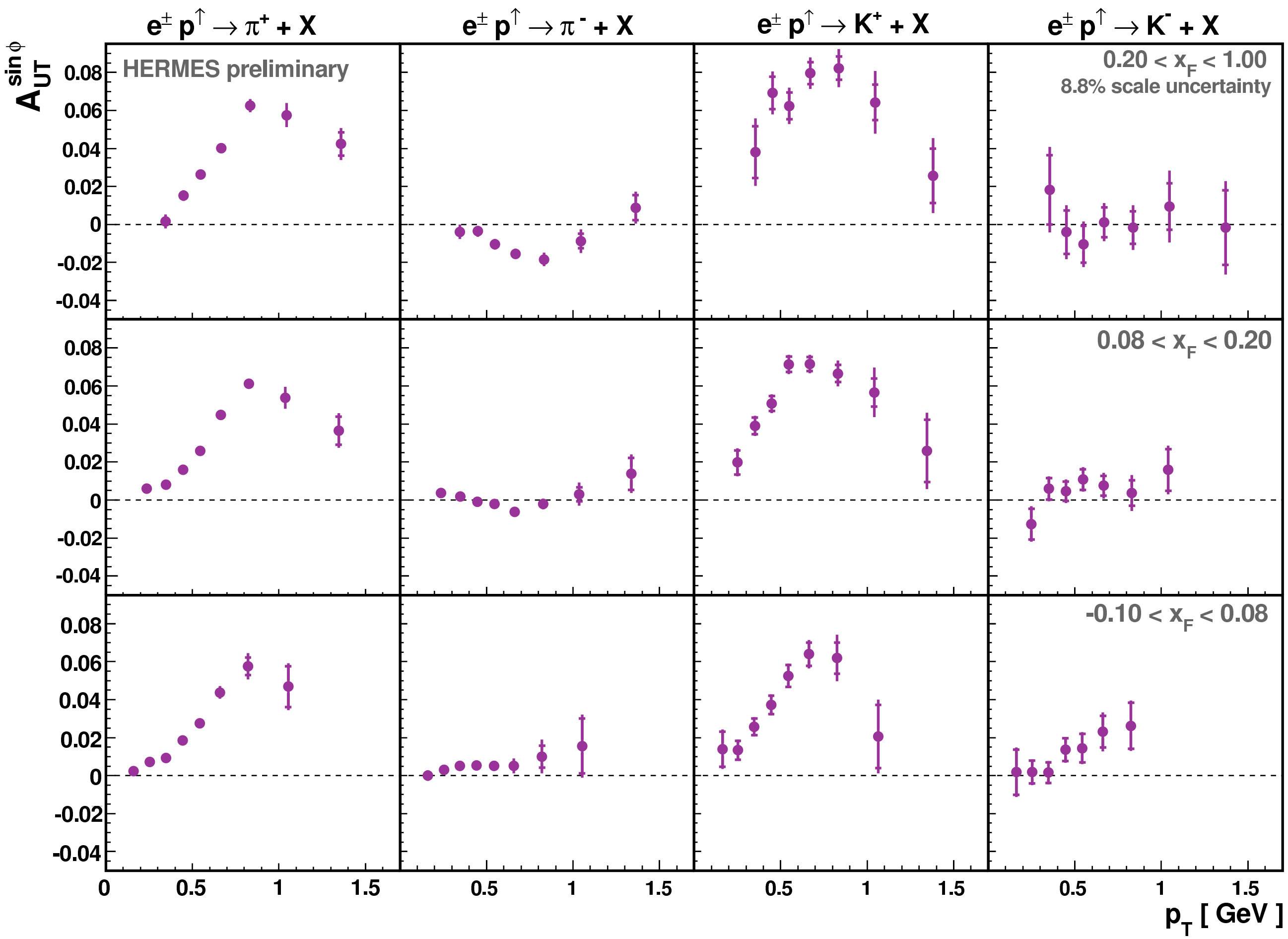
$A_{UT}^{\sin\phi}$ % p_T



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

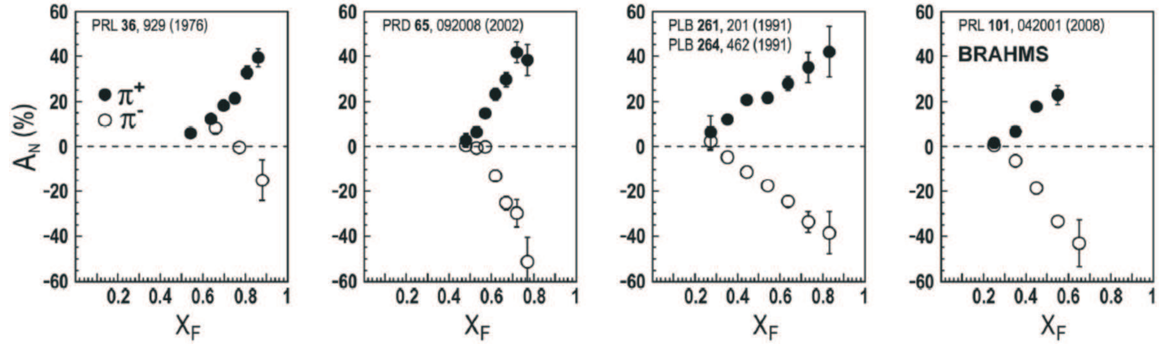
π^+ and K^+ asymmetries decrease at high P_T

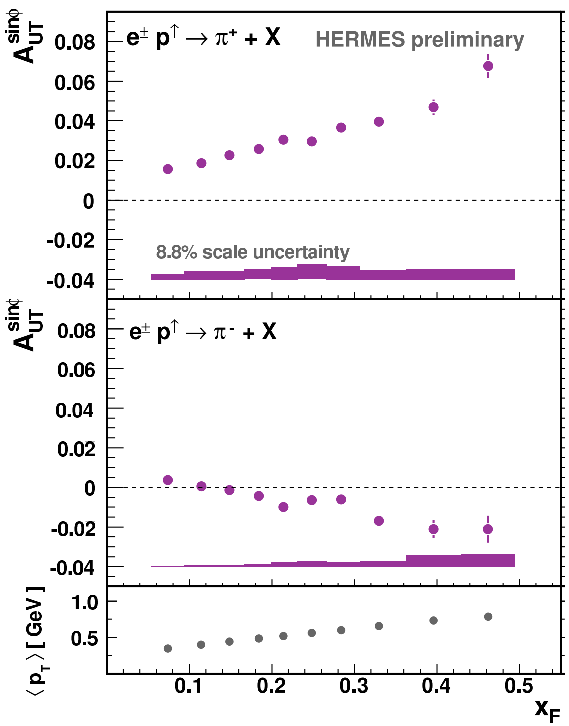
$A_{UT}^{\sin\phi}$ % p_T & x_F



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

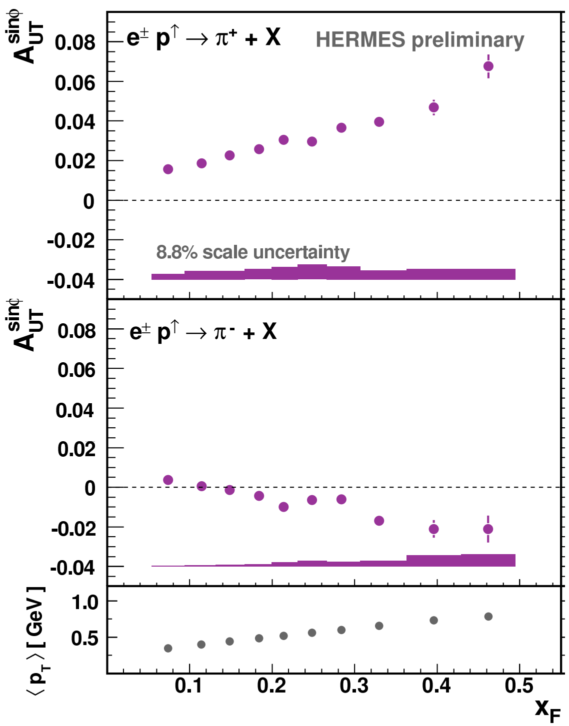
comparison to previous measurements and theory

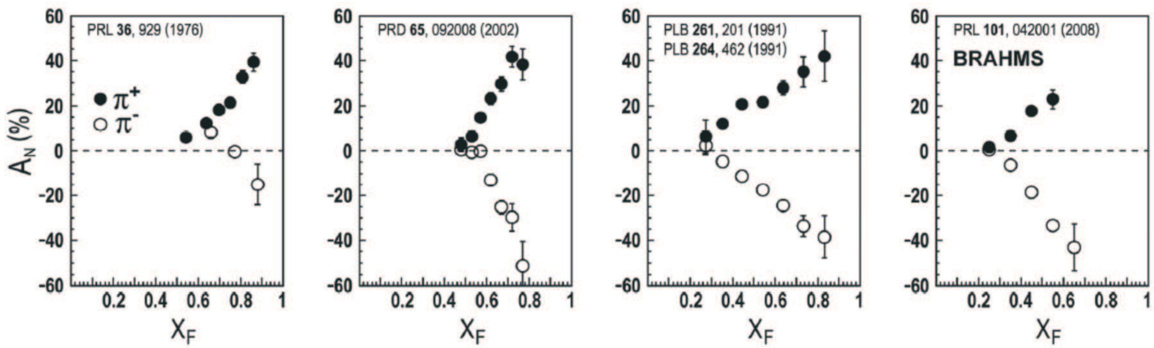




- A_N in $p^\uparrow p$ is larger than in $ep^\uparrow$
- u-quark dominance in $ep^\uparrow$ may explain the smaller size of π^- asymmetry

comparison to previous measurements and theory





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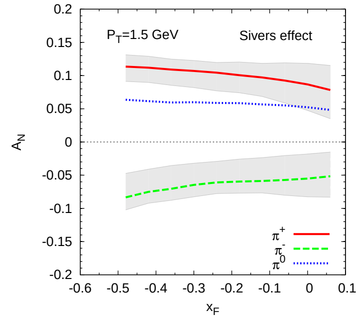
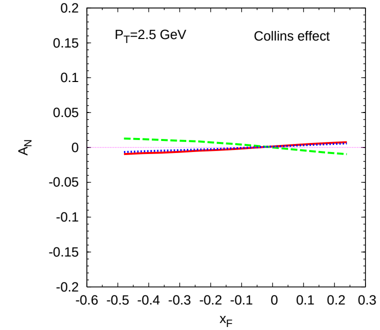
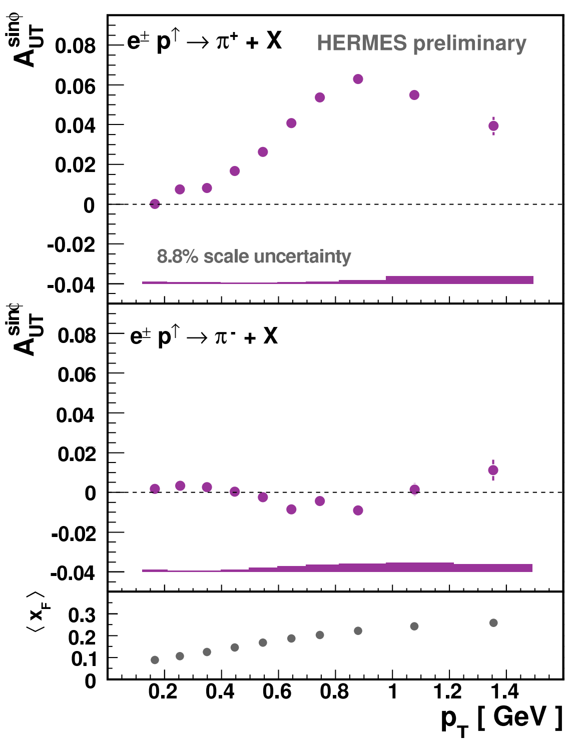


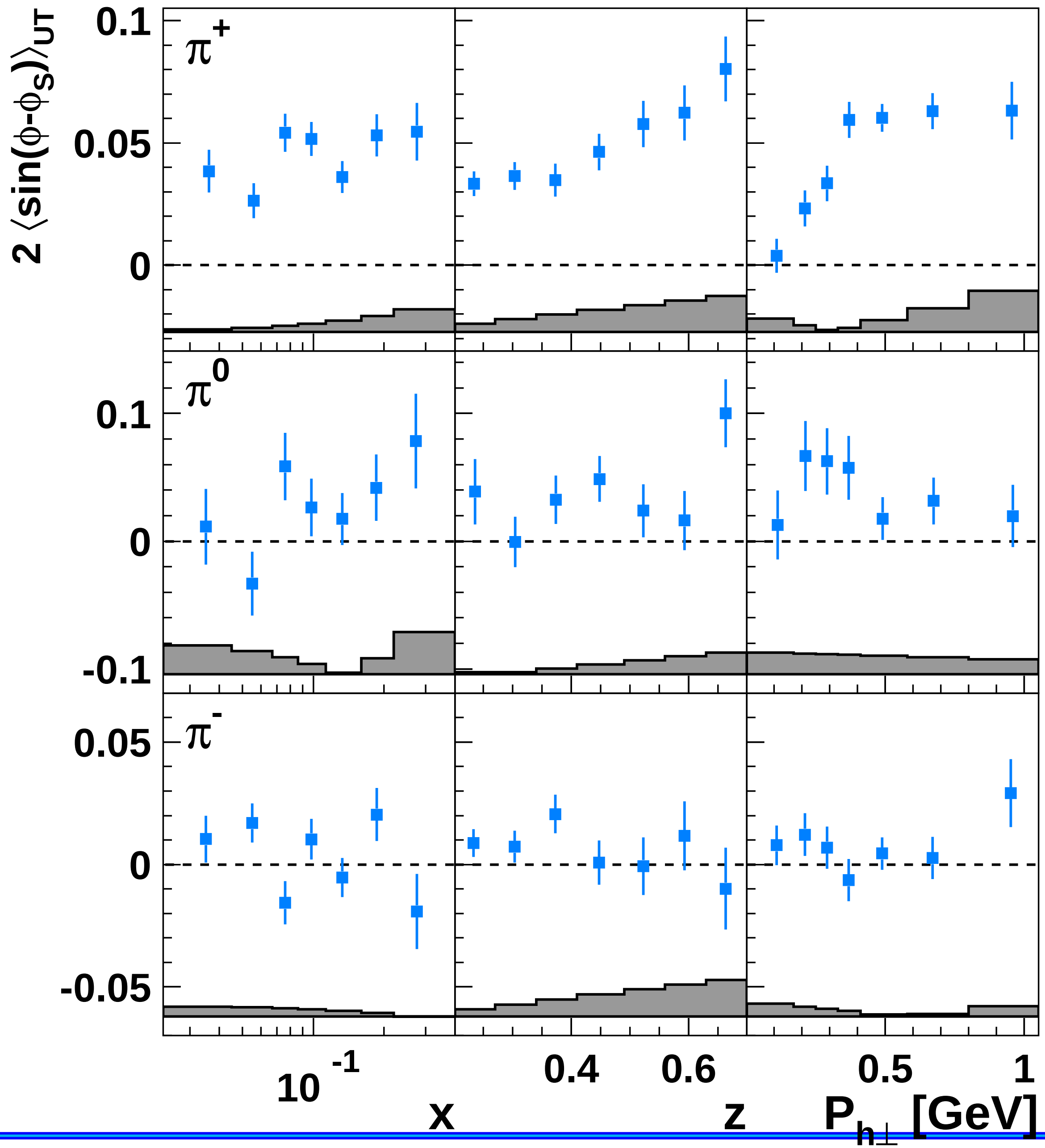


- exp: electron moves along the positive z direction
- theory: proton moves along the positive z direction

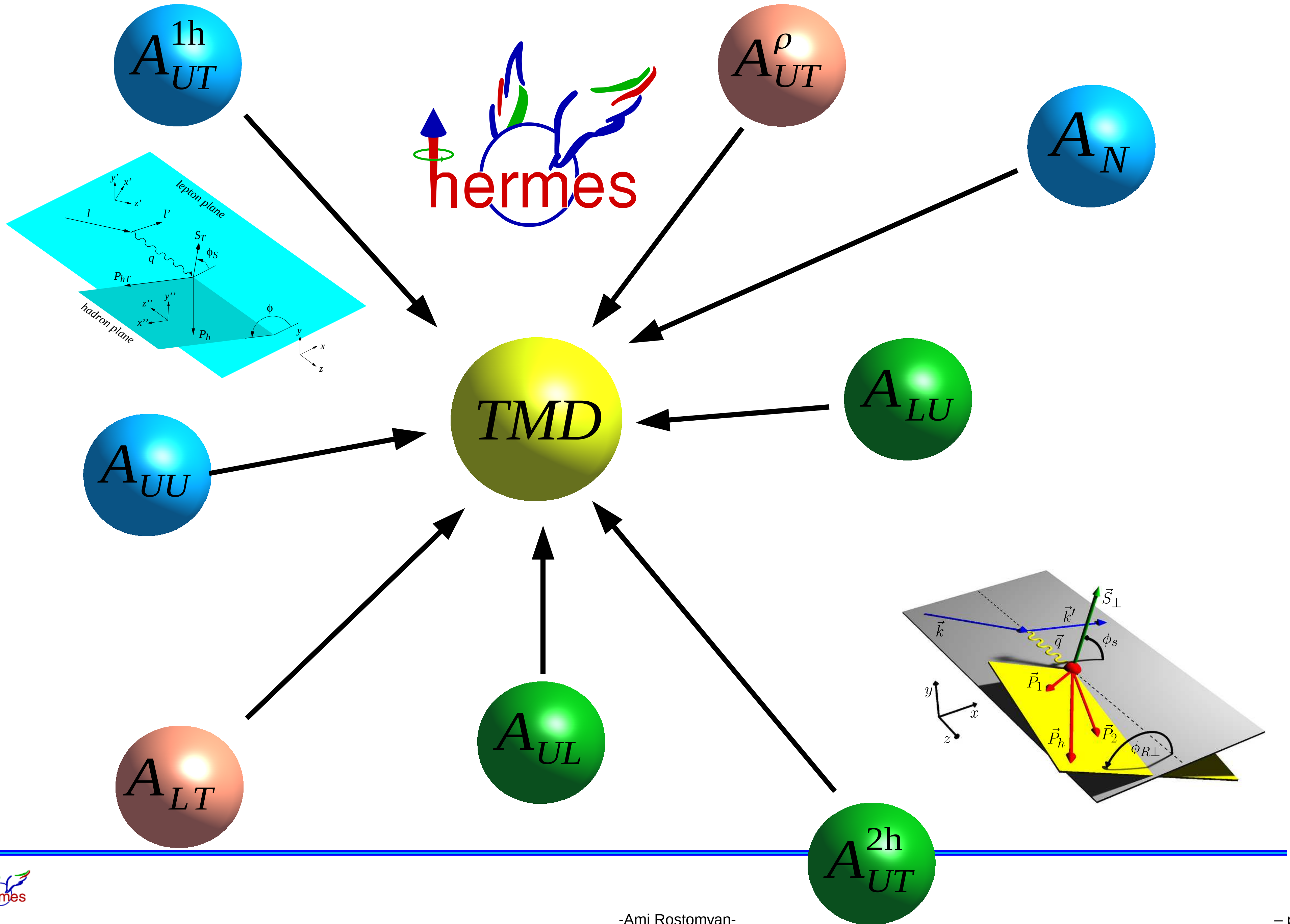
$$A_N^{lp^\uparrow}(x_F, P_T) = -A_N^{lp^\uparrow}(-x_F, P_T)$$

comparison to SIDIS measurements



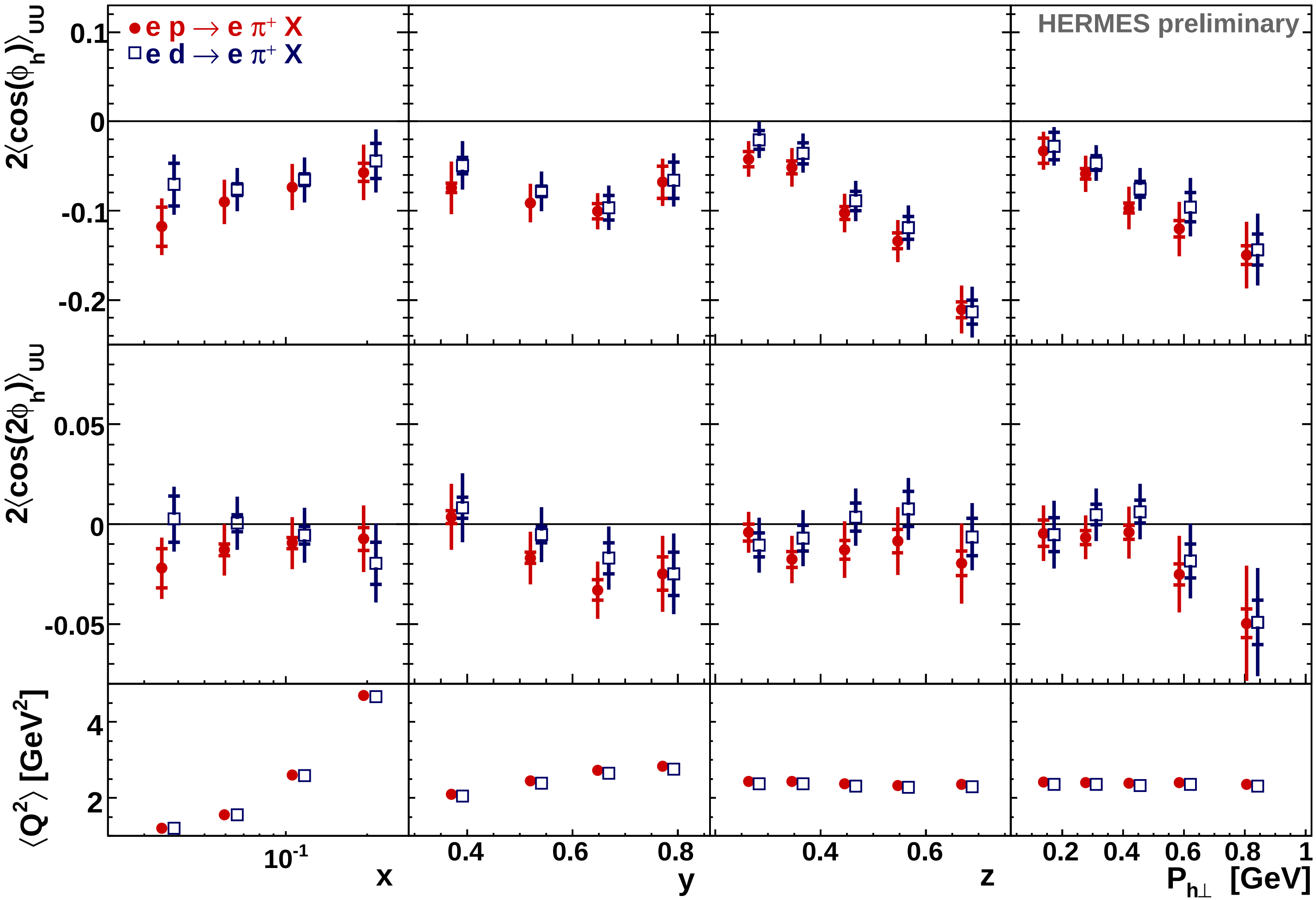


summary



A_{UT}^{1h}
hermes
A_{UT}^{ρ}
A_N
lepton plane
hadron plane
A_{LU}
A_{UU}
TMD
A_{LT}
A_{UL}
A_{UT}^{2h}

BACKUP



- similar results for H and D targets
- implies $h_1^{\perp,u}$ and $h_1^{\perp,d}$ have the same sign