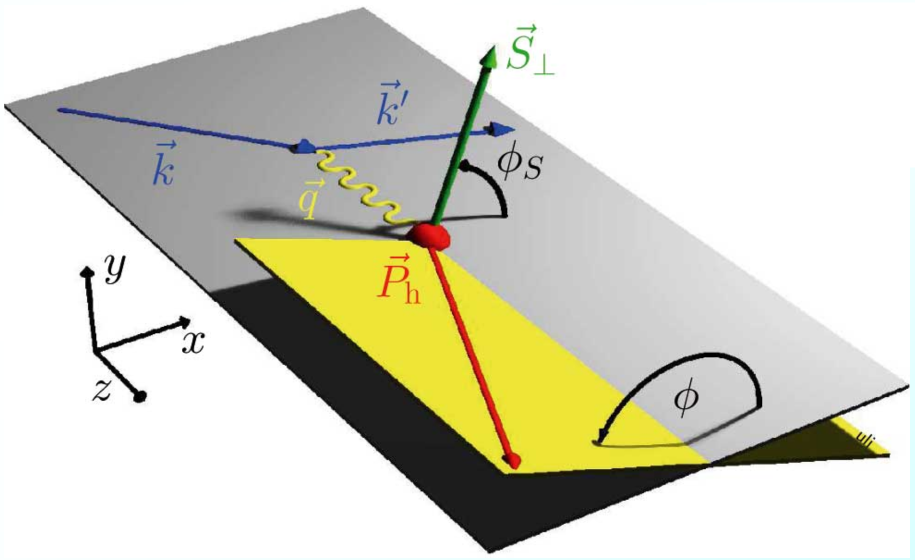
Selected Recent hermes Results on Azimuthal Asymmetries and TMDs

Klaus Rith

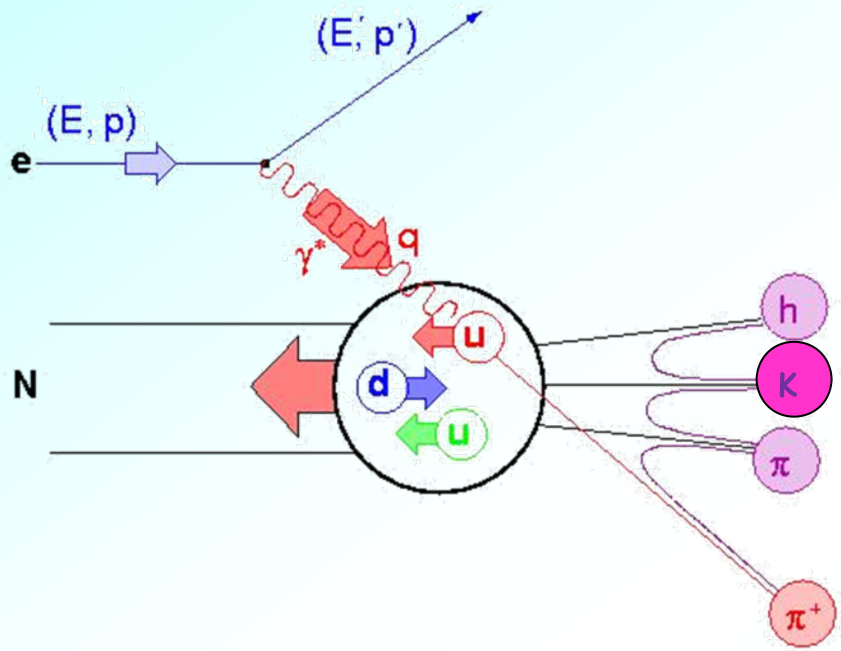
University of Erlangen-Nürnberg & DESY



IWHSS 2010, San Servolo

March 16, 2010

(Semi-)Inclusive Deep-Inelastic Scattering



$$Q^2 \stackrel{lab}{=} 4EE' \sin^2(\theta/2)$$
$$\nu \stackrel{lab}{=} E - E'$$
$$W^2 \stackrel{lab}{=} M^2 + 2M\nu - Q^2$$
$$x \stackrel{lab}{=} Q^2/2M\nu$$
$$y \stackrel{lab}{=} \nu/E$$
$$z \stackrel{lab}{=} E_h/\nu$$

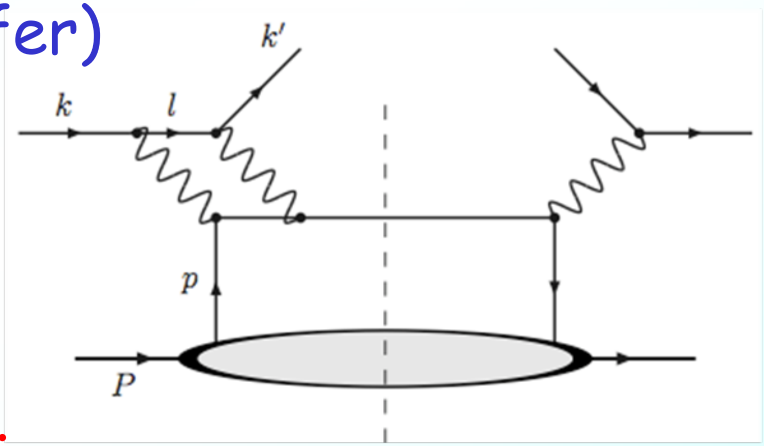
Factorisation ⇒ $\sigma^{eN\rightarrow ehX} = \sum_q DF^{N\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes FF^{q\rightarrow h}$

DF(x,Q^2): Parton Distribution Function – $q(x,Q^2)$, $\Delta q(x,Q^2)$, $\delta q(x,Q^2)$...

FF(z,Q^2): Fragmentation Function – $D_1(z,Q^2)$, $H_1^{\perp}(z,Q^2)$, ...

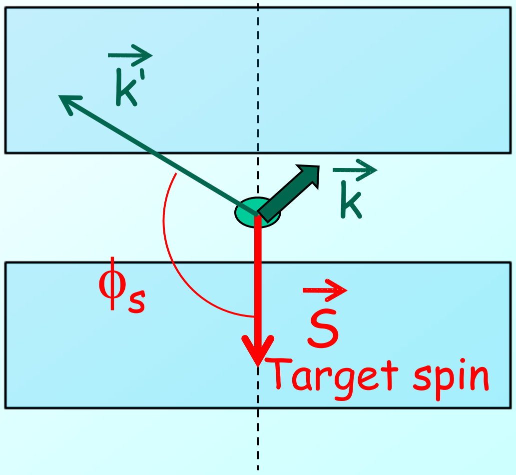
Search for a 2-γ-exchange effect in DIS

- 2-γ exchange best candidate to explain discrepancy in measurements of nucleon form factor $G_E(Q^2)$ (Rosenbluth ↔ polarisation transfer)



- Interference between 1-γ and 2-γ exchange amplitudes
  ➡ transverse target single spin asymmetry (TSA) in inclusive DIS
- TSA ~ beam charge
- TSA ~ $\vec{S}(\vec{k} \times \vec{k}')$ - either measure left-right asymmetries or $\sin(\phi_S)$ modulation

Front view of HERMES



TSA in inclusive DIS

Inclusive DIS: $e^{\pm} p^{\uparrow} \rightarrow e' X$

	$\langle P \rangle$	Events
e+	0.75	2.9 M
e-	0.71	4.8 M

Spin-flip every 90 s

→ acceptance effects cancel

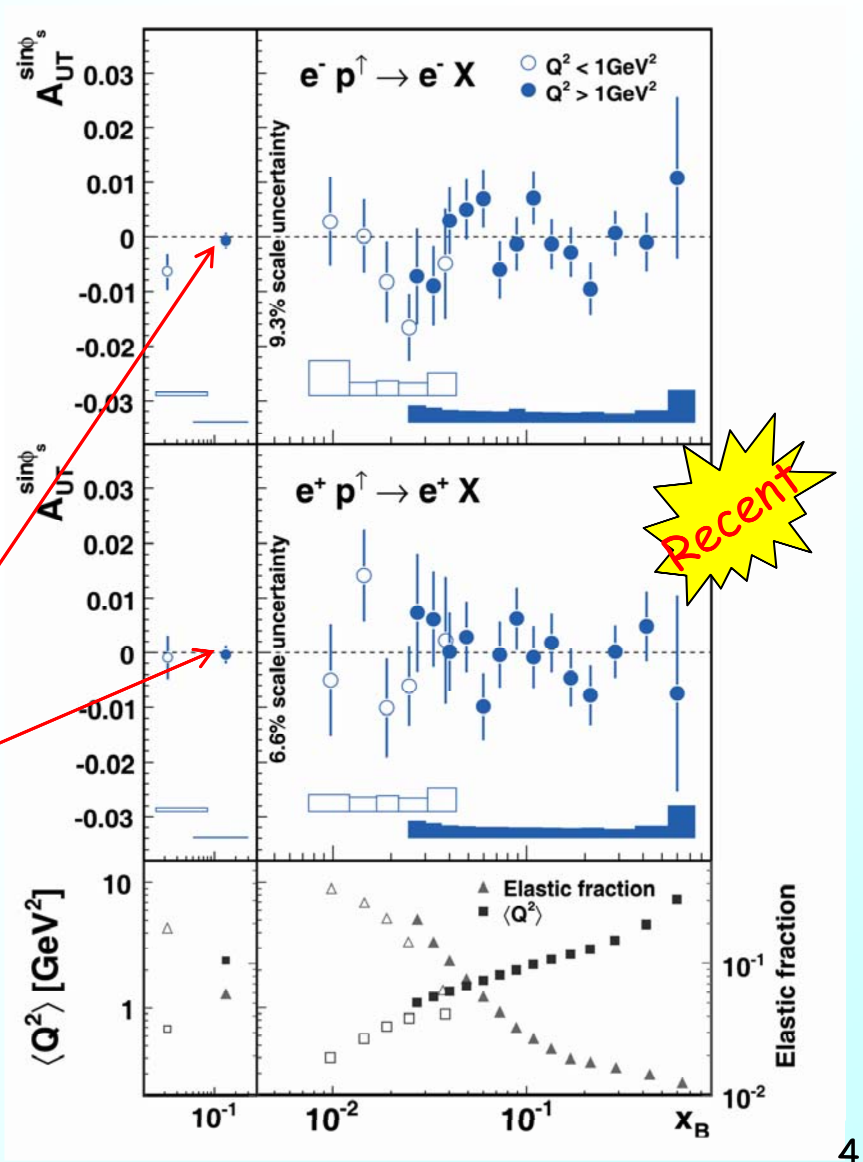
$$A_{UT}(x_B, Q^2, \phi_s) \cong A_{UT}^{\sin\phi_s}(x_B, Q^2) \sin\phi_s$$

$$A_N = 2/\pi \, A_{UT}^{\sin\phi_s} = O(10^{-3})$$

same for e+ and e-

No sign for 2-photon exchange in DIS

PLB 682 (2010) 351

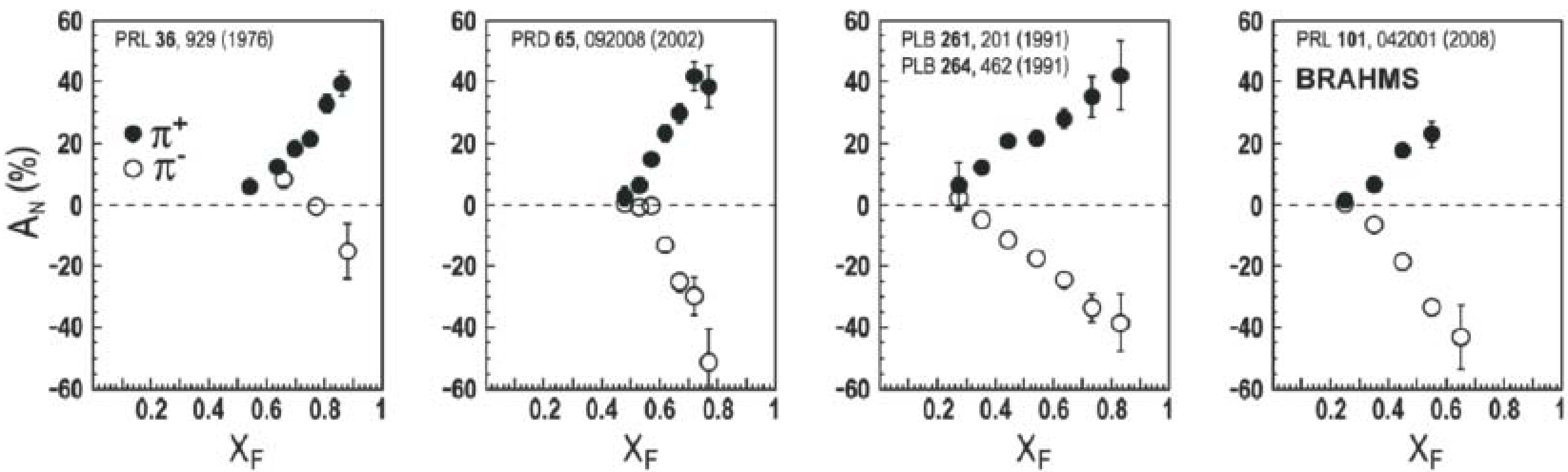


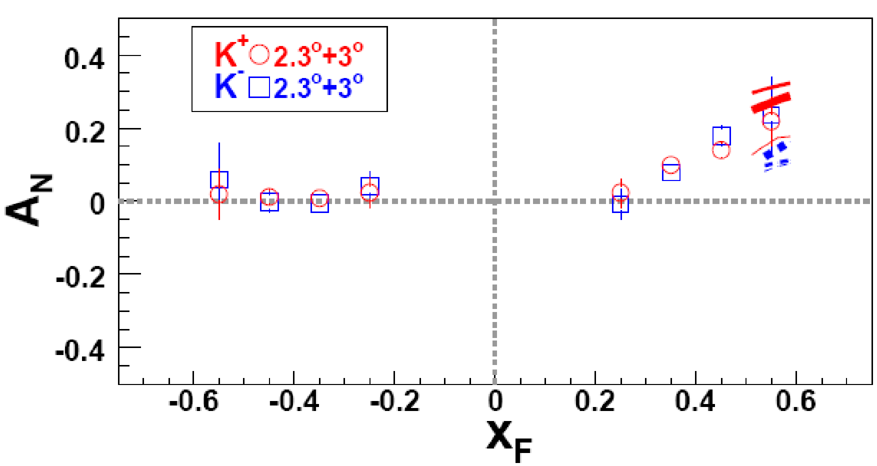
Recent

TSA in inclusive hadron production

Reminder: A_N in $p\uparrow p \rightarrow \pi$ (K) X

	ANL	BNL	FNAL	RHIC
$\sqrt{s}$	4.9 GeV	6.6 GeV	19.4 GeV	62.4 GeV





Interpretation:

- Sivers effect?
- Collins effect?
- twist-3 ?

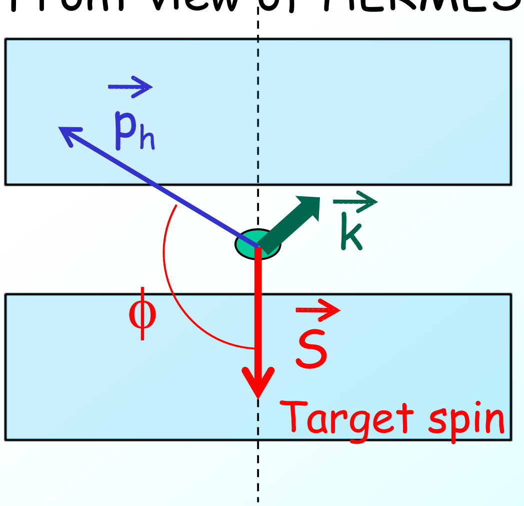
TSA in inclusive hadron electroproduction

Inclusive hadron electroproduction:
$e^{\pm} p^{\uparrow} \rightarrow h\, X$

Scattered lepton not detected:
➡ quasi-real photoproduction

π^+	π^-	K^+	K^-
66.4 M	56.8 M	5.5 M	3.0 M

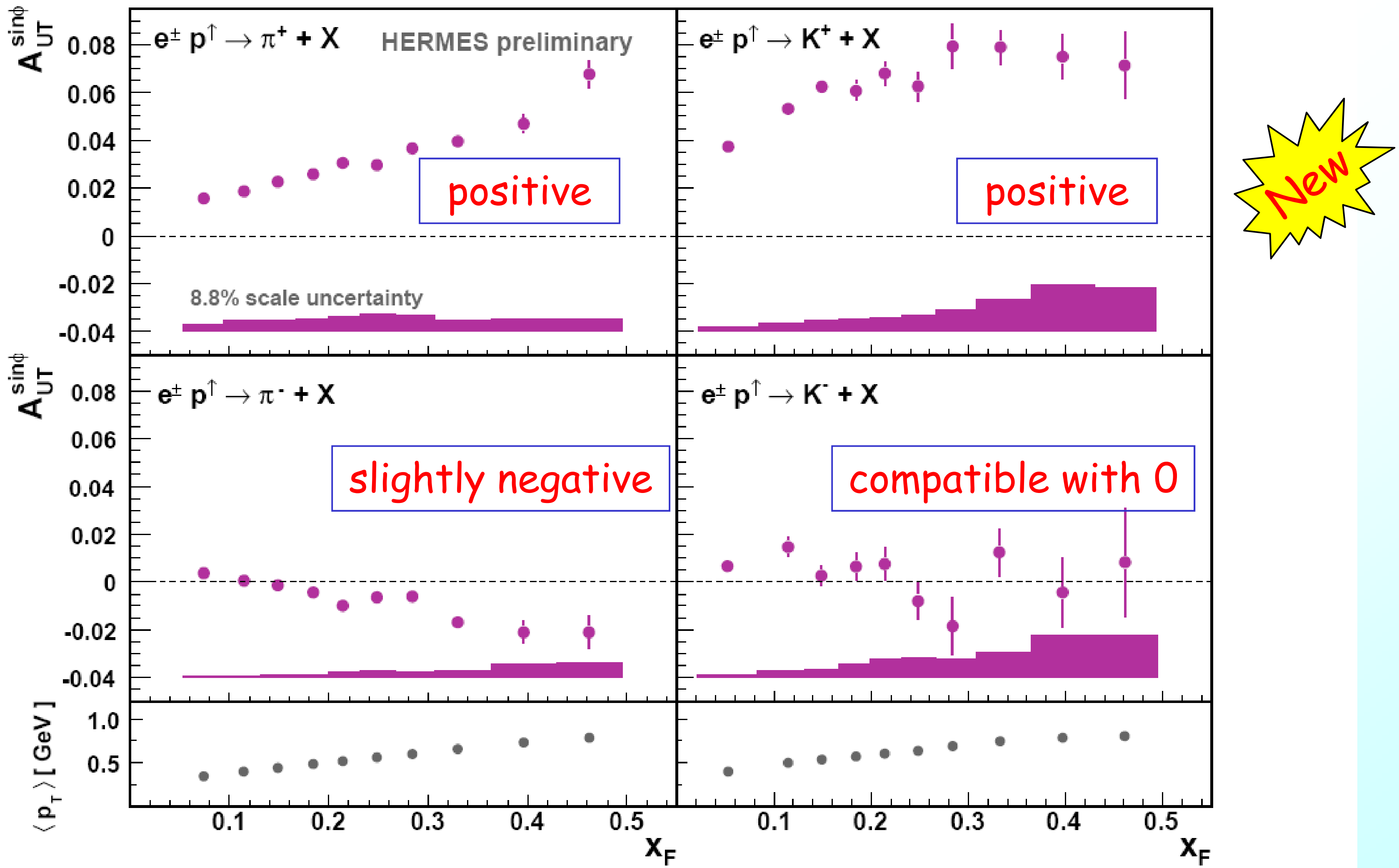
Front view of HERMES



Spin-flip every 90 s
➡ acceptance effects cancel

$$A_{UT}(x_B,Q^2,\phi) \cong A_{UT}^{\sin\phi}(x_B,Q^2)\sin\phi$$

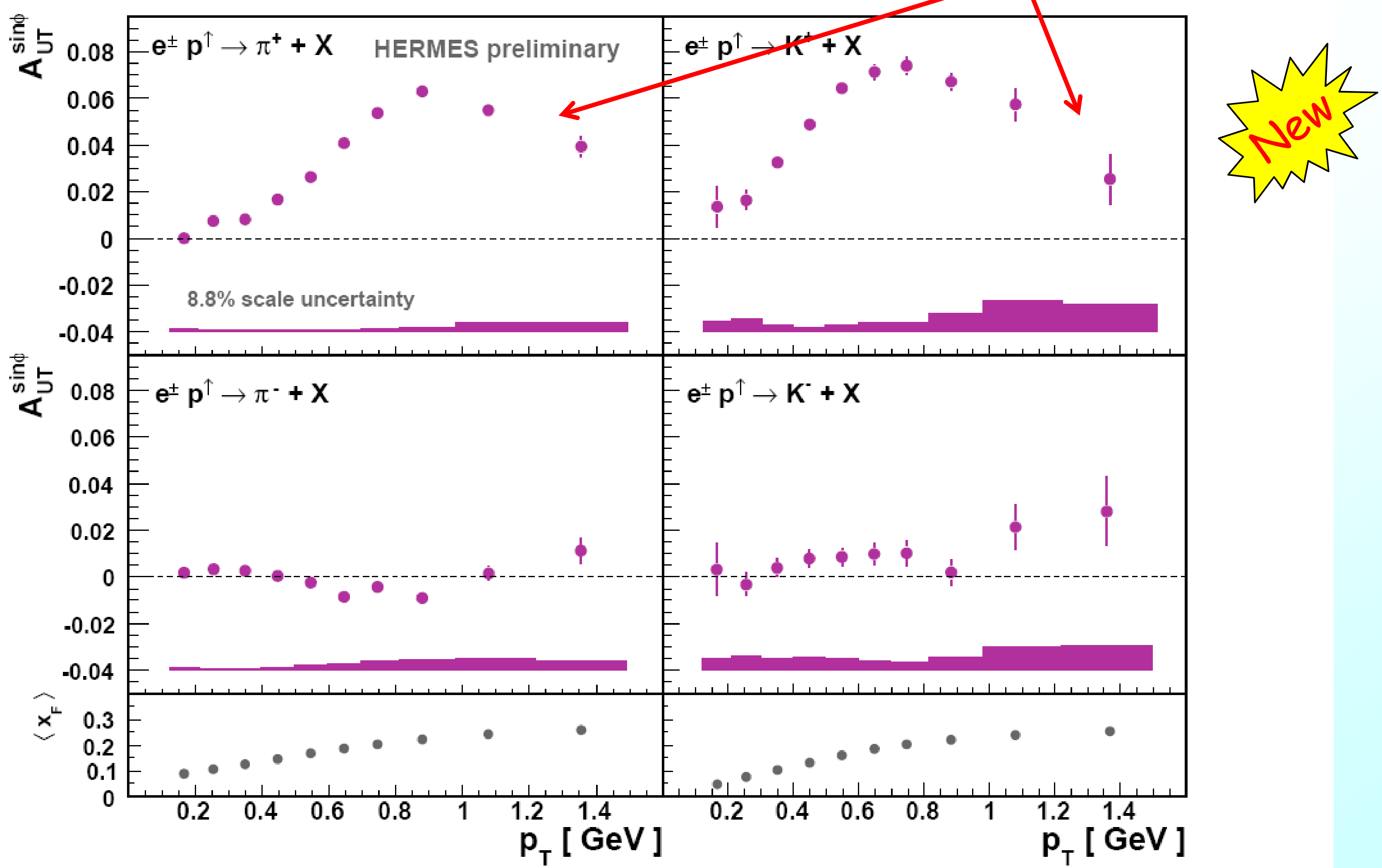
Inclusive hadron TSA



A_N much smaller than in pp↑

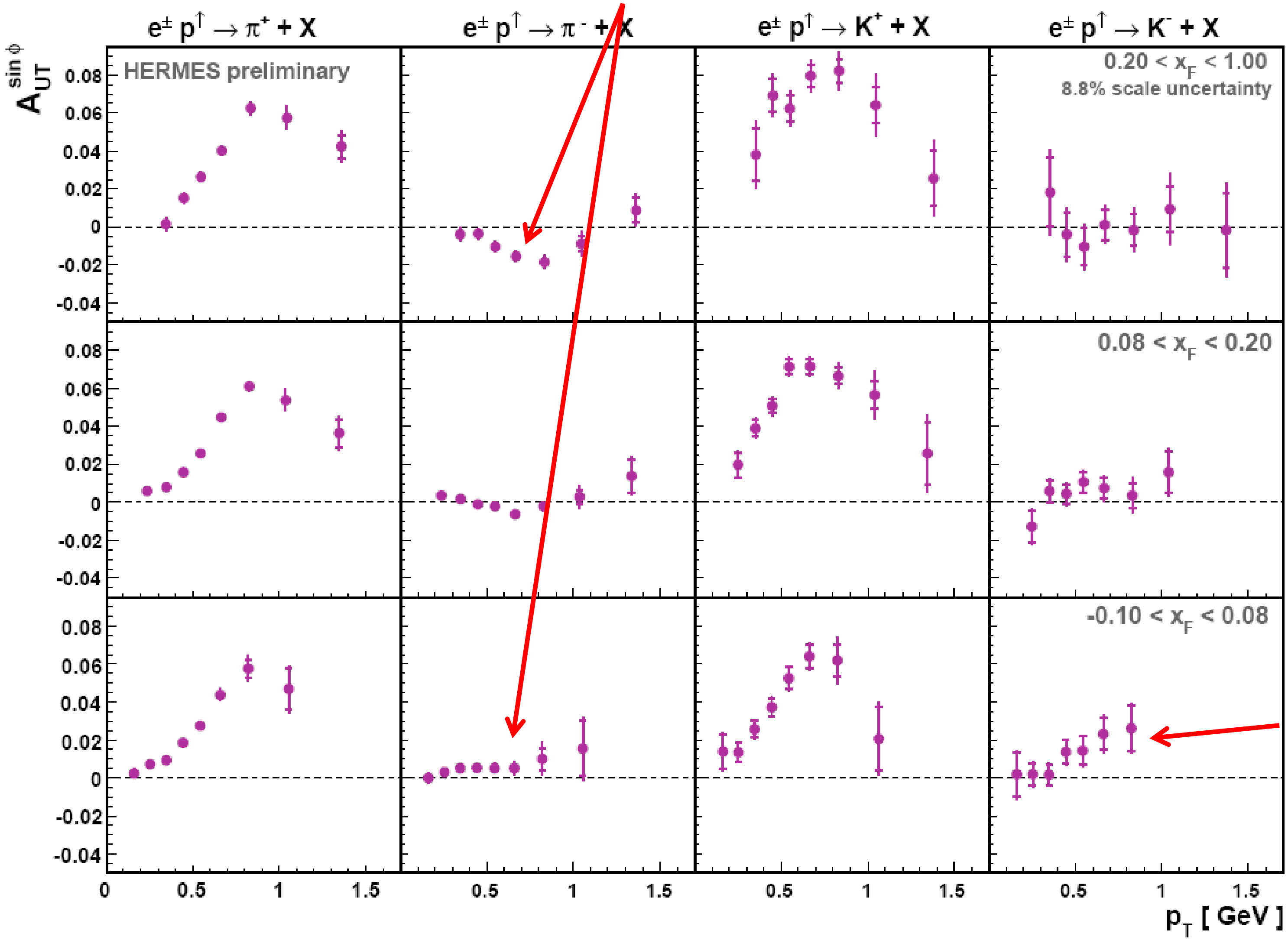
Inclusive hadron TSA

Decrease at high p_T



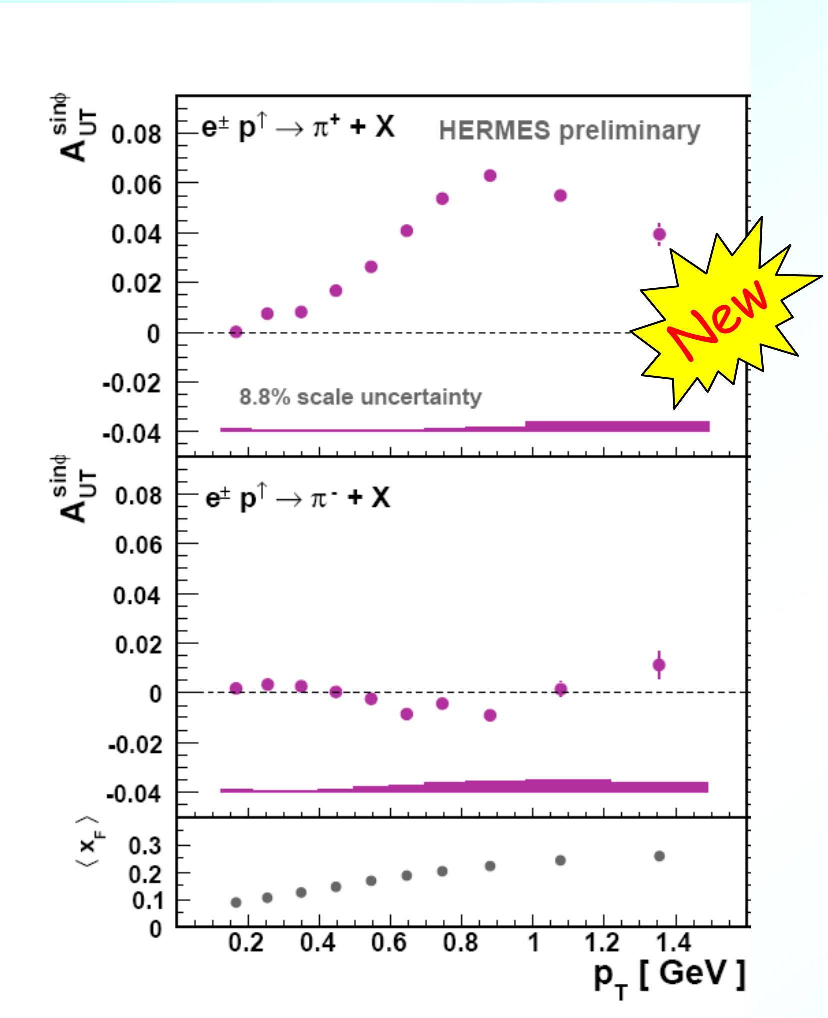
Inclusive hadron TSA

Sign change for π-

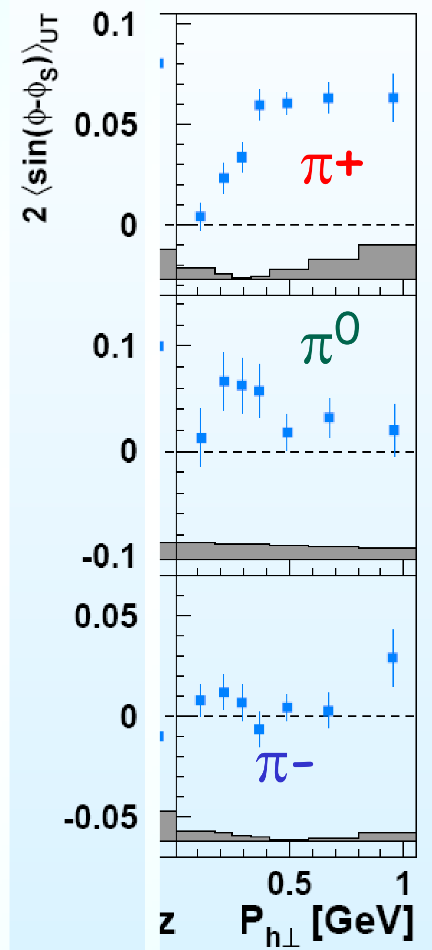


positive for $x_F \cong 0$

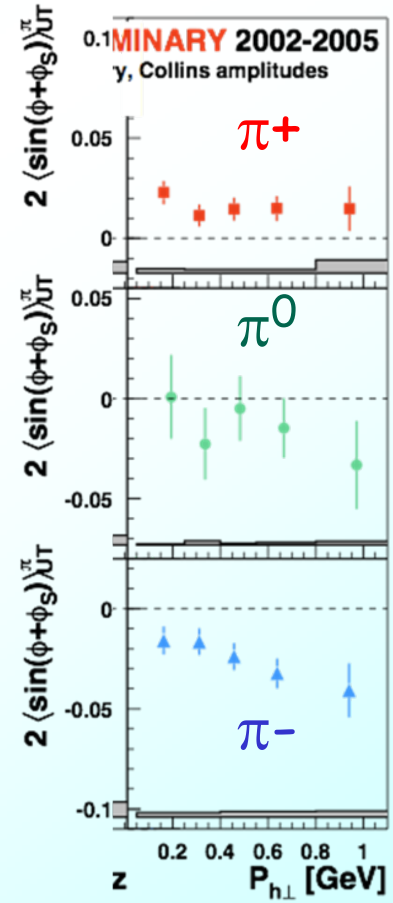
Inclusive hadron TSA



Sivers



Collins



A_N resembles Sivers (more later)

Model predictions:

M. Anselmino et al., PRD 81 (2010) 034007

pions

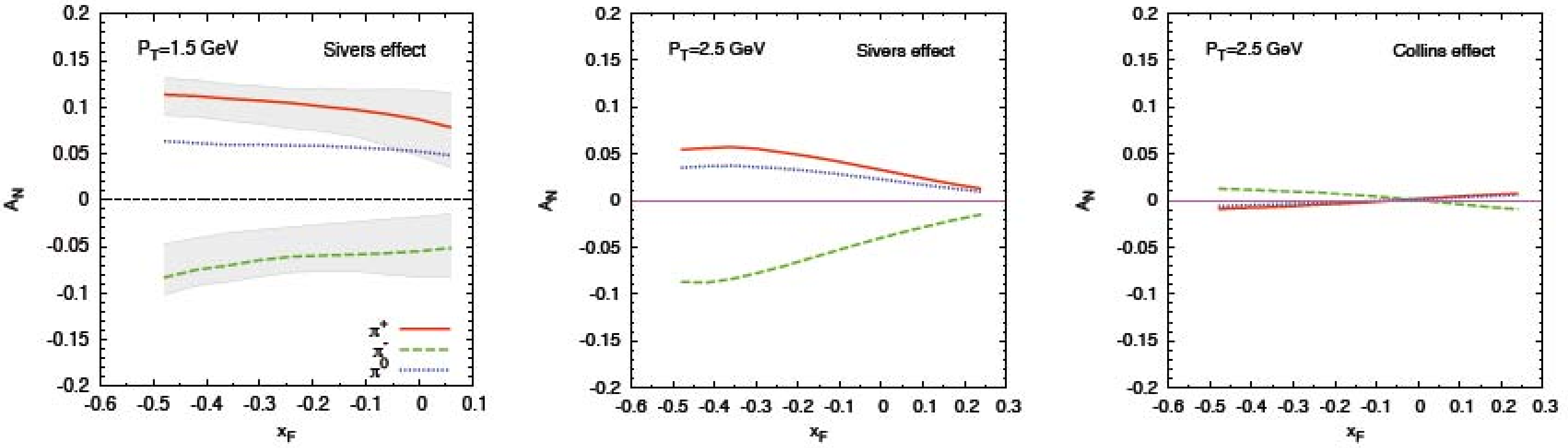


FIG. 2: Estimates of A_N vs. x_F for the $p^\uparrow \ell \to \pi X$ process at HERMES ($\sqrt{s} \simeq 7$ GeV). Left panel: Sivers effect at $P_T = 1.5$ GeV; central panel: Sivers effect at $P_T = 2.5$ GeV; right panel: Collins effect at $P_T = 2.5$ GeV.

Transverse Momentum Dependent DFs

LO quark distribution functions

See discussion by A. Bacchetta

Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197
A. Bacchetta et al., JHEP 0702 (2007)

		quark U	quark L	quark T
nucleon	U	f_1		$h_1^{\perp}$ ← Boer-Mulders DF *#
nucleon	L		g_1	$h_{1L}^{\perp}$ ← 'worm-gear 1' DF #
nucleon	T	$f_{1T}^{\perp}$ ↑ Sivers DF *	$g_{1T}^{\perp}$ ↑ 'worm-gear 2' DF	h_1 ← Transversity DF # $h_{1T}^{\perp}$ ← Prezelosity DF #

Only f_1 and g_1 measurable in inclusive DIS, all others in SIDIS

$D_1 \equiv D_q^h$ = ‚normal' FF,
$H_1^{\perp}$ = spin-dependent Collins FF #

* T-odd
\# chiral-odd

TMDs in SIDIS

$$d\sigma = d\sigma^{0}_{UU} + \cos 2\phi \, d\sigma^{1}_{UU} + \frac{1}{Q}\cos\phi \, d\sigma^{2}_{UU} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma^{3}_{LU}$$

$$+ S_T \Big\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT}$$

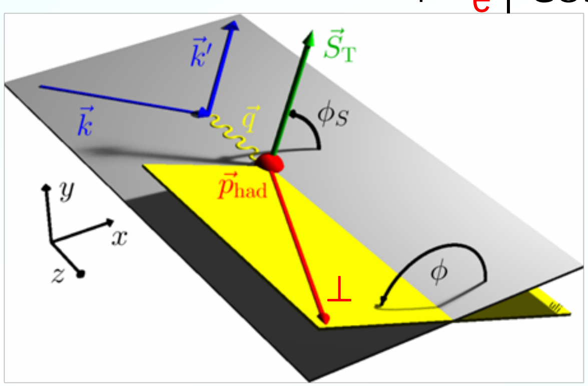
$$+ \frac{1}{Q}\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \frac{1}{Q}\sin\phi_S \, d\sigma^{12}_{UT}$$

$$+ \lambda_e \Big[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\cos\phi_S \, d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \Big] \Big\}$$

$$+ S_L \Big\{ \sin 2\phi \, d\sigma^{4}_{UL} + \frac{1}{Q}\sin\phi \, d\sigma^{5}_{UL} + \lambda_e \Big[d\sigma^{6}_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^{7}_{LL} \Big] \Big\}$$

$d\sigma_{XY}$ — X: **Beam**, Y: **Target**

Polarization



TMDs in SIDIS

LO Function	Moment	Convolution	Name
$d\sigma^{9}_{UT}$	$\sin(\phi + \phi_s)$	$h_1 \otimes H_1^{\perp}$	Transversity
$d\sigma^{8}_{UT}$	$\sin(\phi - \phi_s)$	$f_{1T}^{\perp} \otimes D_1$	Sivers
$d\sigma^{1}_{UU}$	$\cos(2\phi)$	$h_1^{\perp} \otimes H_1^{\perp}$	Boer-Mulders
$d\sigma^{10}_{UT}$	$\sin(3\phi - \phi_s)$	$h_{1T}^{\perp} \otimes H_1^{\perp}$	Prezelosity
$d\sigma^{4}_{UL}$	$\sin(2\phi)$	$h_{1L}^{\perp} \otimes H_1^{\perp}$	Worm-gear 1
$d\sigma^{13}_{LT}$	$\cos(\phi - \phi_s)$	$g_{1T}^{\perp} \otimes D_1$	Worm-gear 2

The others are subleading, i.e., suppressed by 1/Q

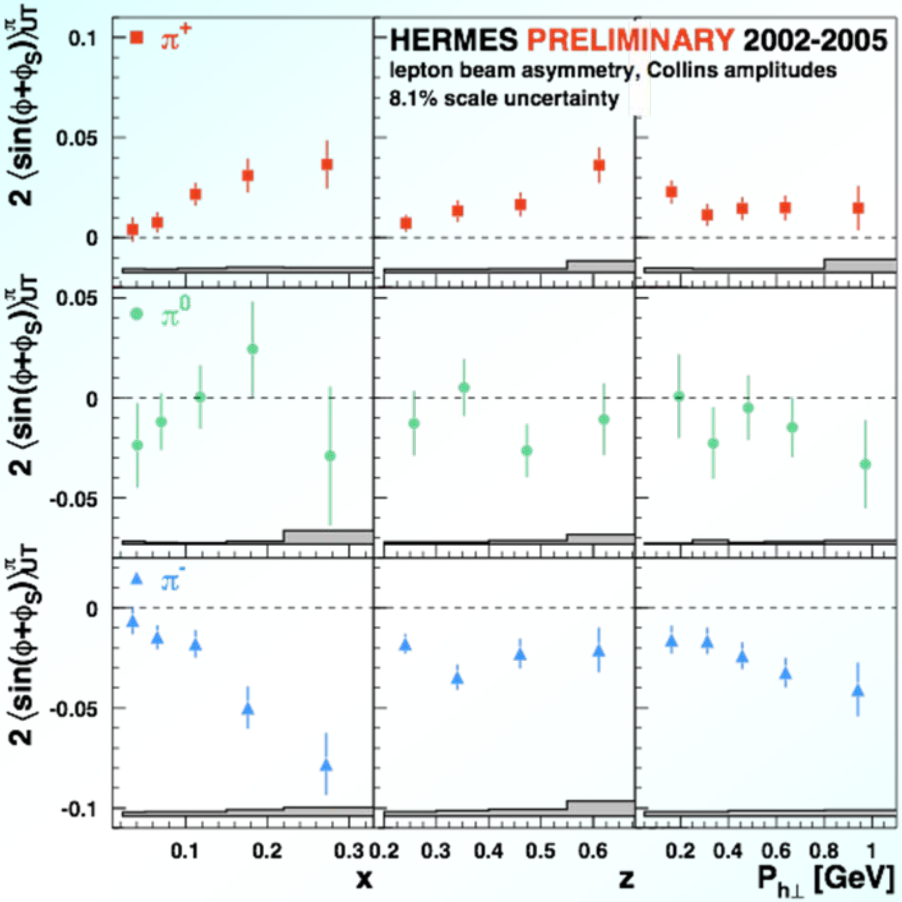
Transversity, Collins Amplitudes

Transversity DF

$$2\langle \sin(\phi + \phi_S)\rangle^h_{UT} \sim h_1^q(x) \otimes H_1^{\perp q}(z)$$

Collins FF

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation, i.e. $u \rightarrow \pi^-$

$$H_1^{\perp}{}_{,disf} \approx - H_1^{\perp}{}_{,fav}$$

- Final results to be published soon

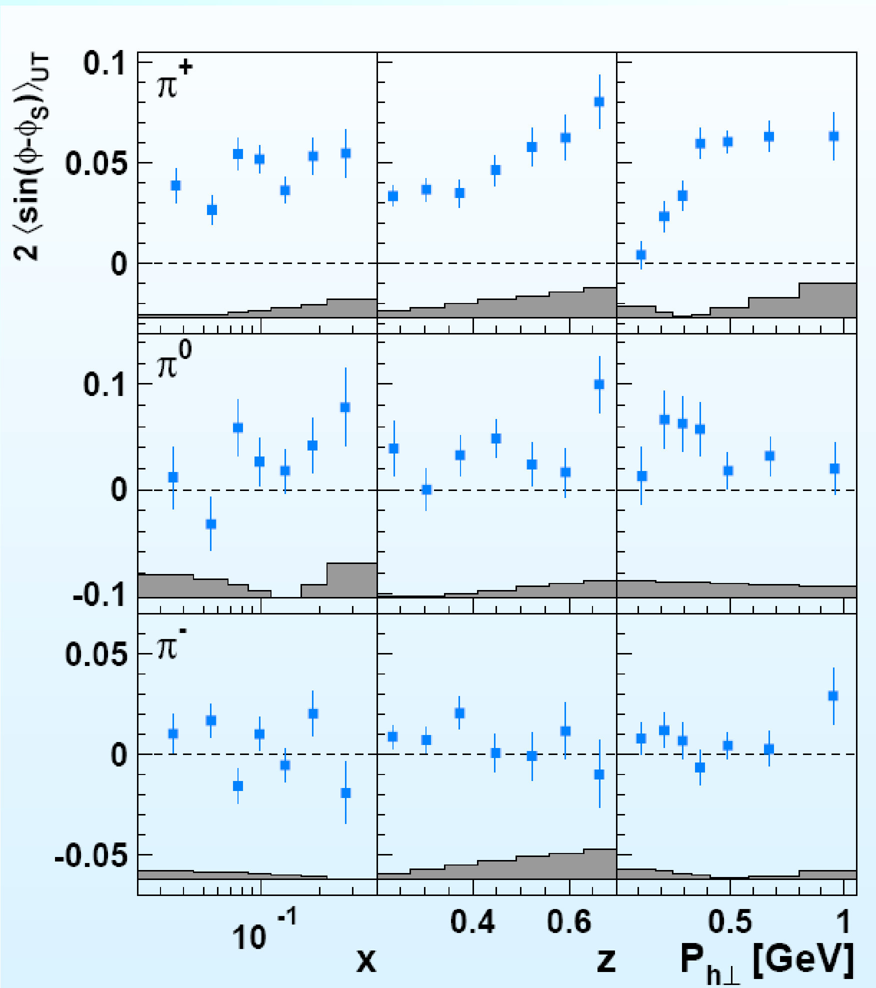
Sivers Amplitudes for Pions

Sivers DF

$$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

PRL 103 (2009) 152002

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



See discussion by S. Melis

- First observation of non-zero Sivers distribution function in DIS

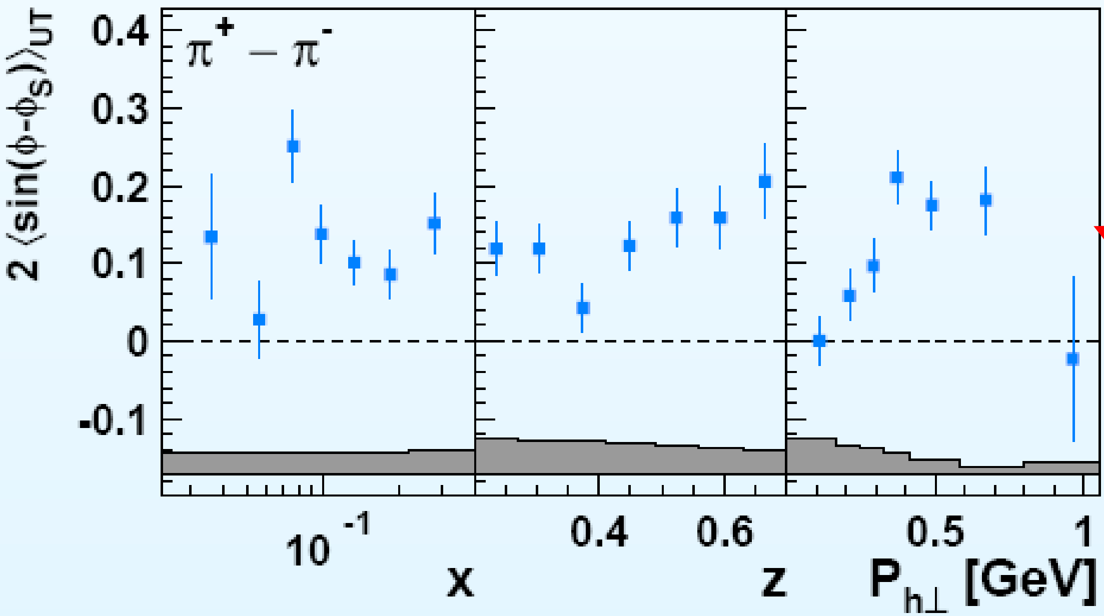
→ Experimental evidence for orbital angular momentum L_q of quarks

But: Quantitative contribution of L_q to nucleon spin still unclear

Transverse SSA for $\pi^+ - \pi^-$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

PRL 103 (2009) 152002



access to Sivers valence distribution

$$2\langle\sin(\phi-\phi_S)\rangle_{UT}^{\pi^+-\pi^-} = -2\frac{4 f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4 f_1^{\perp,u_v} - f_1^{\perp,d_v}}$$

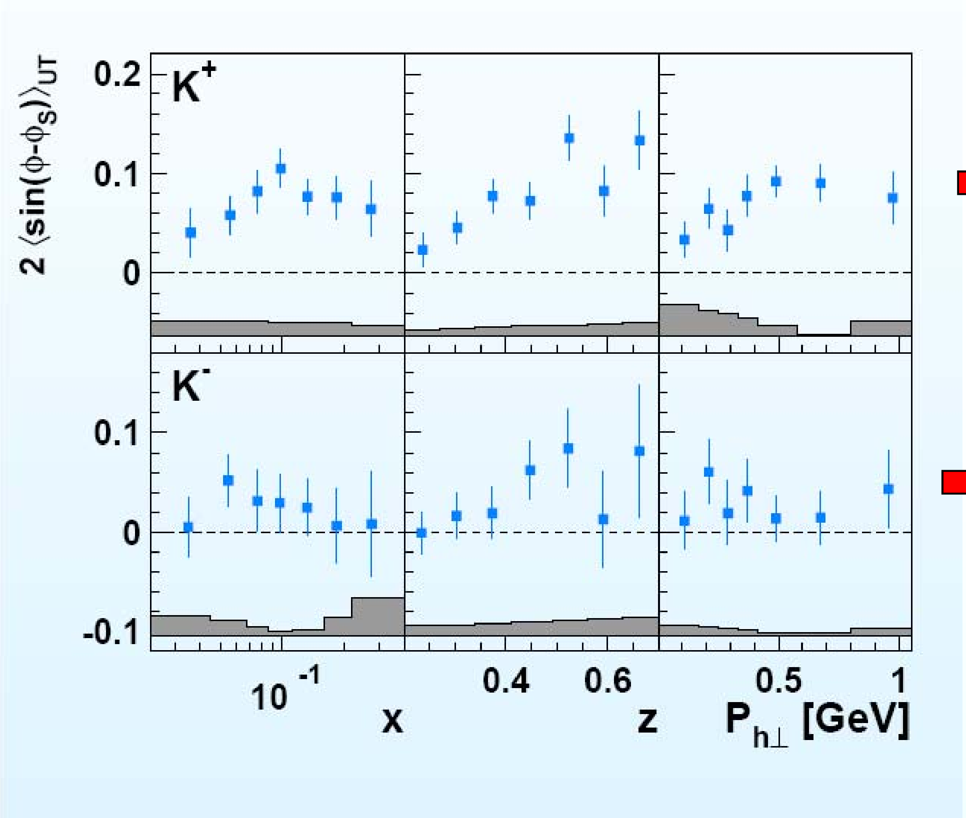
Sivers Amplitudes for Kaons

Sivers DF

$$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

PRL 103 (2009) 152002



See discussion by S. Melis

Large and positive

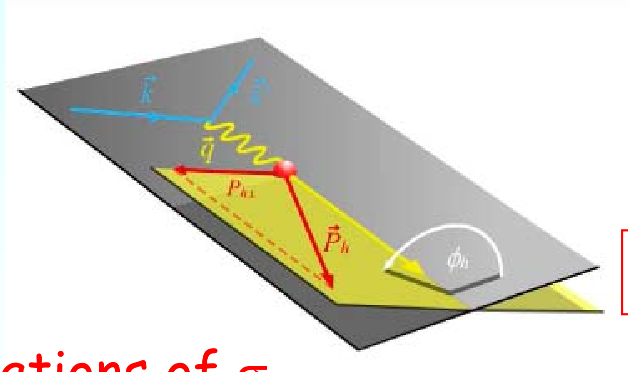
(but smaller than preliminary data)

Slightly positive

Boer-Mulders DF

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Signals for Boer-Mulders DF $h_1^\perp$



See discussion by S. Melis

Azimuthal modulations of σ_{UU}

Twist-4

- leading-twist: $2\langle\cos(2\phi)\rangle_{UU}$ sensitive to $(h_1^\perp \otimes H_1^\perp)$ $(+1/Q^2\ (f_1 \otimes D_1))$
- subleading-twist: $2\langle\cos(\phi)\rangle_{UU}$ sensitive to both $(h_1^\perp \otimes H_1^\perp)$ and $(f_1 \otimes D_1)$ - Cahn effect

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

➡ Correction for finite acceptance, QED radiation, kinematic smearing, detector resoultion

Previously shown: moments for $h^\pm$ from H and D targets

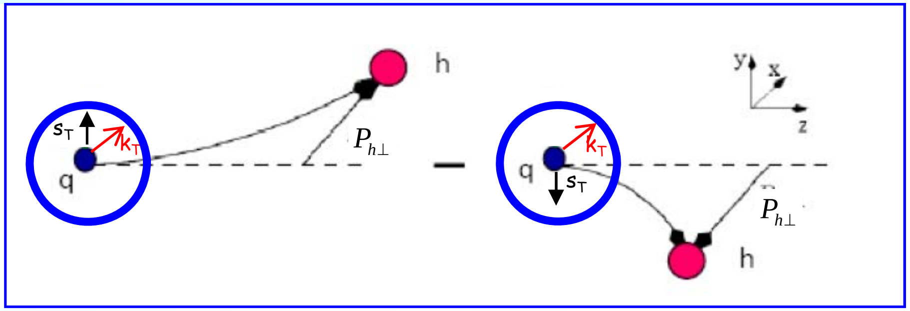
New: moments for $\pi^\pm$ with improved systematics

Boer-Mulders DF

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

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

$\langle \cos 2\phi \rangle_{UU}$



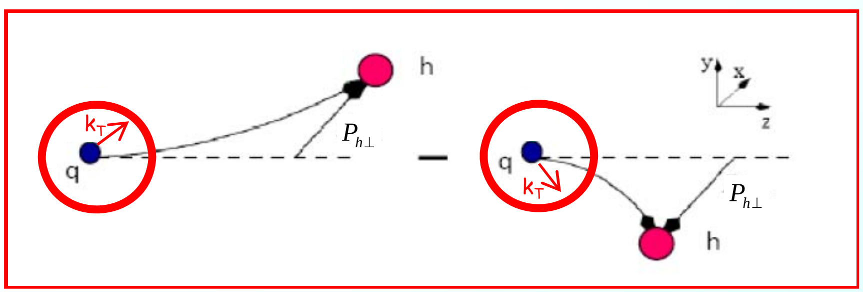
transversely polarised quarks with k_T in unpolarised nucleon

---

$$F_{UU}^{\cos\phi} = \frac{2M}{Q} C\left[-\frac{\hat{h}\cdot\vec{p}_T}{M_h} x h_1^\perp H_1^\perp - \frac{\hat{h}\cdot\vec{k}_T}{M} x f_1 D_1\right]$$

Cahn effect

$\langle \cos\phi \rangle_{UU}$

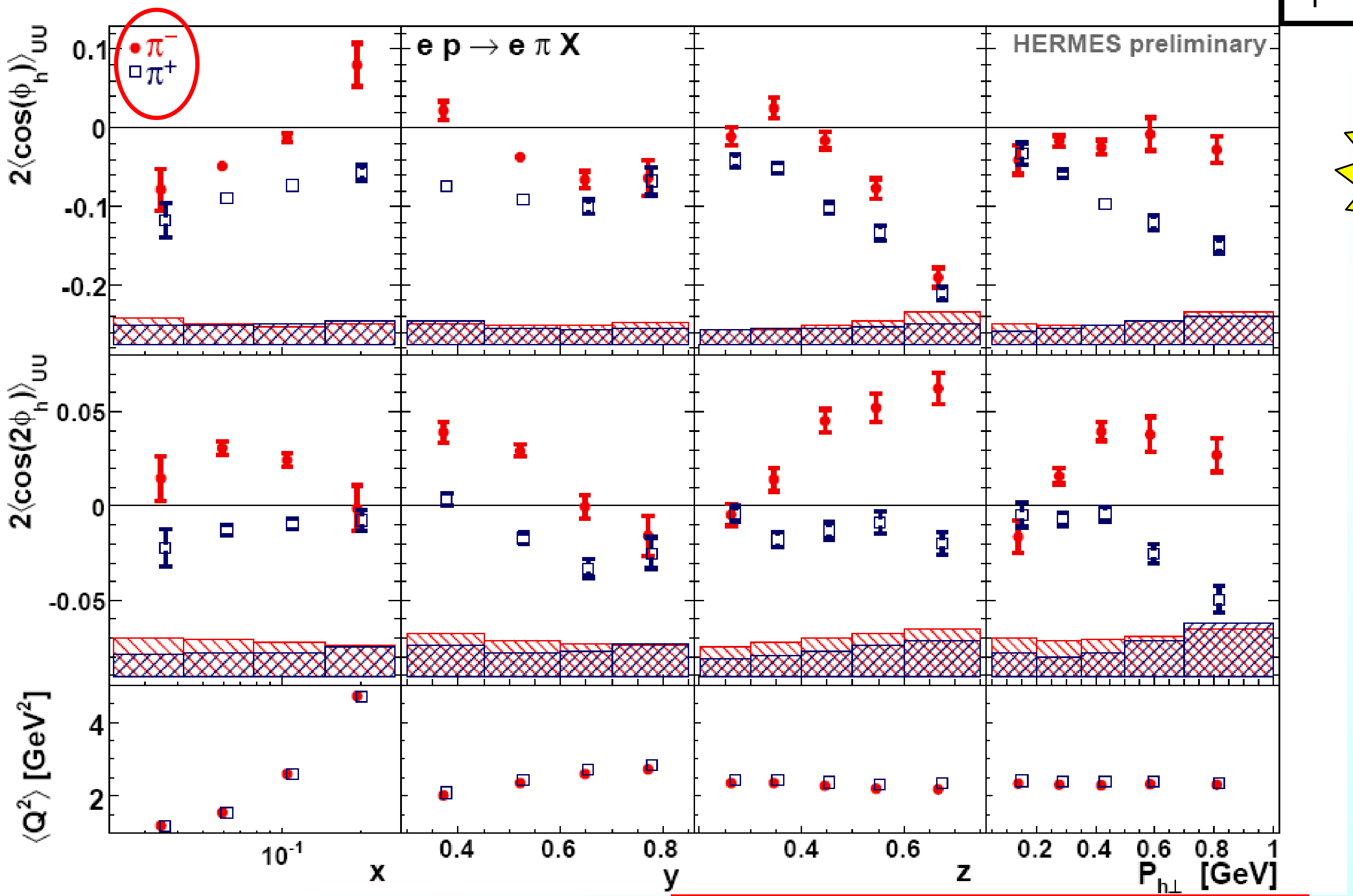


Intrinsic transverse momentum k_T of quarks

$\cos(n\phi)_{UU}$ moments for $\pi^{\pm}$ - H target

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

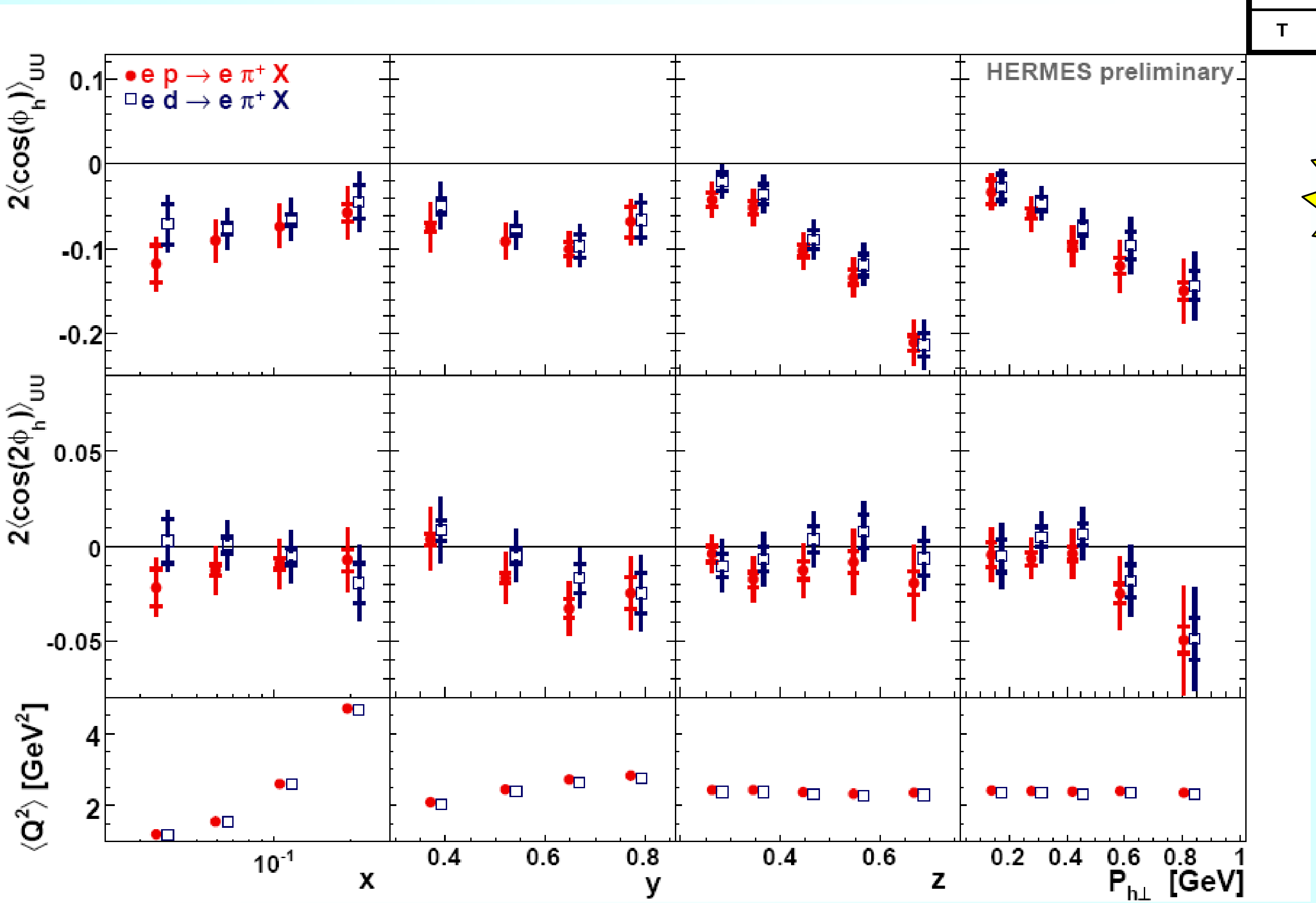
New



See discussion by S. Melis

$\cos(n\phi)_{UU}$ moments for π^+ - H, D target

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



See discussion by S. Melis

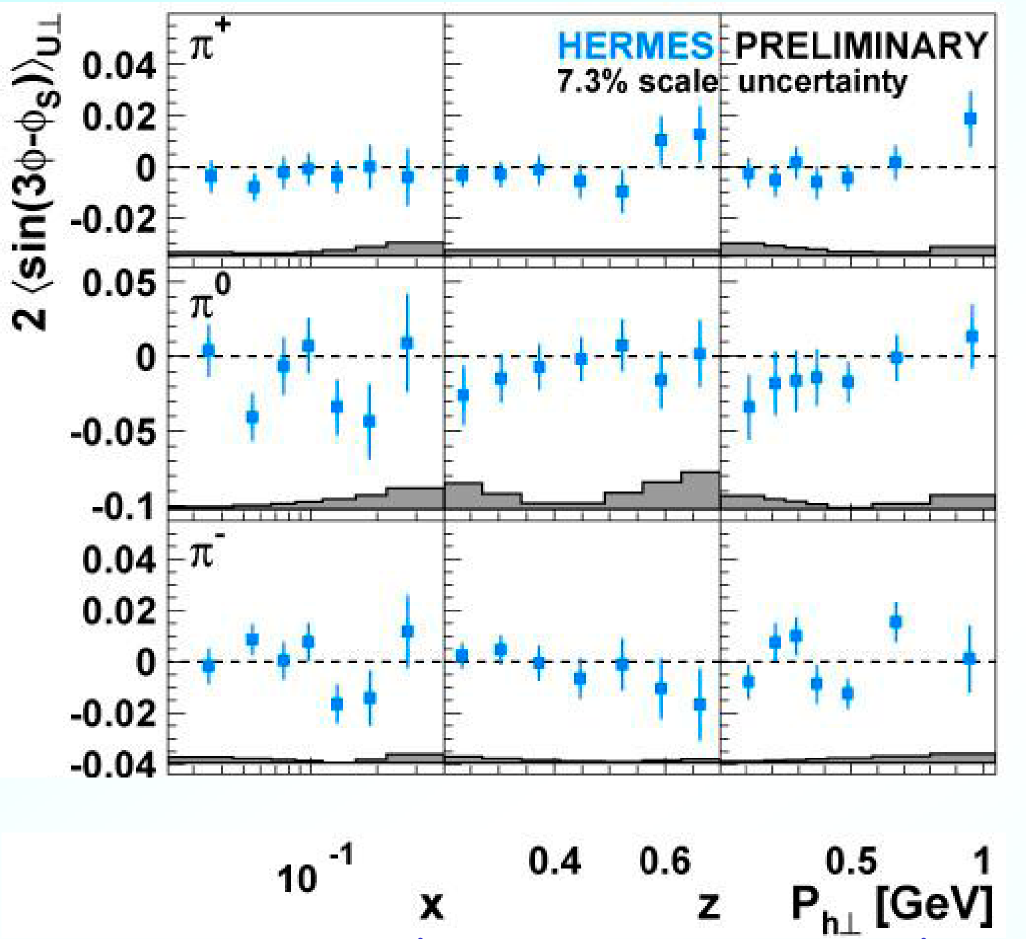
Pretzelosity DF $h_{1T}^{\perp}$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

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

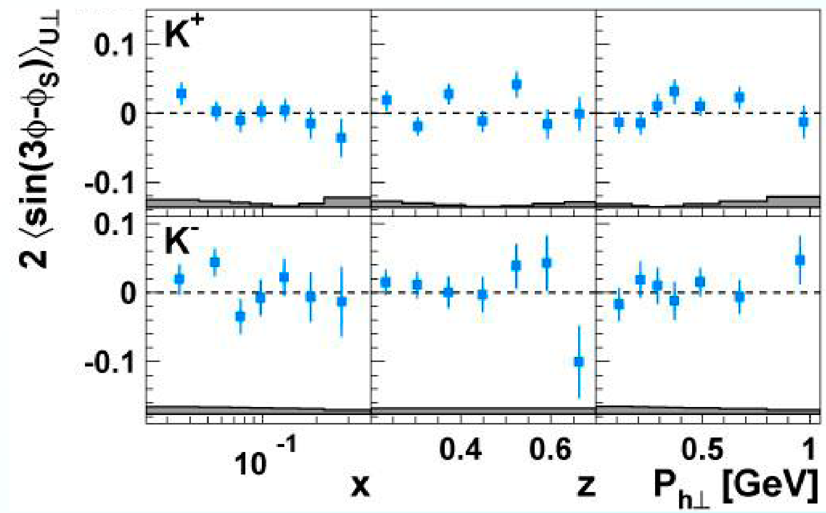
- leading-twist
- Expected to scale with $(p_T)^2 k_T$
- Suppressed w.r.t - Collins and Sivers (these scale with k_T, p_T)
  - Cahn, Boer-Mulders ($\langle\cos\phi\rangle$ scales with k_T, p_T)
  - Boer-Mulders ($\langle\cos 2\phi\rangle$ scales with $k_T p_T$)

Pretzelosity DF $h_{1T}^{\perp}$



Recent

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



Suppressed w.r.t. Sivers and Collins amplitudes

Compatible with zero within uncertainties

$h_{1T}^{\perp}$ might be non-zero, look at higher p_T

Worm-gear DF $h_{1L}^{\perp}$, g_{1T}

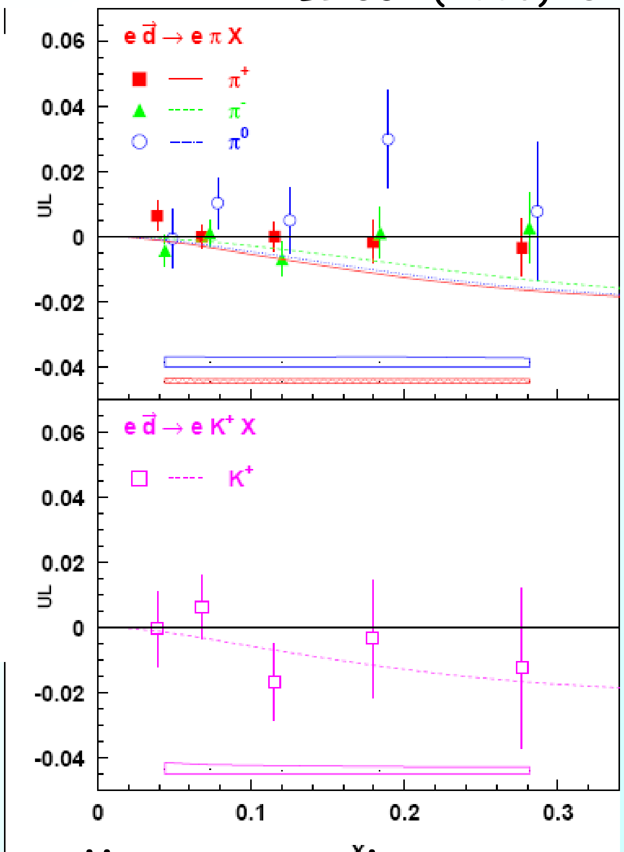
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$$A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} \otimes H_1^{\perp}$$

First attempt:

PLB 562 (2003) 182

	meson	deuterium target	proton target [2, 3]
$A_{UL}^{\sin\phi}$	π^+	$0.012 \pm 0.002 \pm 0.002$	$0.022 \pm 0.005 \pm 0.003$
	π^0	$0.021 \pm 0.005 \pm 0.003$	$0.019 \pm 0.007 \pm 0.003$
	π^-	$0.006 \pm 0.003 \pm 0.002$	$-0.002 \pm 0.006 \pm 0.004$
	K^+	$0.013 \pm 0.006 \pm 0.003$	—
$A_{UL}^{\sin 2\phi}$	π^+	$0.004 \pm 0.002 \pm 0.002$	$-0.002 \pm 0.005 \pm 0.003$
	π^0	$0.009 \pm 0.005 \pm 0.003$	$0.006 \pm 0.007 \pm 0.003$
	π^-	$0.001 \pm 0.003 \pm 0.002$	$-0.005 \pm 0.006 \pm 0.005$
	K^+	$-0.005 \pm 0.006 \pm 0.003$	—



→ small !

$$A_{LT}^{\cos(\phi-\phi s)} \sim g_{1T} \otimes D_1$$

P_B rather small, errors large,
→ PhD M. Diefenthaler

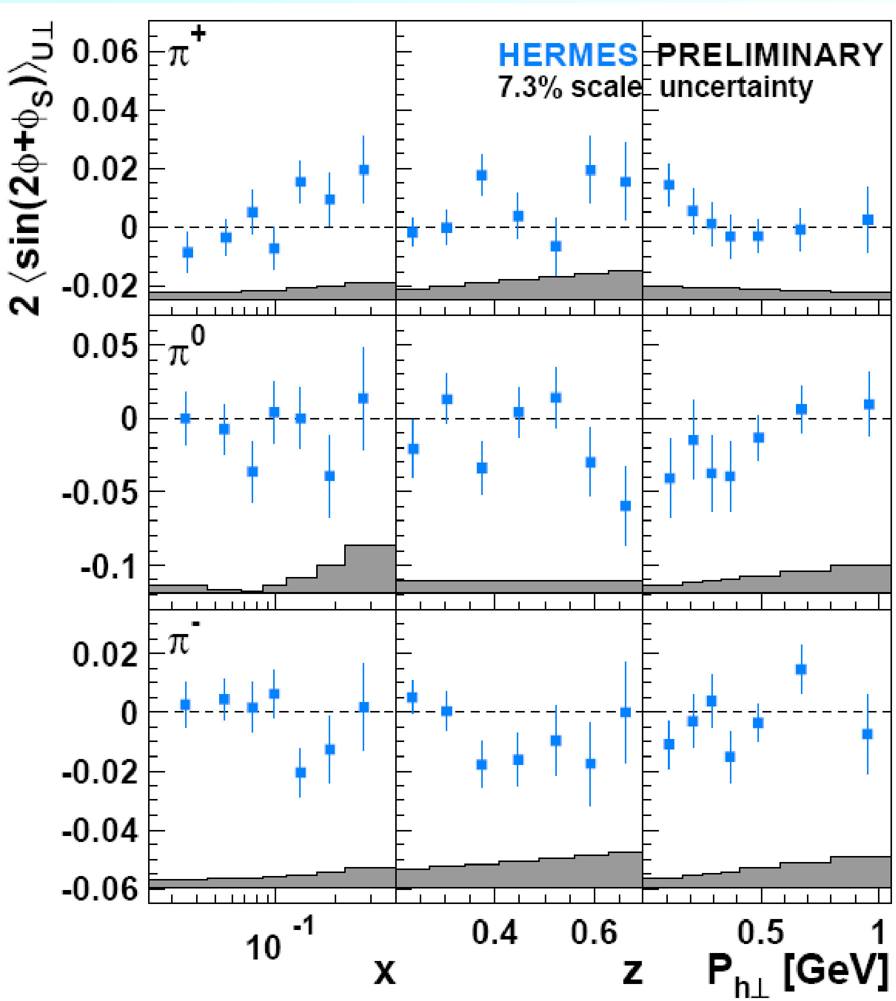
Worm-gear DF $h_{1L}^{\perp}$

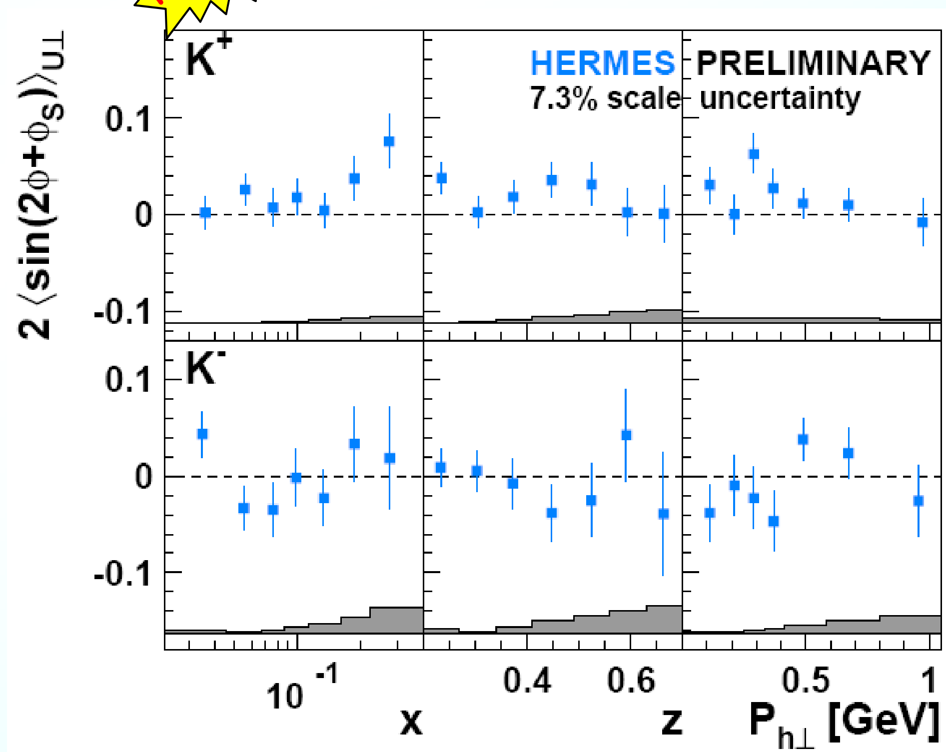
$\langle \sin(2\phi+\phi_s)\rangle_{U\perp}$

expected to scale as: $\sin\theta_{\gamma^*}\ \langle \sin(2\phi)_{UL}\rangle$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Recent





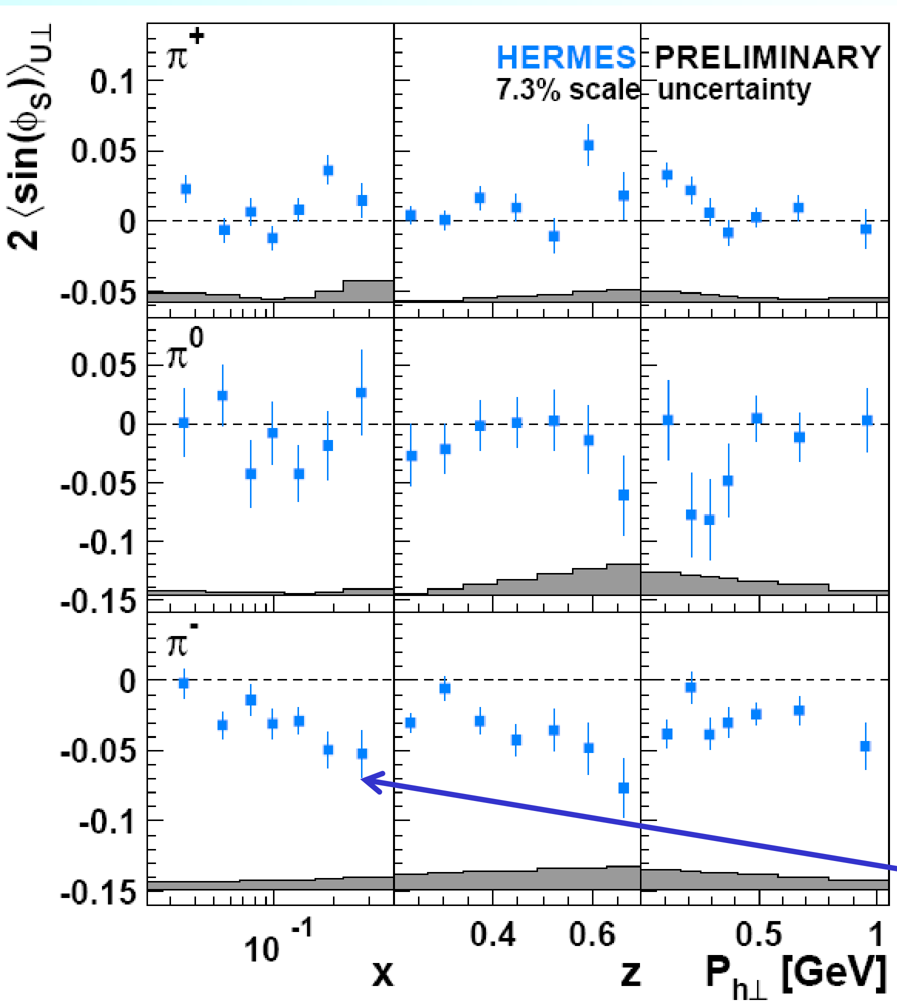
Compatible with zero within uncertainties

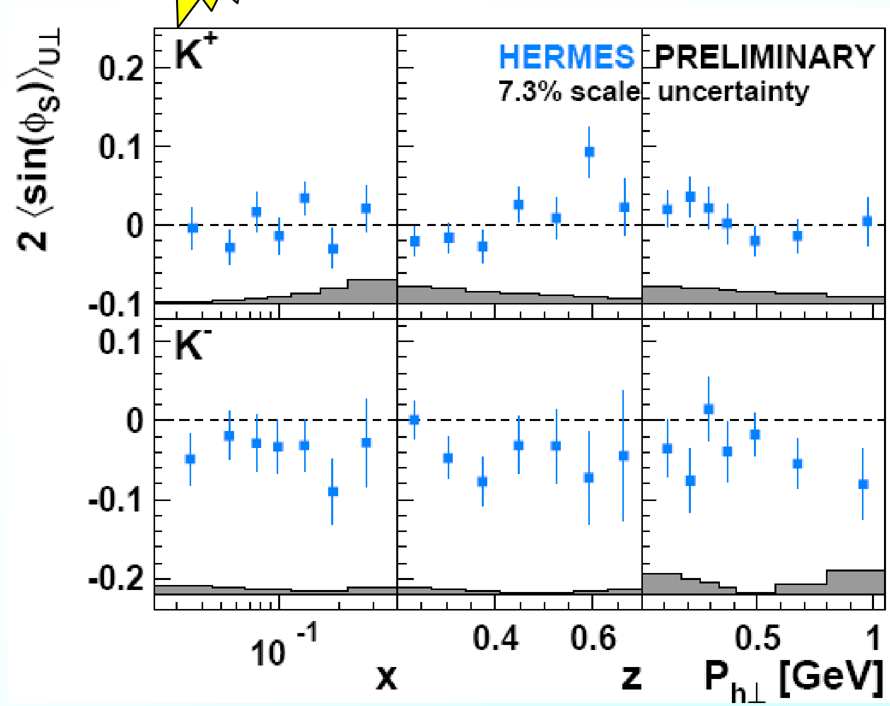
Subleading term $\sin(\phi_s)_{UT}$

$$\langle \sin(\phi_s) \rangle_{UT} \sim h_1 \otimes H_1^{\perp} + f_{1T}^{\perp} \otimes D_1$$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Recent





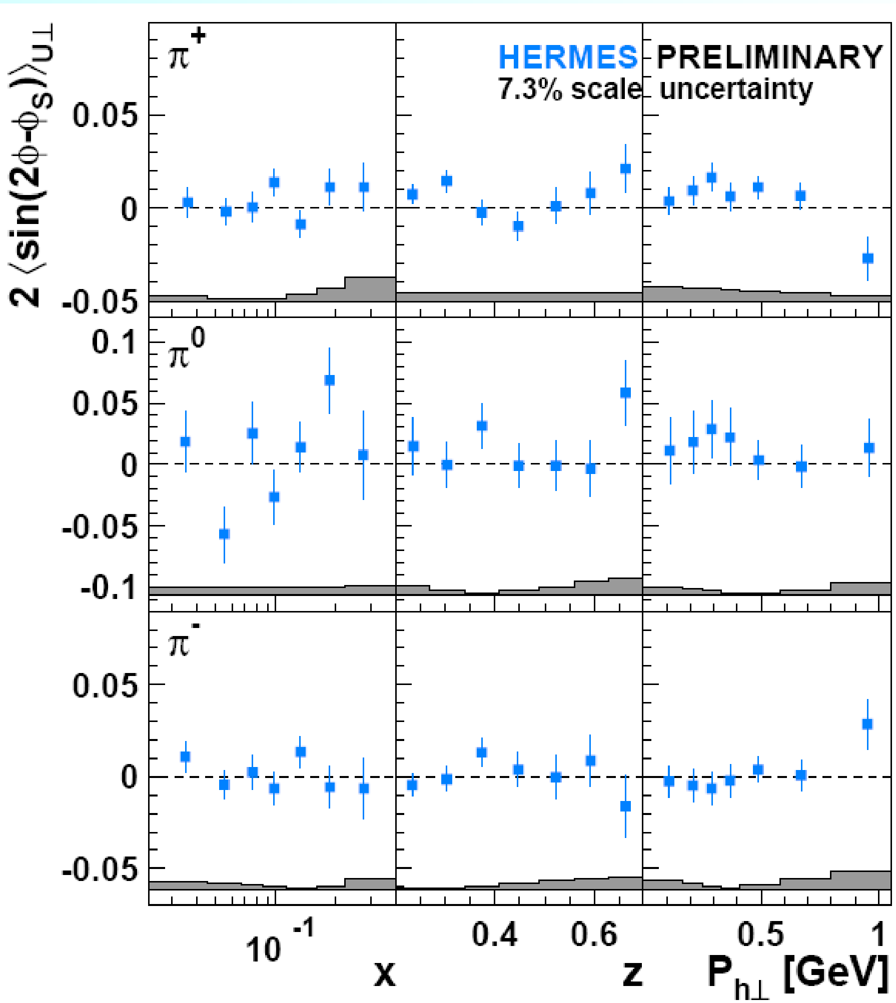
Similar to Collins

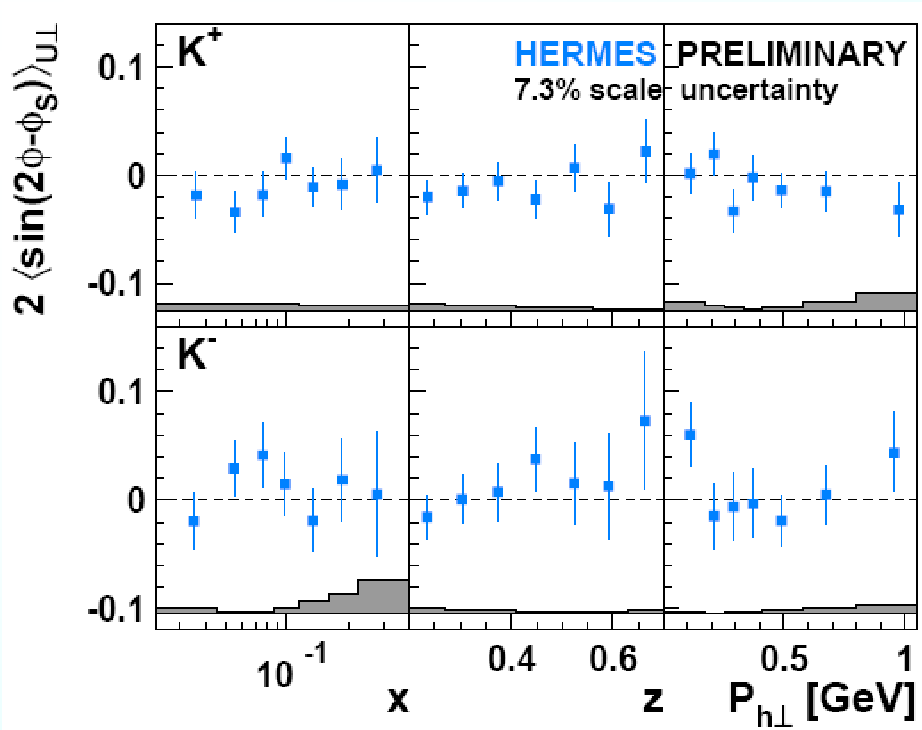
Subleading term $\sin(2\phi-\phi_s)_{UT}$

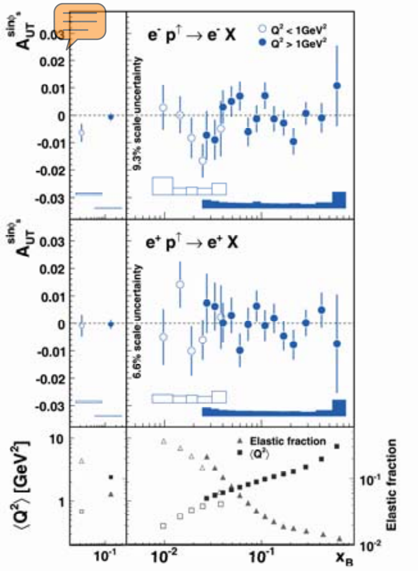
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

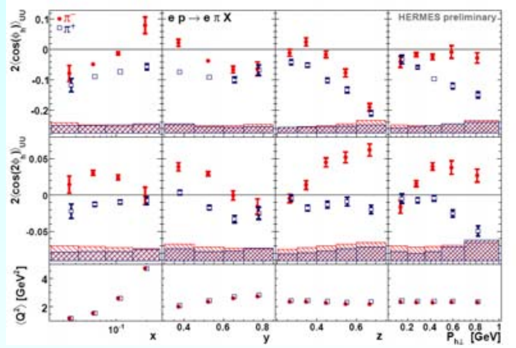
$$\langle \sin(2\phi-\phi_s)\rangle_{UT} \sim h_{1T}^{\perp} \otimes H_1^{\perp} + f_{1T}^{\perp} \otimes D_1$$

Recent



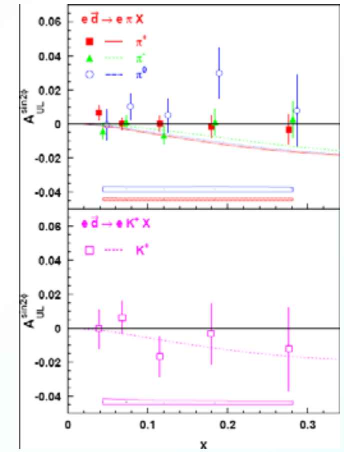




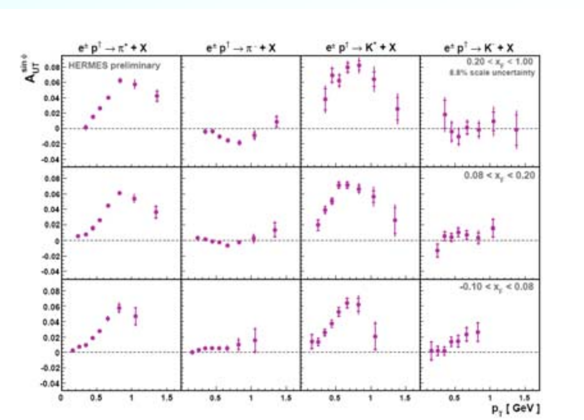


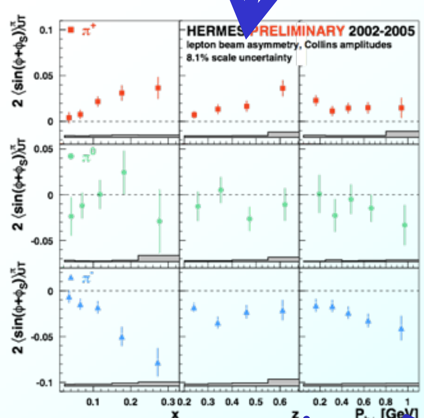
Boer-Mulders DF, Cahn

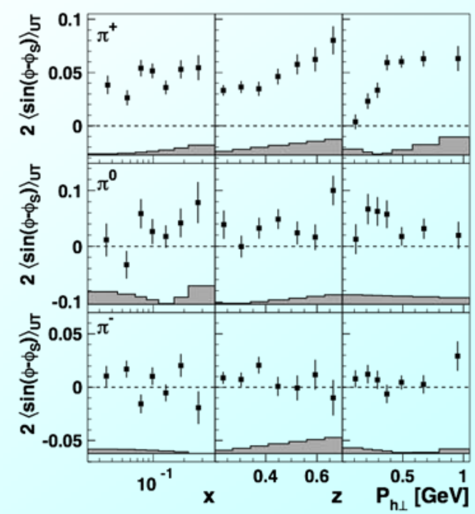
2-γ exchange



Worm-gear DF







Inclusive hadron TSA

transversity DF

Sivers DF