Accessing TMDs at HERMES

Luciano Pappalardo
pappalardo@fe.infn.it
(for the HERMES Collaboration)

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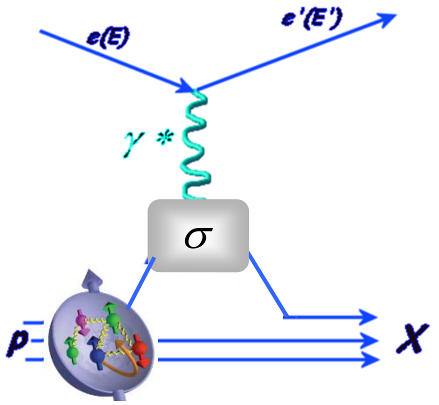
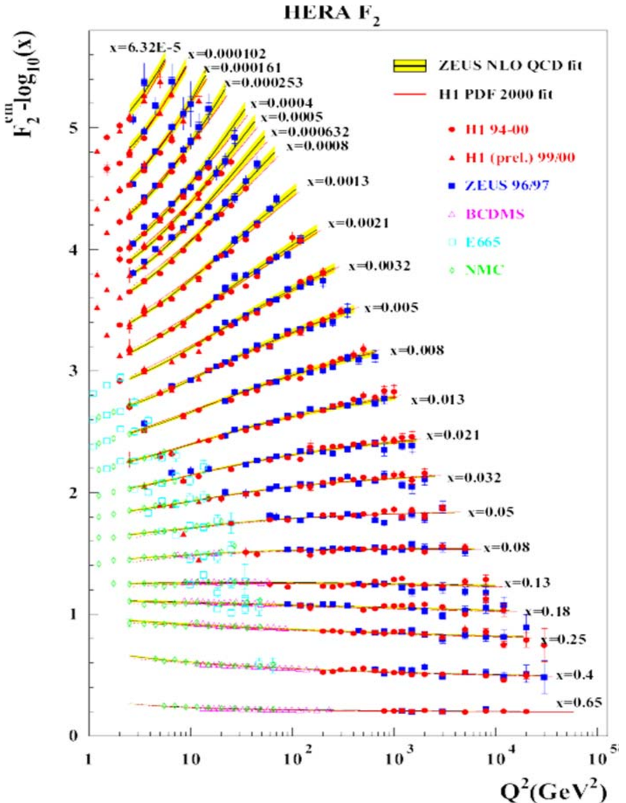
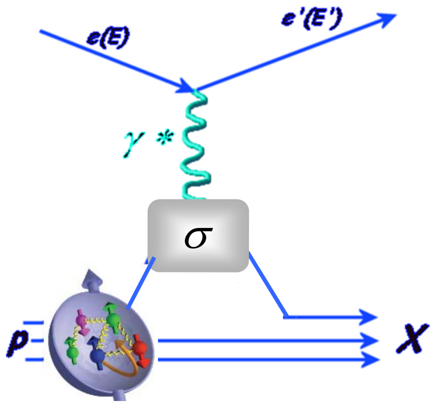
Quantum phase-space tomography of the nucleon

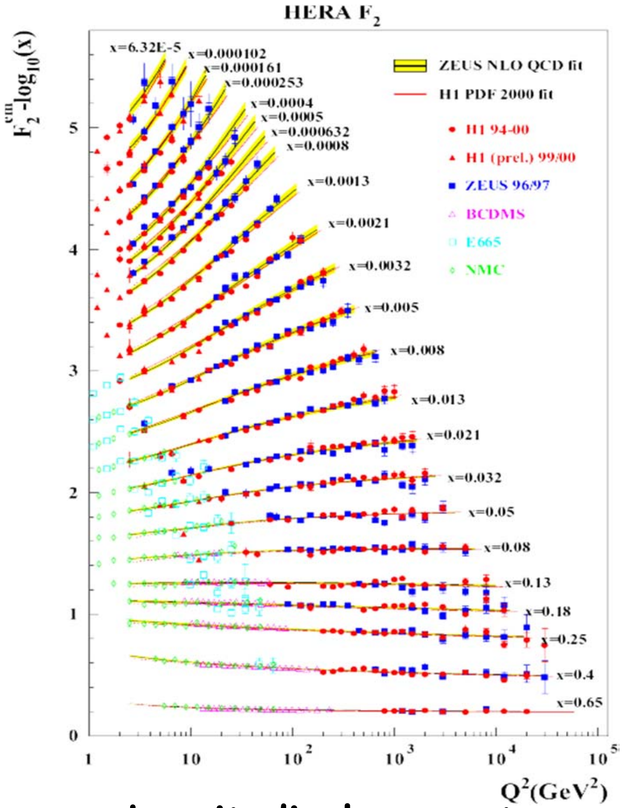




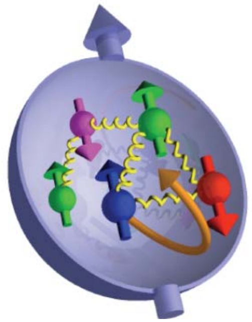
Longitudinal momentum distribution of quarks

Quantum phase-space tomography of the nucleon

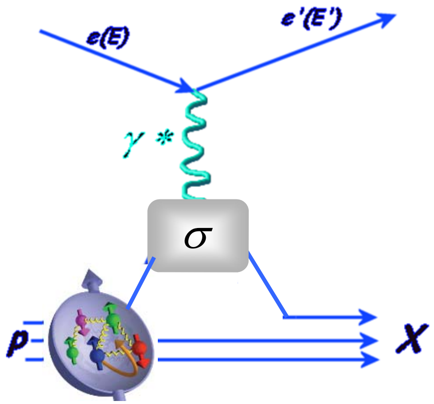


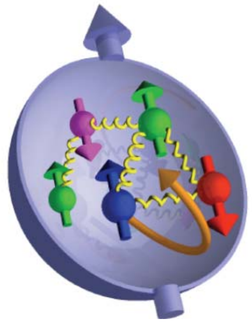


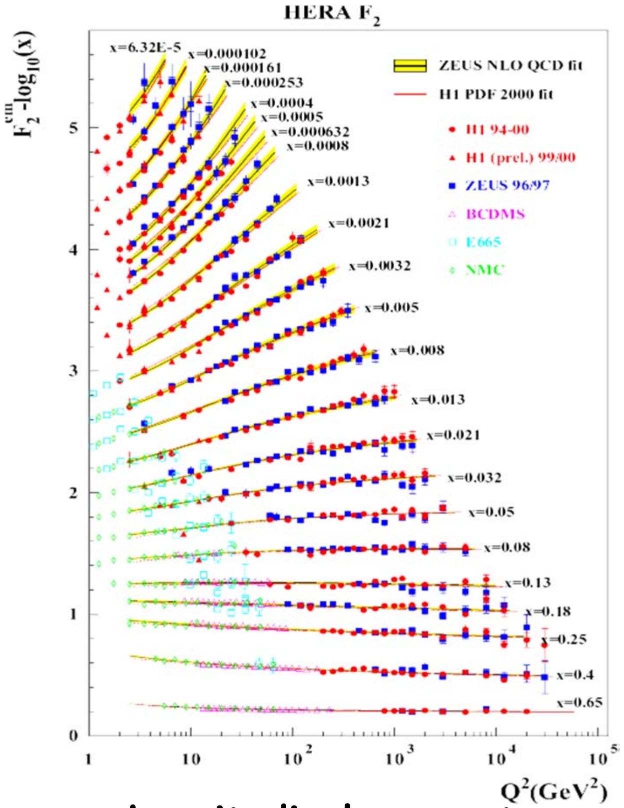
Longitudinal momentum distribution of quarks



Quantum phase-space tomography of the nucleon







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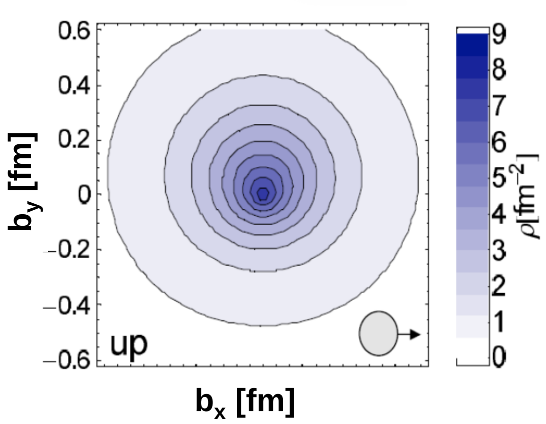
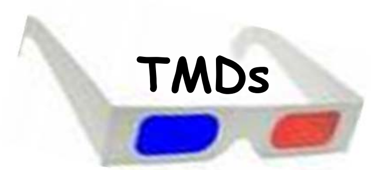
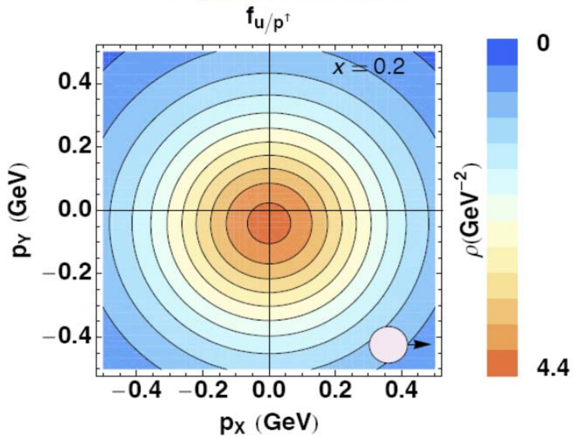


QCDSF/UKQCD, PRL 98 (07)

3D picture in coordinate space

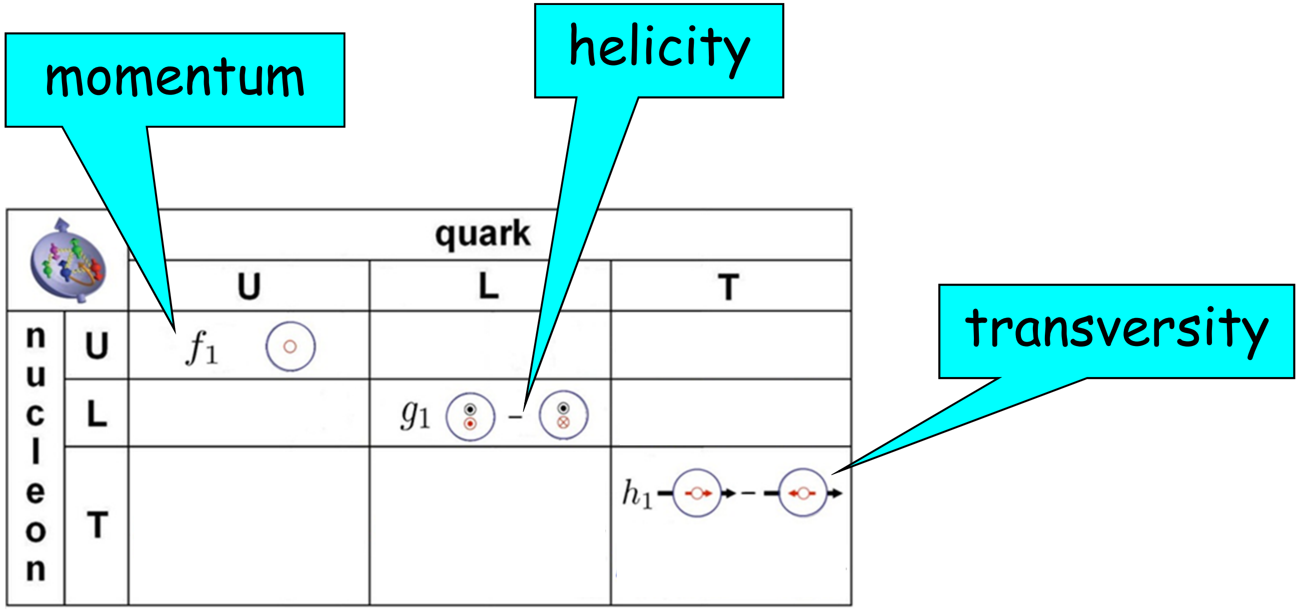




A.B., F. Conti, M. Radici, PRD78 (08)

3D picture in momentum space

The table of TMDs



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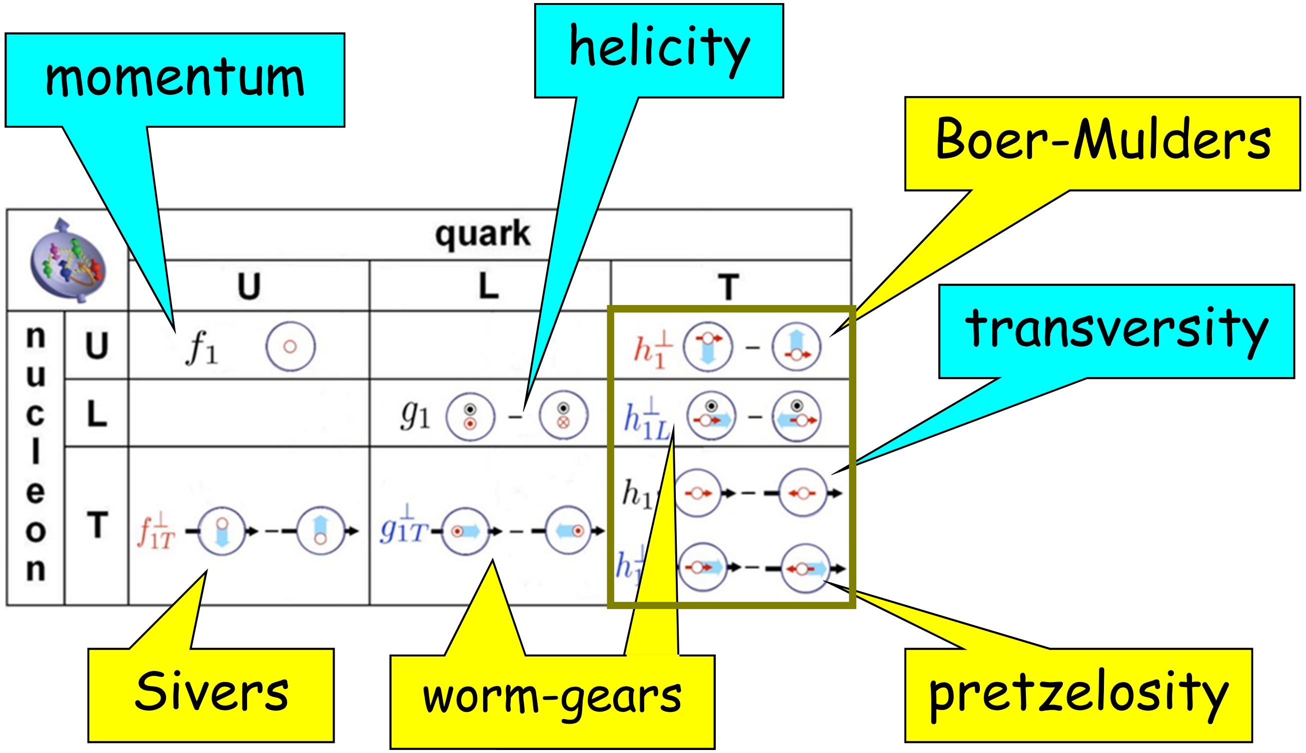


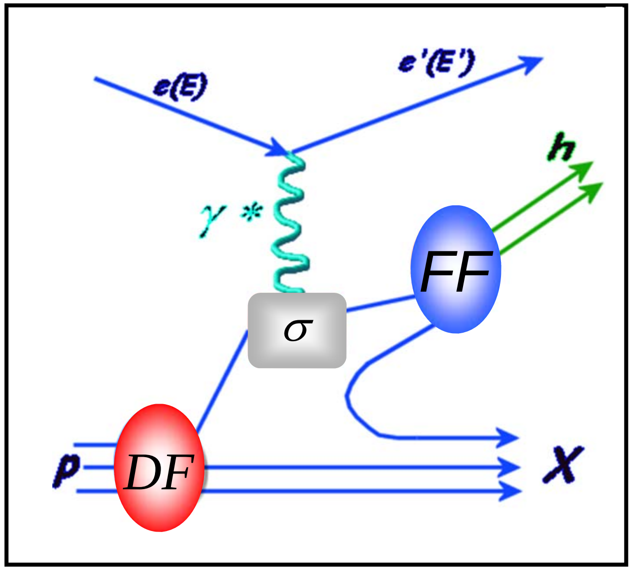
functions in red are naive T-odd

functions in green box are chirally odd

TMDs can be studied by measuring azimuthal asymmetries in SIDIS

Distribution Functions (DF)

nucleon \ quark	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$



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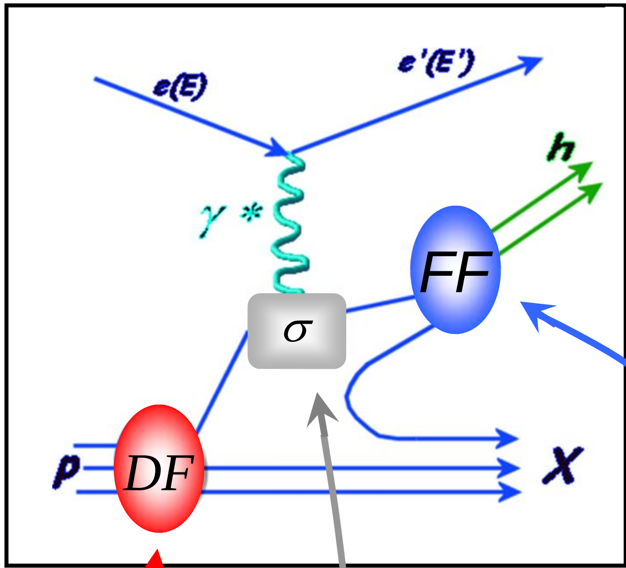

$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

Fragmentation Functions (FF)

had. \ quark	U	L	T
U	D_1 Unpol. FF		$H_1^\perp$ Collins FF

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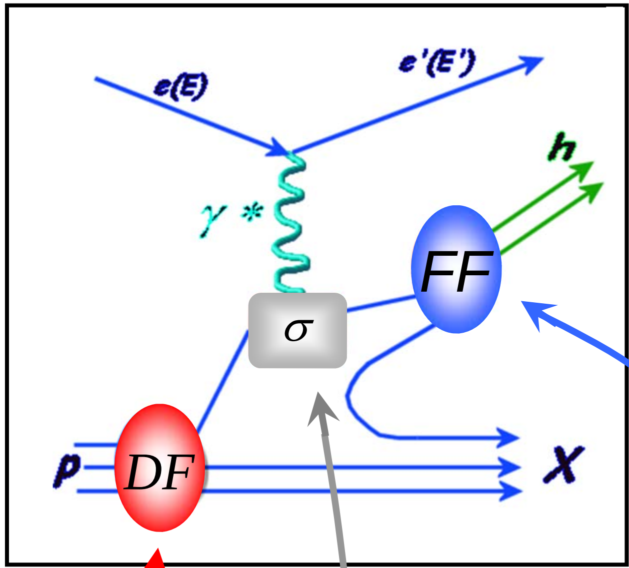

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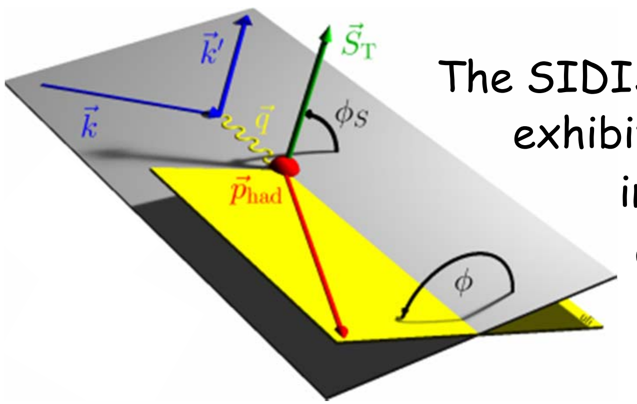

The SIDIS cross section exhibits asymmetries in the azimuthal angles ϕ and ϕ_S

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had.	quark: U	L	T
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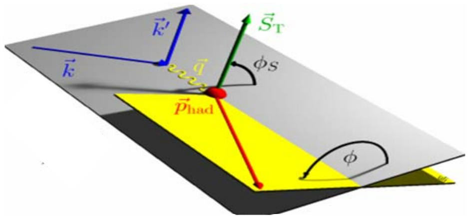

The SIDIS cross-section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

nucleon \ quark	U	L	T
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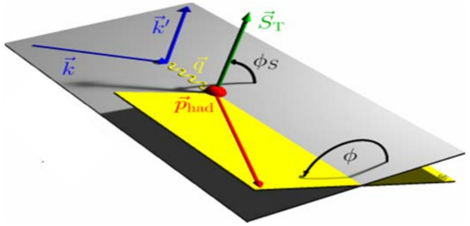
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$



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$$\Big\{ \left[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\right]$$

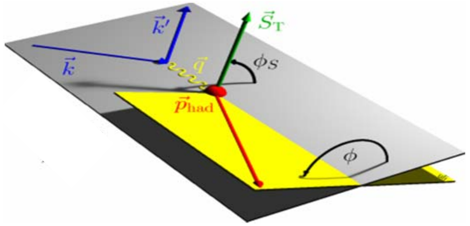
$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\right]$$

$$+ S_L \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\right]$$

$$+ S_L\,\lambda_l \left[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\right]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\}$$



The SIDIS cross-section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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$$+ \quad \lambda_l\left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\right]$$

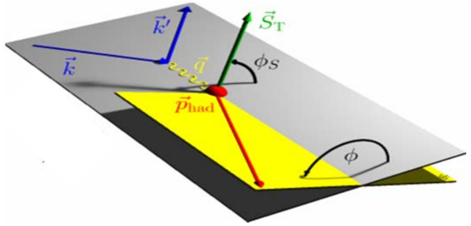
$$+ S_L \quad \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\right]$$

$$+ S_L\ \lambda_l \left[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\right]$$

$$+ S_T \quad \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\ \lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$



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$$

$$
\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big]
$$

$$
+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\Big]
$$

$$
+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\Big]
$$

$$
+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\Big]
$$

$$
\begin{aligned}
+ S_T \Big[&\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) \\
&+\epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \\
&+\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} \\
&+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]
\end{aligned}
$$

$$
\begin{aligned}
+ S_T\,\lambda_l \Big[&\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} \\
&+\sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} \\
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\end{aligned}
$$

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		U	L	T
nucleon	U	f_1		$h_1^\perp$
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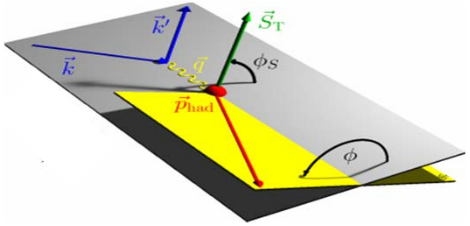

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$$\Big\{ \left[F_{\rm UU,T} + \epsilon F_{\rm UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\rm UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\rm UU}^{\cos(2\phi)}\right]$$

$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\rm LU}^{\sin(\phi)}\right]$$

$$+ S_L \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\rm UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\rm UL}^{\sin(2\phi)}\right]$$

$$+ S_L\,\lambda_l \left[\sqrt{1-\epsilon^2} F_{\rm LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\rm LL}^{\cos(\phi)}\right]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{\rm UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{\rm UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S) F_{\rm UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\rm UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\rm UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\rm UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\rm LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\rm LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\rm LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

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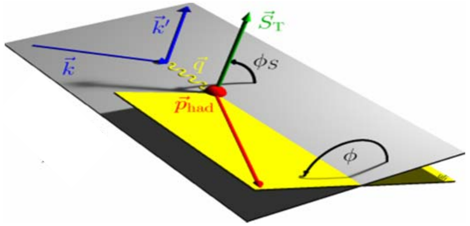

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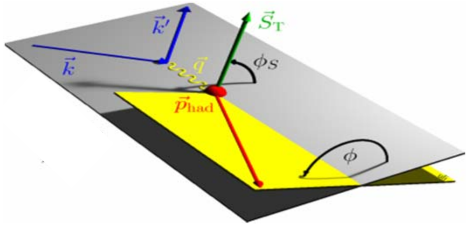
How can we disentangle all these contributions ?

EXPERIMENT: setting the proper beam and target polarization states (U, L, T)

ANALYSIS: e.g. fitting the cross section asymmetry for opposite spin states and extracting the relevant Fourier components based on their peculiar azimuthal dependences.



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$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\Big]$$

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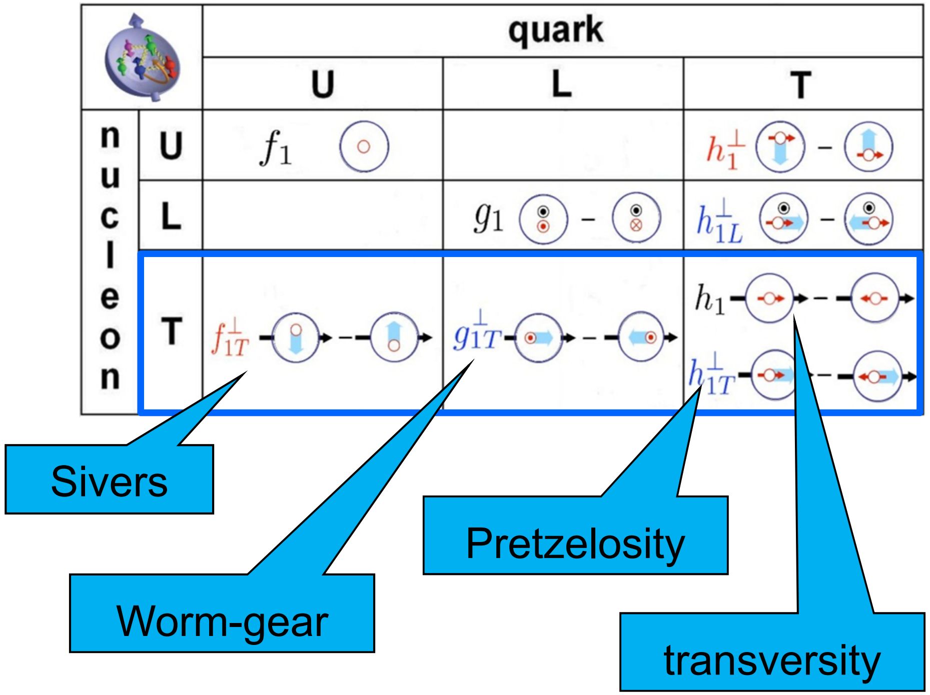
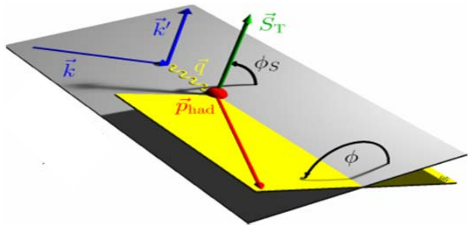


Selected results from A_{UT} SSAs



The Sivers effect

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

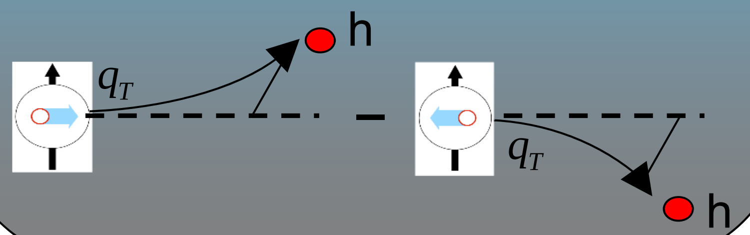
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Sivers effect

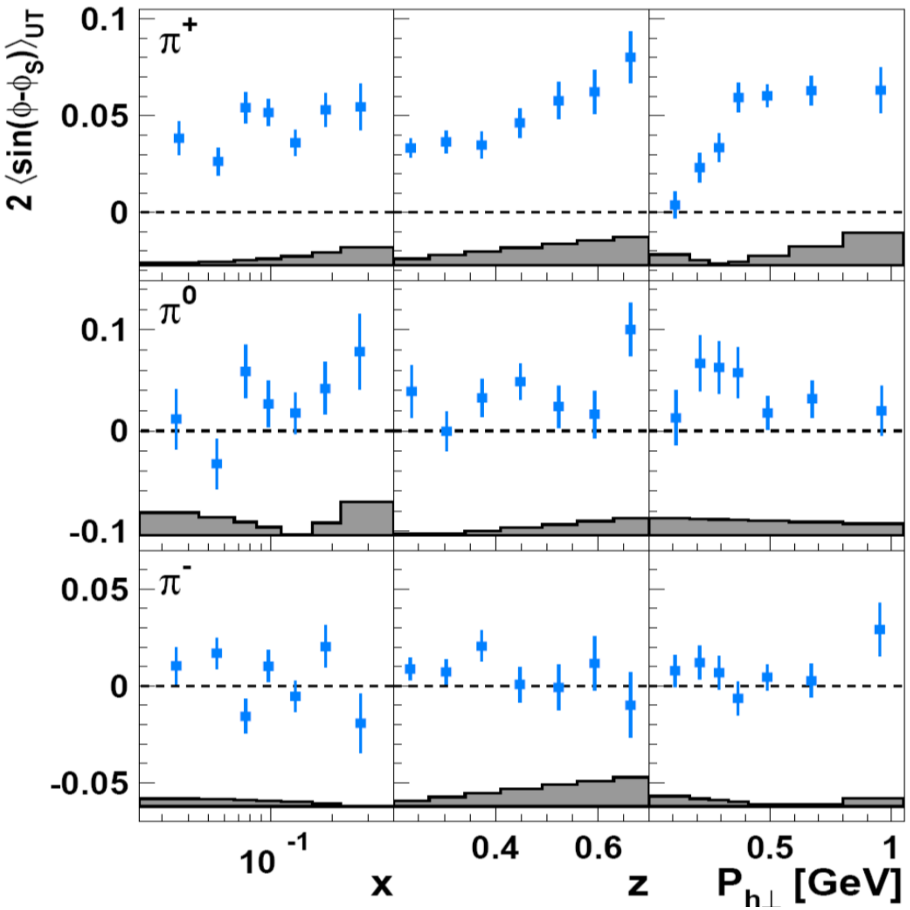
$$\propto f_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$$

- correlation between parton transverse momentum and nucleon transverse polarization
- requires orbital angular momentum



Sivers pions amplitudes

[Airapetian *et al*., Phys. Rev. Lett. 103 (2009) 152002]

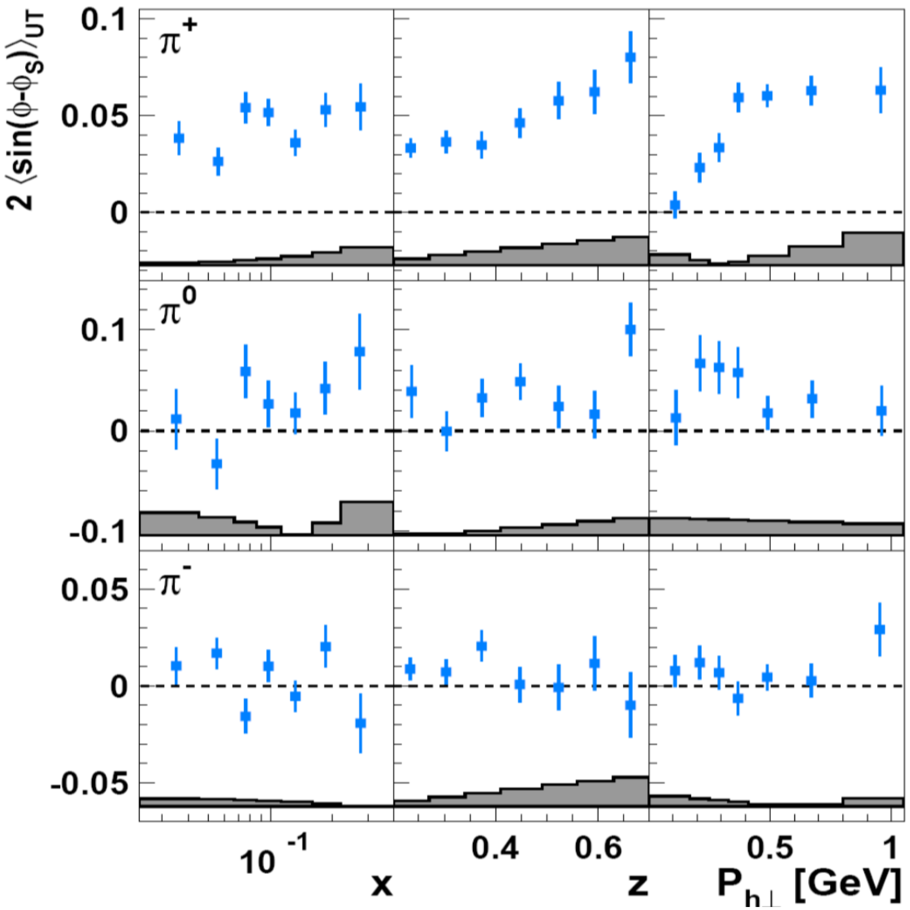


- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- slightly positive
- consistent with zero

☑ First evidence of non-zero Sivers func.

Sivers pions amplitudes

[Airapetian *et al.*, Phys. Rev. Lett. 103 (2009) 152002]



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

First evidence of non-zero Sivers func.

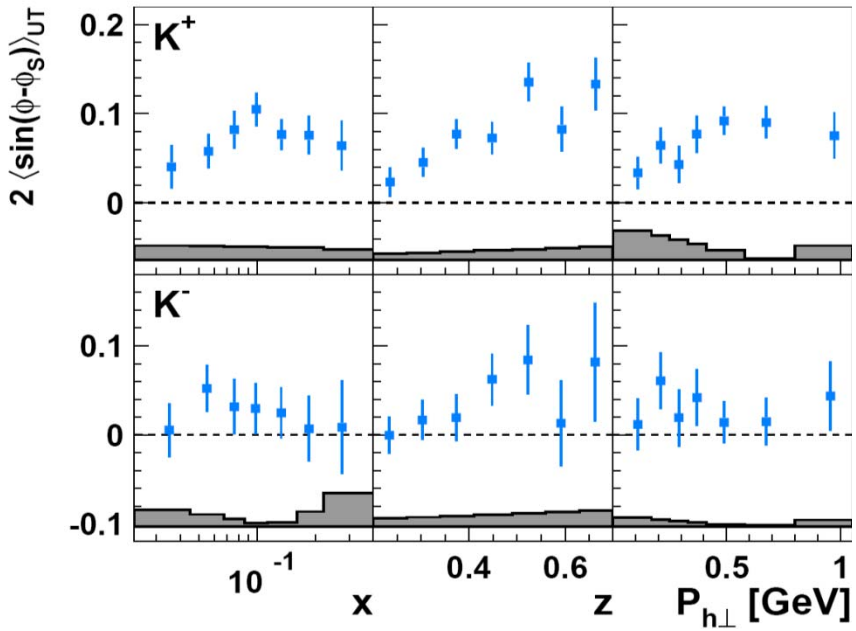
Large positive π^+ signal is dominated by scattering off u-quarks:

$$2\langle\sin(\phi-\phi_S)\rangle_{UT}^{\pi^+} \propto -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_W D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$ → **u-quark Sivers DF < 0**

null signal for π^- indicates that d-quark Sivers DF > 0 (cancellation)

confirmed by phenomenological fits (Torino group) and several theoretical predictions!

Sivers kaons amplitudes [Airapetian *et al.*, Phys. Rev. Lett. 103 (2009) 152002]

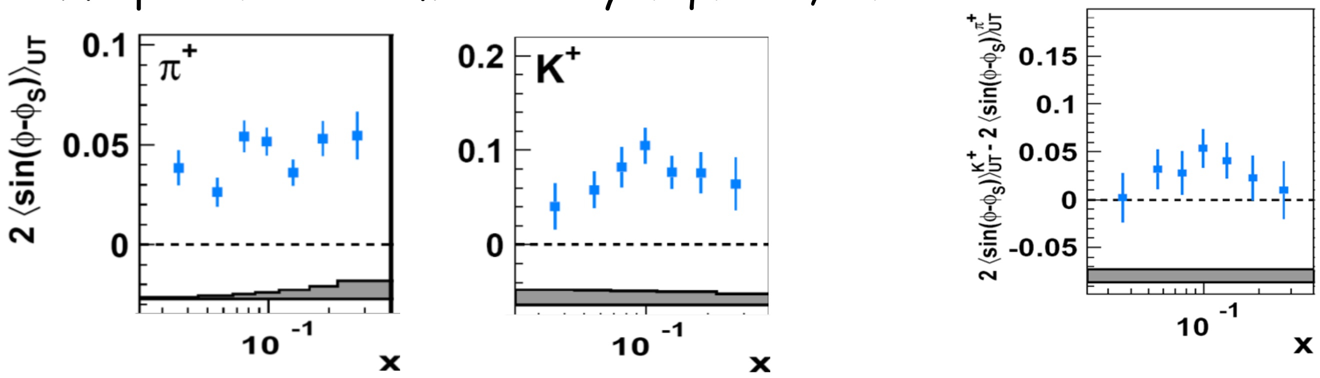


- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$

- slightly positive

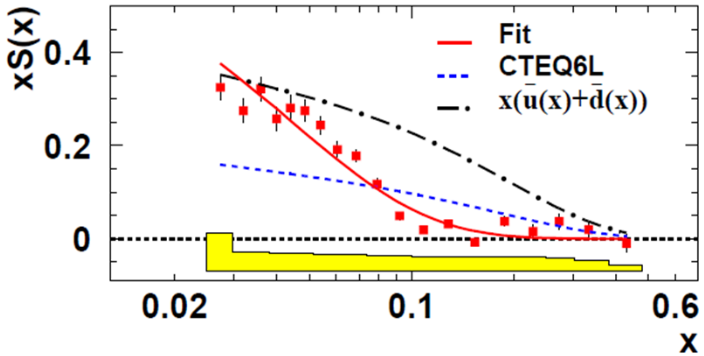
Sivers kaons amplitudes: open questions

π^+/K^+ production dominated by u-quarks, but:



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

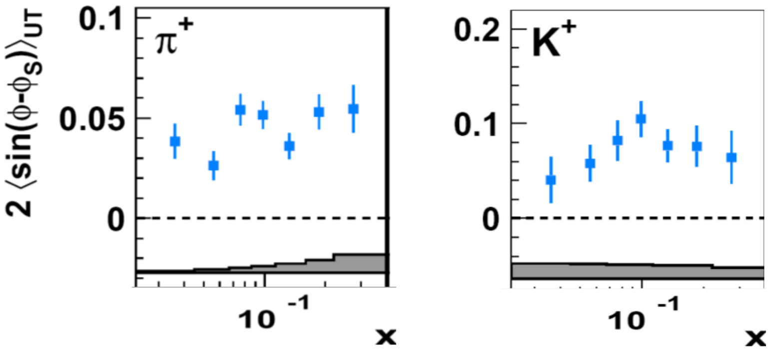
different role of various sea quarks ?

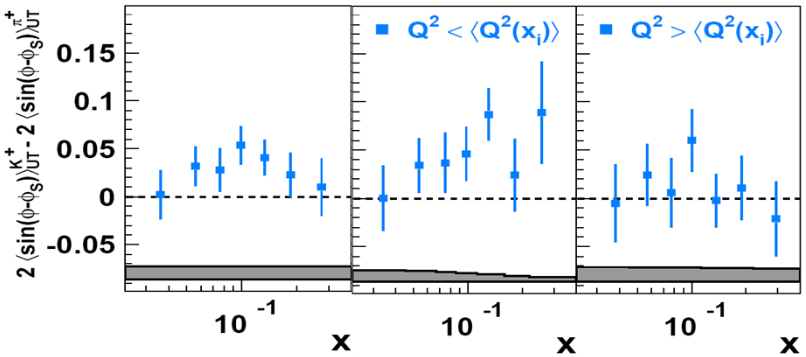


impact of different k_T dependence of FFs in the convolution integral

Sivers kaons amplitudes: open questions

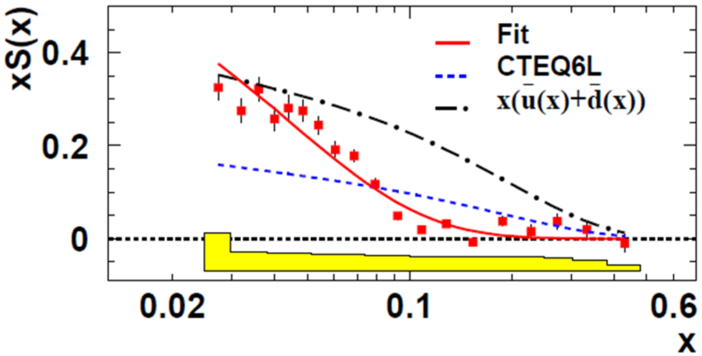
π^+/K^+ production dominated by u-quarks, but:





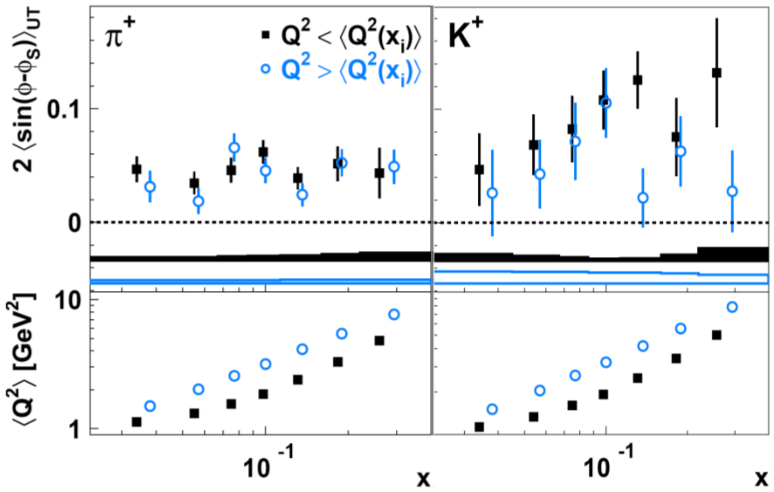
$$\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle \ \rightarrow$$

different role of various sea quarks ?

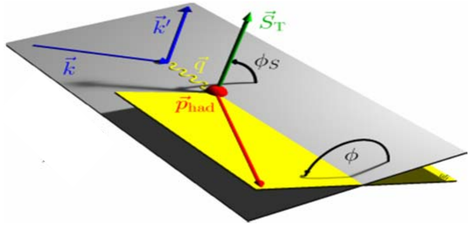


- each x-bin divided into two Q^2 bins
- only in low-Q^2 region significant (90% C.L.) deviation is observed

impact of different k_T dependence of FFs in the convolution integral



Higher-twist contrib. for Kaons



The Collins effect

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l\Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin(\phi)}\Big]$$

$$+ S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l\Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\Big]$$

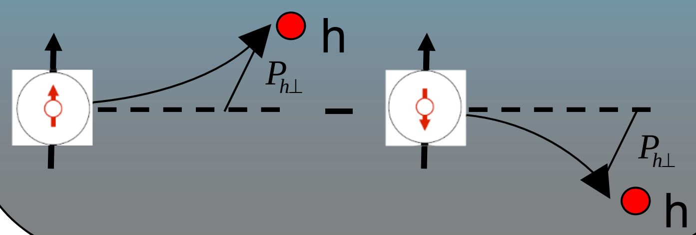
$$+ S_T\Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

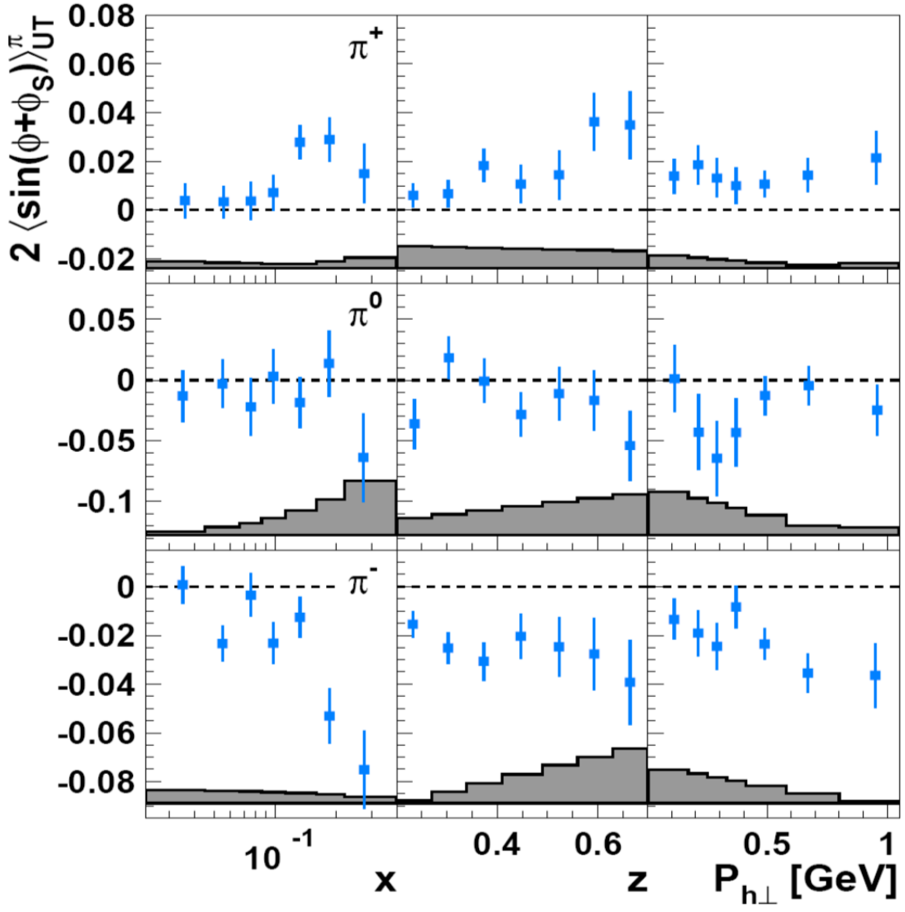
Collins effect

- $\propto h_1(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$
- correlation between parton transverse polarization in a transversely polarized nucleon and transverse momentum of the produced hadron



Collins pions amplitudes

[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]

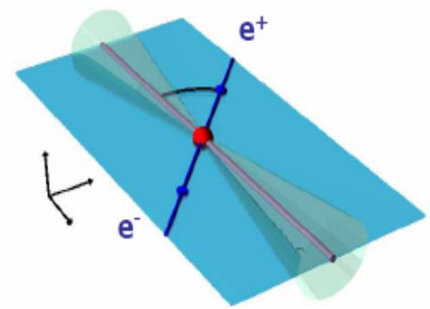


- significantly positive
- rise with x and z
- consistent with zero
- large and negative!

$$H_1^{\perp,\text{unfav}}(z) \approx -H_1^{\perp,\text{fav}}(z)$$

Consistent with Belle measurements at e^+e^- collider machines

$$e^+e^- \to \pi^+_{\text{jet1}}\,\pi^-_{\text{jet2}}\,X$$

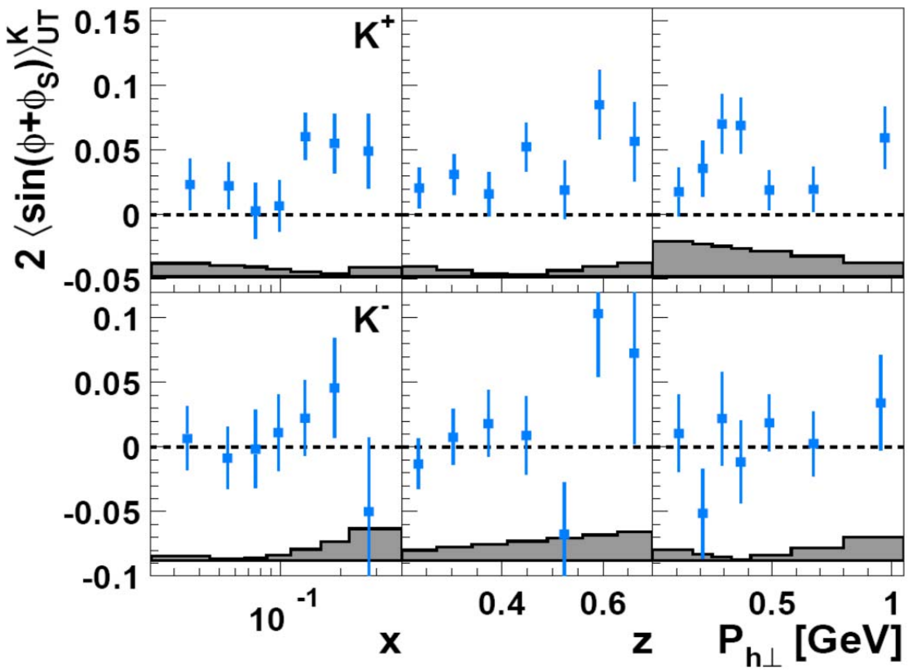


☑ Non-zero Collins effect observed

☑ Both transversity and Collins function sizeable!

Collins kaons amplitudes

[Airapetian *et al*., Phys. Lett. B 693 (2010) 11-16]



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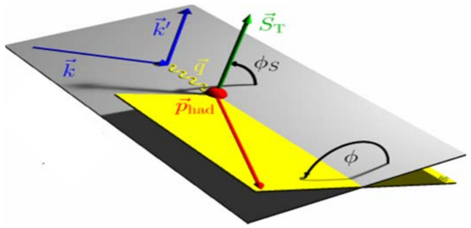


The "pretzelosity"

$$\frac{d\sigma^h}{dx\, dy\, d\phi_S\, dz\, d\phi\, d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\Big]$$

$$+ S_L\, \lambda_l \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\, \lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

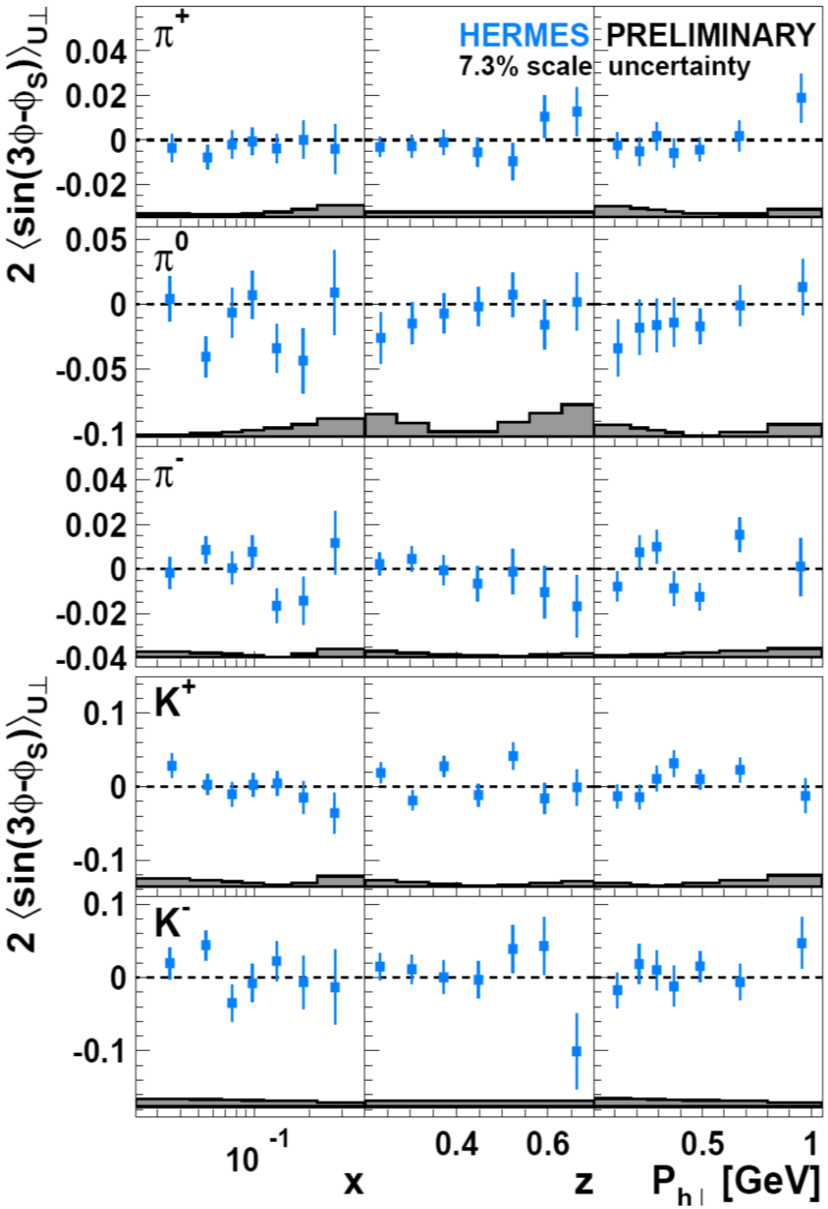
		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

pretzelosity

$$\propto h_{1T}^\perp(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$$

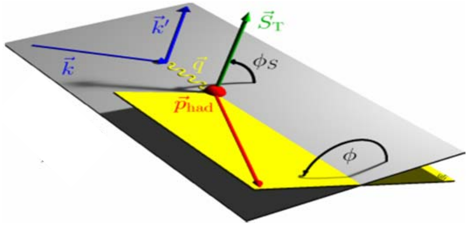
- characterizes the p_T dependence of the transverse quark polarization in a transversely polarized nucleon.
- can be linked to the non-spherical shape of the nucleon resulting from substantial quark orbital angular momentum

The sin(3ϕ-ϕ$_S$) Fourier component



All amplitudes consistent with zero

…suppressed by two powers of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes



The worm-gear $g_{1T}^{\perp}$

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

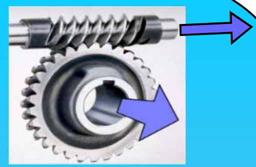
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

		quark		
		U	L	T
nucleon	U	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Worm-gear



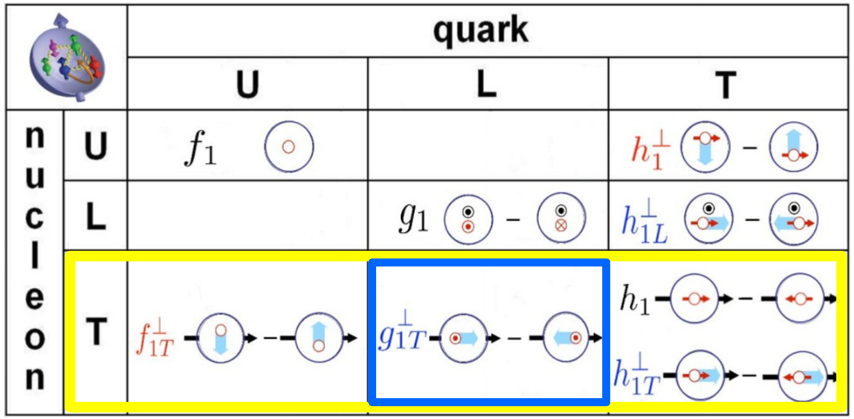
$$\propto g_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$$

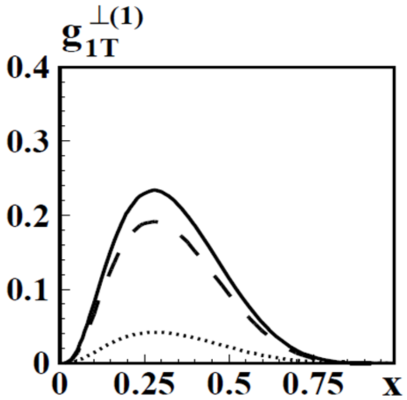
- describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon ($\rightarrow$ "**trans-helicity**")
- accessible in LT DSAs through the leading-twist $\cos(\phi-\phi_S)$ Fourier component

The worm-gear $g_{1T}{}^{\perp}$

- The only TMD that is both chiral-even and naïve-T-even

- requires interference between wave funct. components that differ by 1 unit of OAM



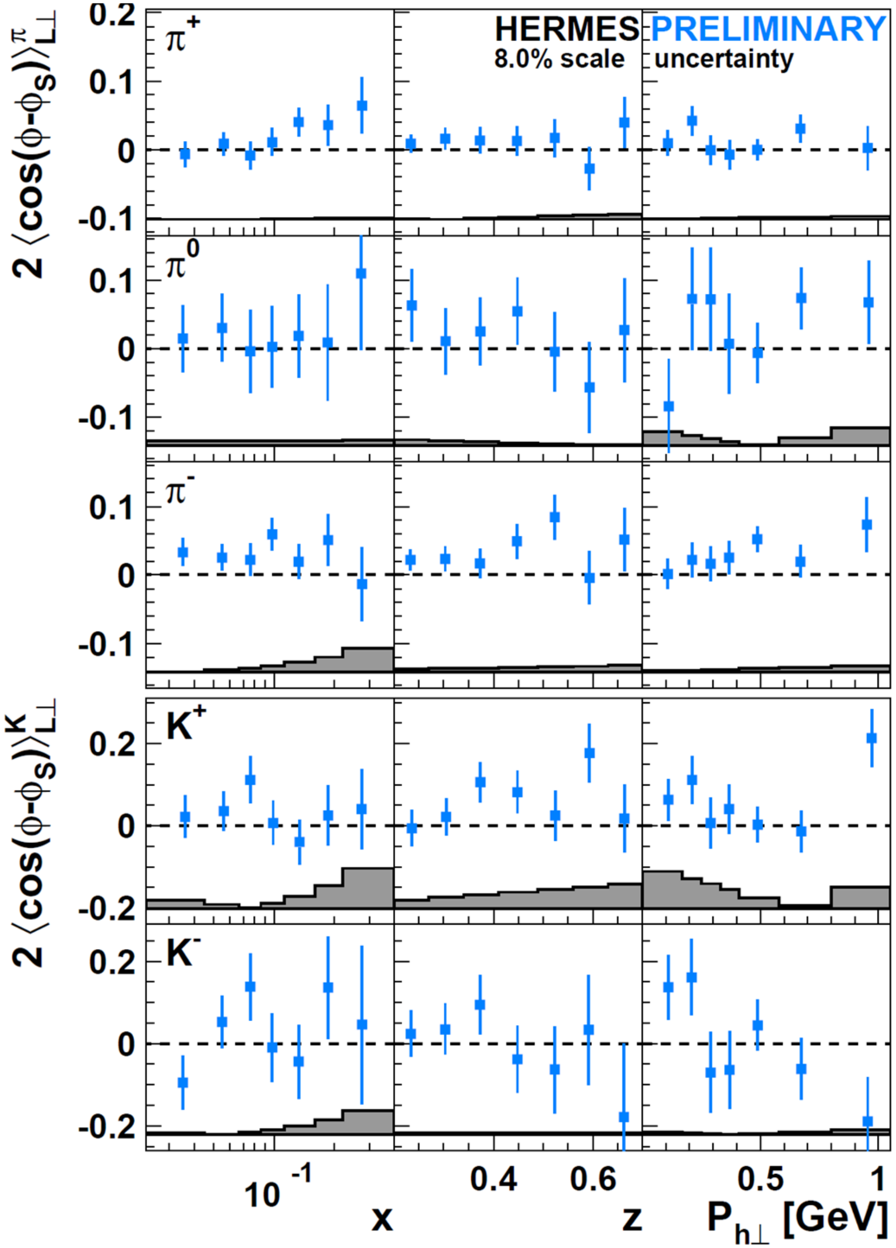


S. Boffi et al. (2009)
Phys. Rev. D 79 094012
Light cone constituent quark model
flavorless
dashed line: interf. L=0, L=1
dotted line: interf L=1, L=2

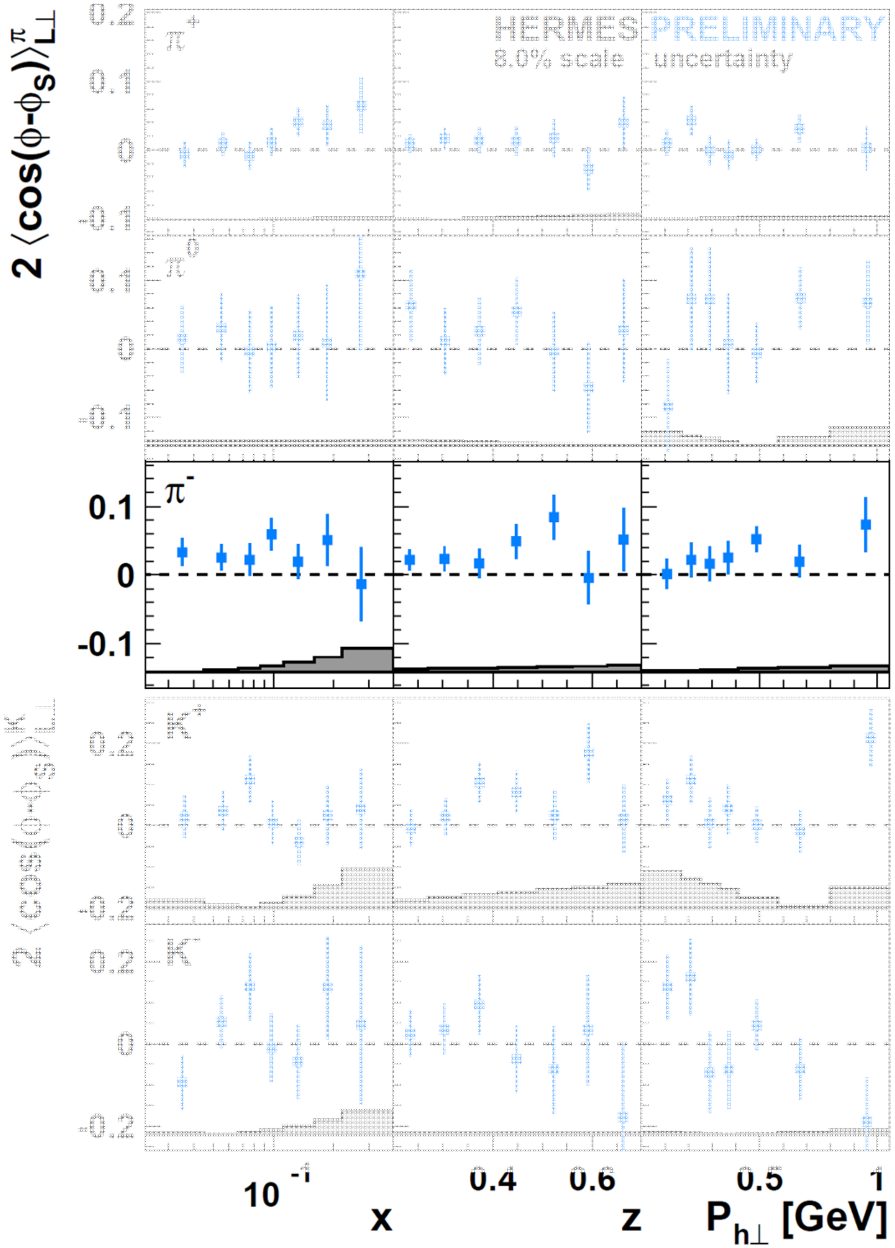
$\Rightarrow$ related to quark orbital motion inside nucleons

- Many models support simple relations among $g_{1T}^{\perp}$ and other TMDs:
  - $g_{1T}^{q} = -h_{1L}^{\perp q}$ (also supported by Lattice QCD and first data)
  - $g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$ (Wandzura-Wilczek appr.)

The cos(ϕ-ϕ$_S$) Fourier component

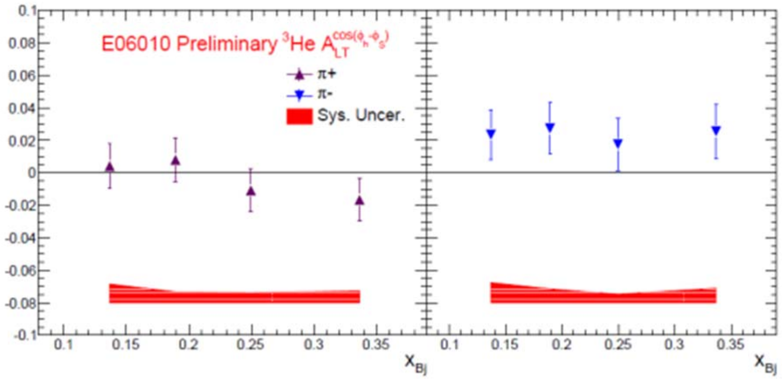


The cos(ϕ-ϕ$_S$) Fourier component

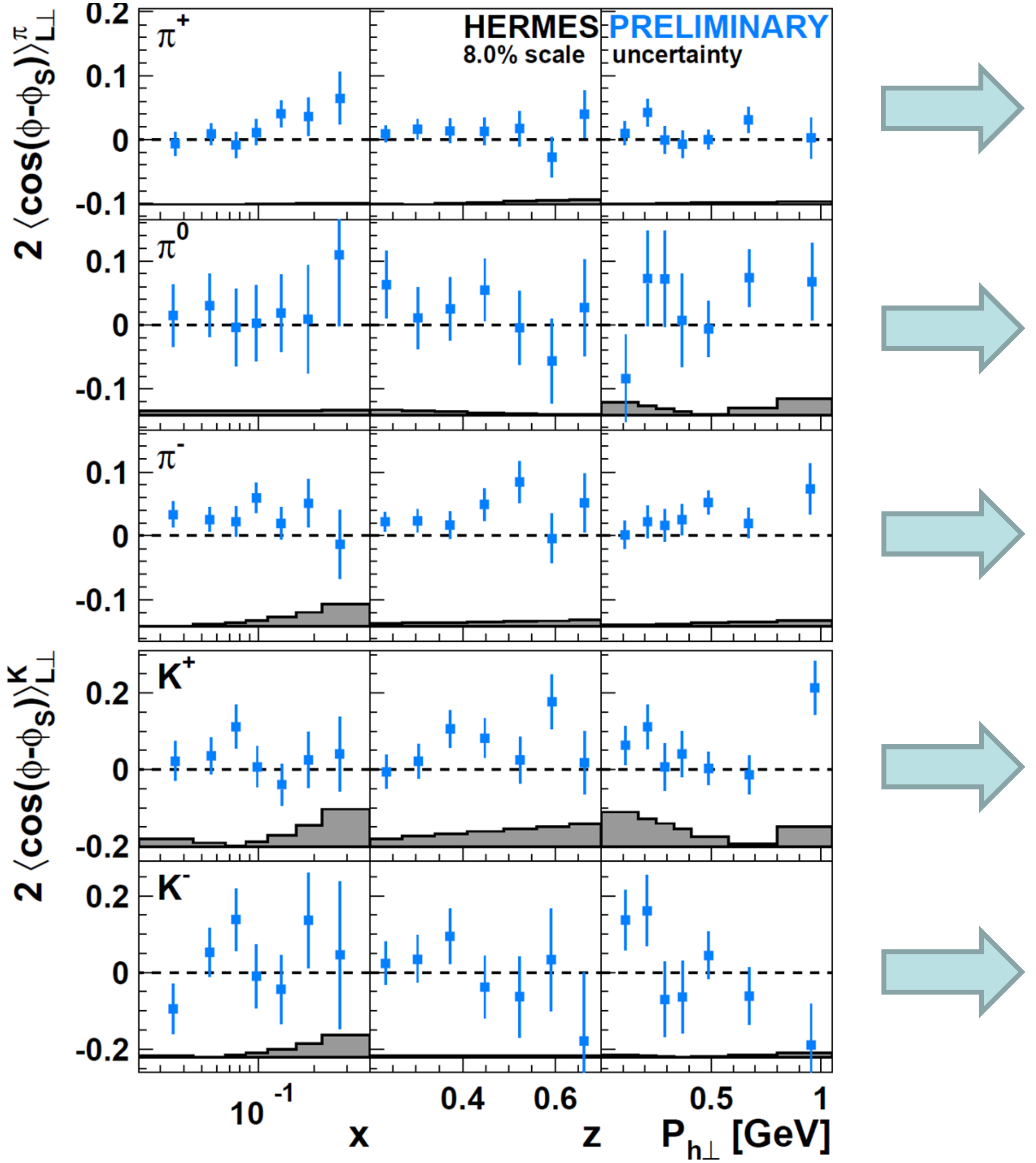


positive!

Resembles Hall-A results on trans. pol. 3He targ



The cos(ϕ-ϕ$_S$) Fourier component



slightly positive ?

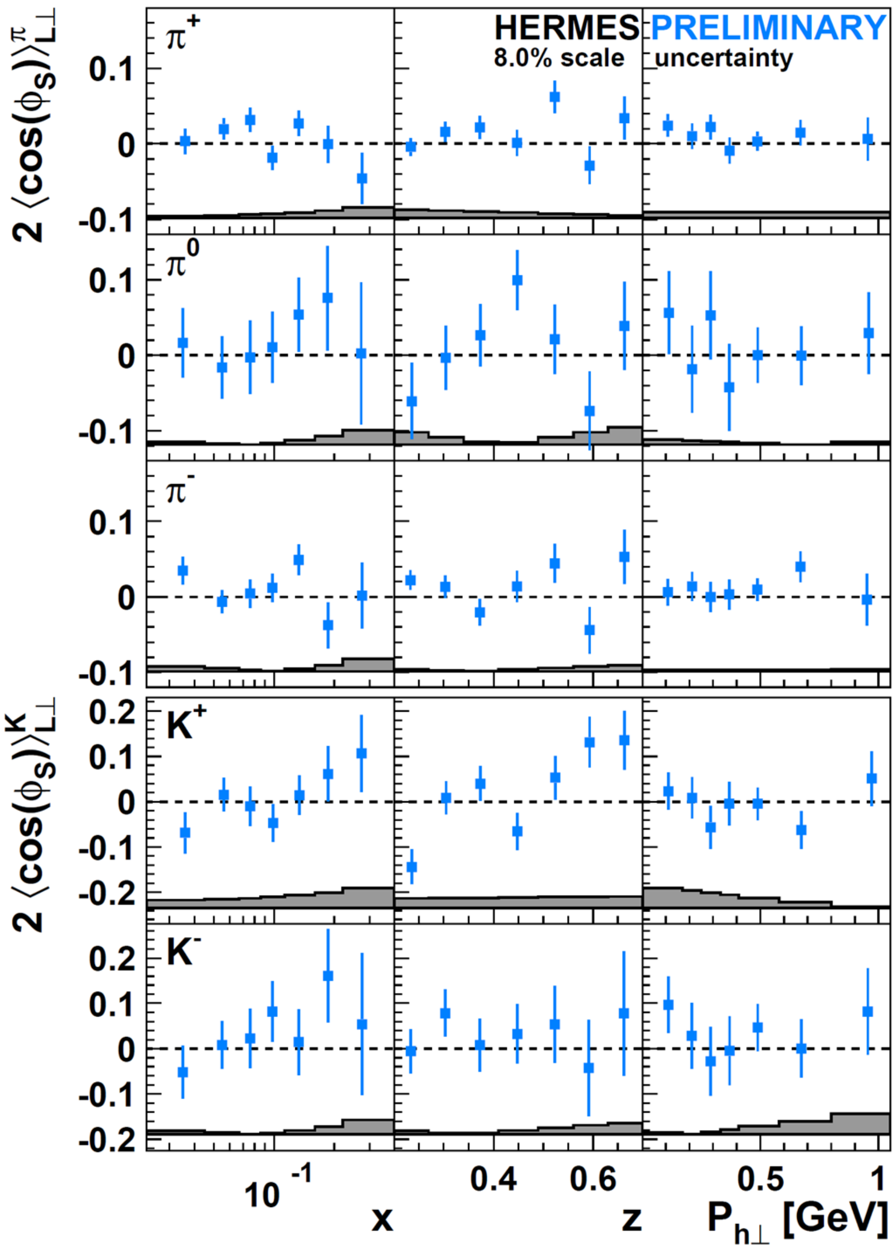
≈ 0

positive!

slightly positive ?

≈ 0

The cos(ϕ_S) Fourier component



≈ 0

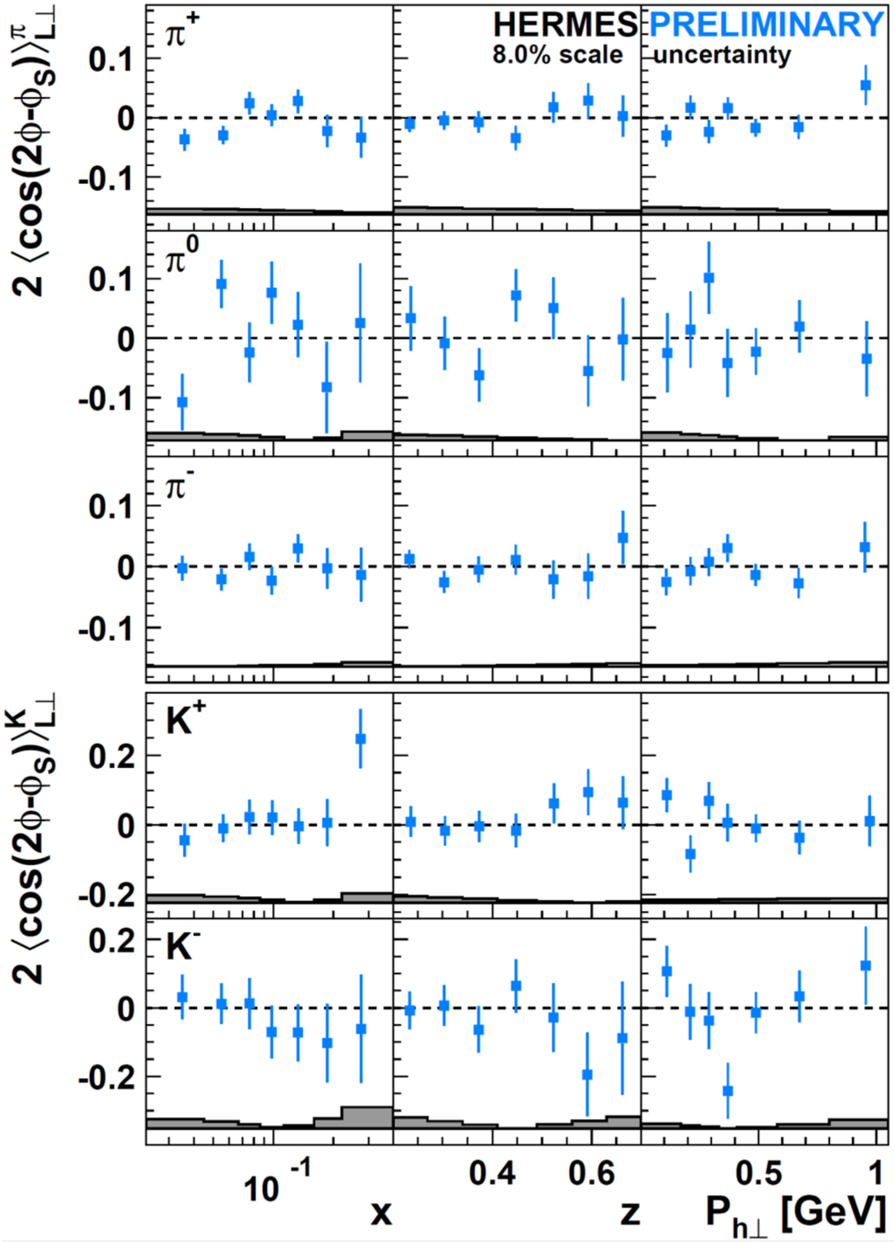
≈ 0

≈ 0

$\approx$ 0
sign change?

≈ 0

The cos(2ϕ-ϕ$_S$) Fourier component



≈ 0

≈ 0

≈ 0

≈ 0
sign change?

≈ 0

Conclusions

The existence of an intrinsic **quark transverse motion** gives origin to azimuthal asymmetries in the hadron production direction in SIDIS

- **significant Collins amplitudes observed for charged pions and K^+**

→ preliminary results enabled first extraction of transversity and Collins FF (by Torino group)

- **significant Sivers amplitudes observed for π^+ and K^+**

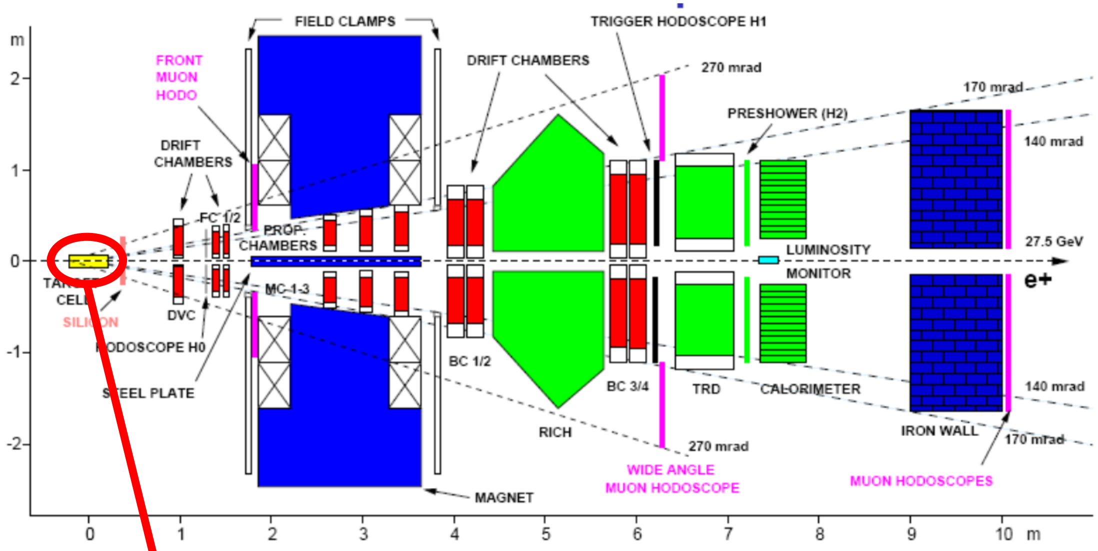
→ clear evidence of non-zero T-odd Sivers function
→ (indirect) evidence for non-zero quark orbital angular momentum
→ hint of non-trivial role of sea quarks and of higher-twist contrib. for positive kaons

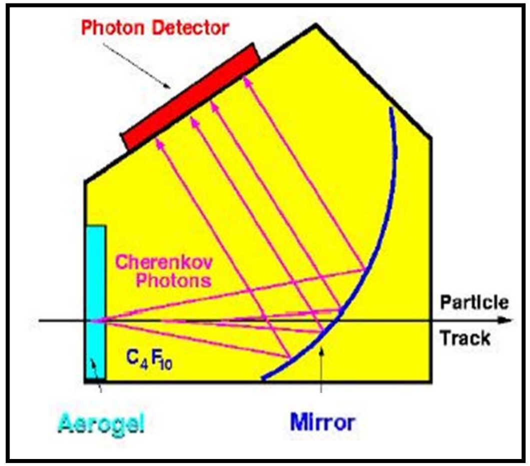
- **new results on A_{LT} DSAs sensitive to worm-gear $g_{1T}{}^{\perp}$**

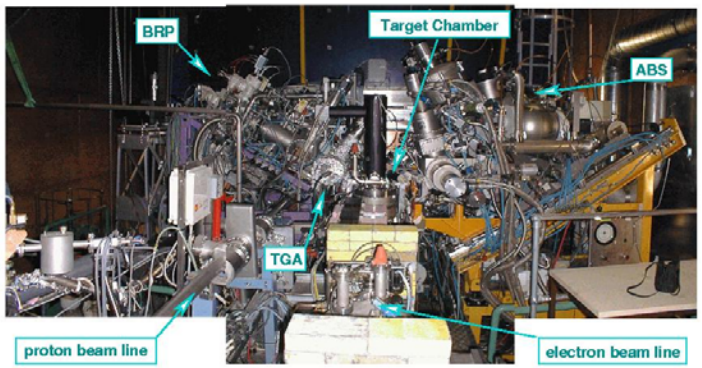
→ non-zero amplitudes observed for the $\cos(\phi - \phi_S)$ Fourier component for π^- $(\pi^+, K^+ ?)$

Back-up slides

The HERMES experiment at HERA

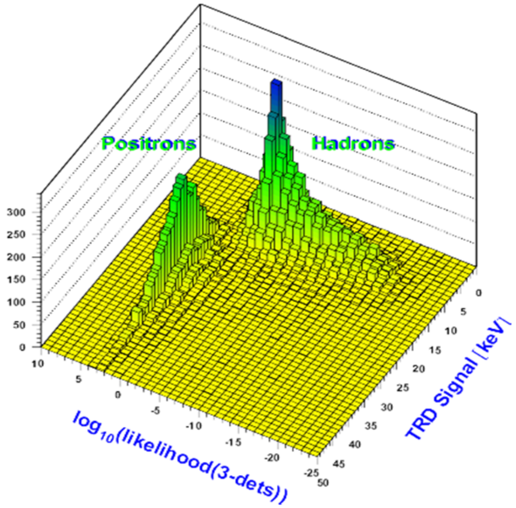




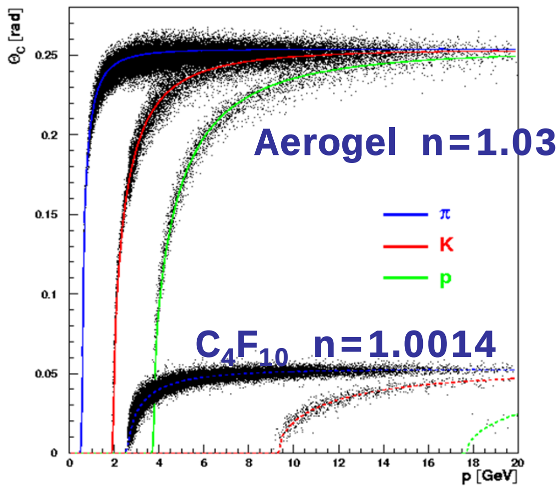


TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%



hadron separation



π ~ 98%, K ~ 88% , P ~ 85%

Accessing the polarized cross section through SSAs

Full HERMES transverse data **(02-05 data with $\langle P_T \rangle \approx 73\%$)**

The relevant Fourier components were extracted through a ML fit of the hadron yields for opposite target transverse spin states, alternately binned in x, z, and $P_{h\perp}$, but unbinned in ϕ and ϕ_S ($\rightarrow$ acceptance effects on azimuthal angles cancel out)

$Q^2 > 1\,\mathrm{GeV}^2$
$W^2 > 10\,\mathrm{GeV}^2$
$0.023 < x < 0.4$
$y < 0.95$
$0.2 < z < 0.7$
$2\,\mathrm{GeV} < P_h < 15\,\mathrm{GeV}$

$$L = \prod_i^{N^h} P_i\left(\phi_i\,, \phi_{S,i}, P_{T,i}; 2\langle \sin(m\phi \pm n\phi_S)\rangle_{UT}^h\right) = \prod_i^{N^h}\left[1 + P_{T,i}\left(2\langle \sin(m\phi \pm n\phi_S)\rangle_{UT}^h \sin(m\phi_i \pm n\phi_{S,i})\right)\right]$$

probability of i_{th} SIDIS event — free parameter

This is equivalent to perform a Fourier decomposition of the cross section asymmetry in the limit of vanishingly small ϕ and ϕ_S bins

$$A_{UT}^h(\phi,\phi_S) = \frac{1}{|P_T|}\frac{d\sigma^h(\phi,\phi_S) - d\sigma^h(\phi,\phi_S+\pi)}{d\sigma^h(\phi,\phi_S) + d\sigma^h(\phi,\phi_S+\pi)}$$

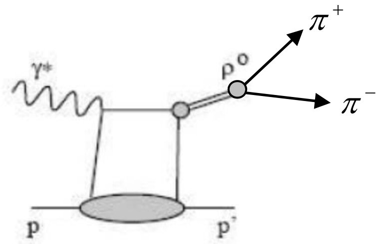
$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\, \mathcal{I}\left[\frac{k_T \hat{P}_{h\perp}}{M_h} h_1^q(x,p_T^2) H_1^{\perp,q}(z,k_T^2)\right]$$

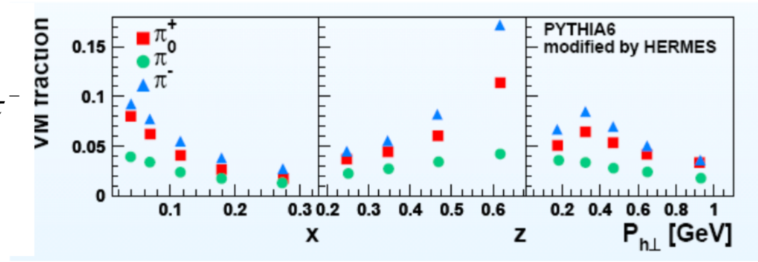
$$+ \sin(\phi-\phi_S)\sum_q e_q^2\, \mathcal{I}\left[\frac{p_T \hat{P}_{h\perp}}{M} f_{1T}^{\perp,q}(x,p_T^2) D_1^q(z,k_T^2)\right] + \ldots$$

I [...]: convolution integral over initial (p_T) and final (k_T) quark transverse momenta

The pion-difference asymmetry

Contribution by decay of exclusively produced vector mesons (ρ^0,ω,ϕ) is not negligible (6-7% for pions and 2-3% for kaons), though substatially limited by the requirement $z<0.7$.

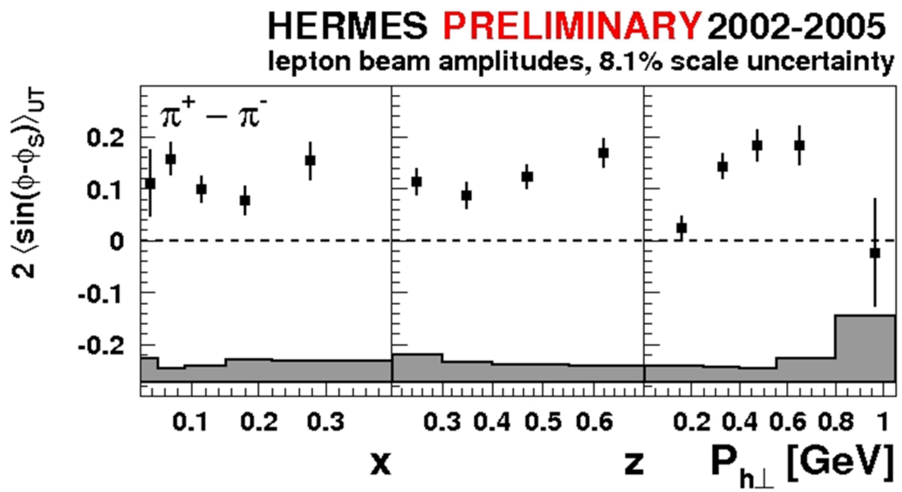


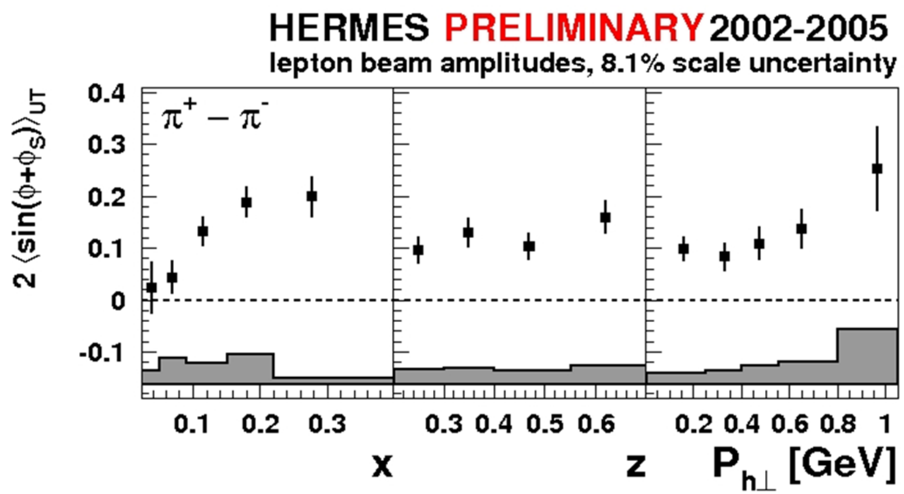


a new observable

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{P_T}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})-(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})+(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}$$

Contribution from exclusive ρ^0 largely cancels out!

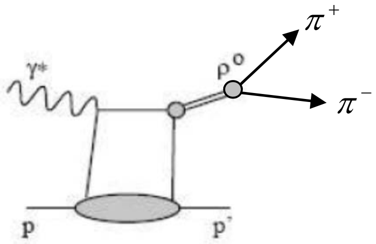


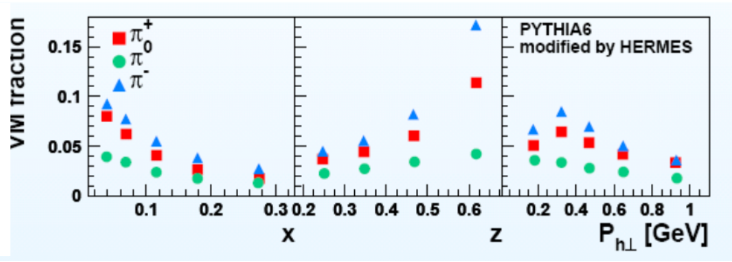


- significantly positive Sivers and Collins amplitudes are obtained
- measured amplitudes are not generated by exclusive VM contribution

The pion-difference asymmetry

Contribution by decay of exclusively produced vector mesons (ρ^0,ω,ϕ) is not negligible (6-7% for pions and 2-3% for kaons), though substatially limited by the requirement z<0.7.

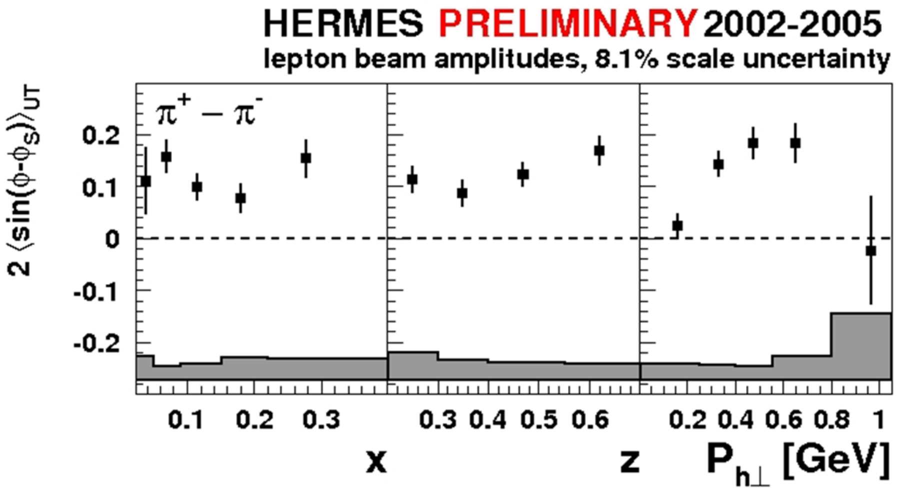




a new observable

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S)\equiv\frac{1}{P_T}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})-(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})+(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}$$

Contribution from exclusive ρ^0 largely cancels out!



$$A_{UT}^{\pi^+-\pi^-}=-\frac{4f_{1T}^{\perp,u_v}-f_{1T}^{\perp,d_v}}{4f_1^{u_v}-f_1^{d_v}}$$

(cancellation of FFs assuming charge-conjugation and isospin symmetry)

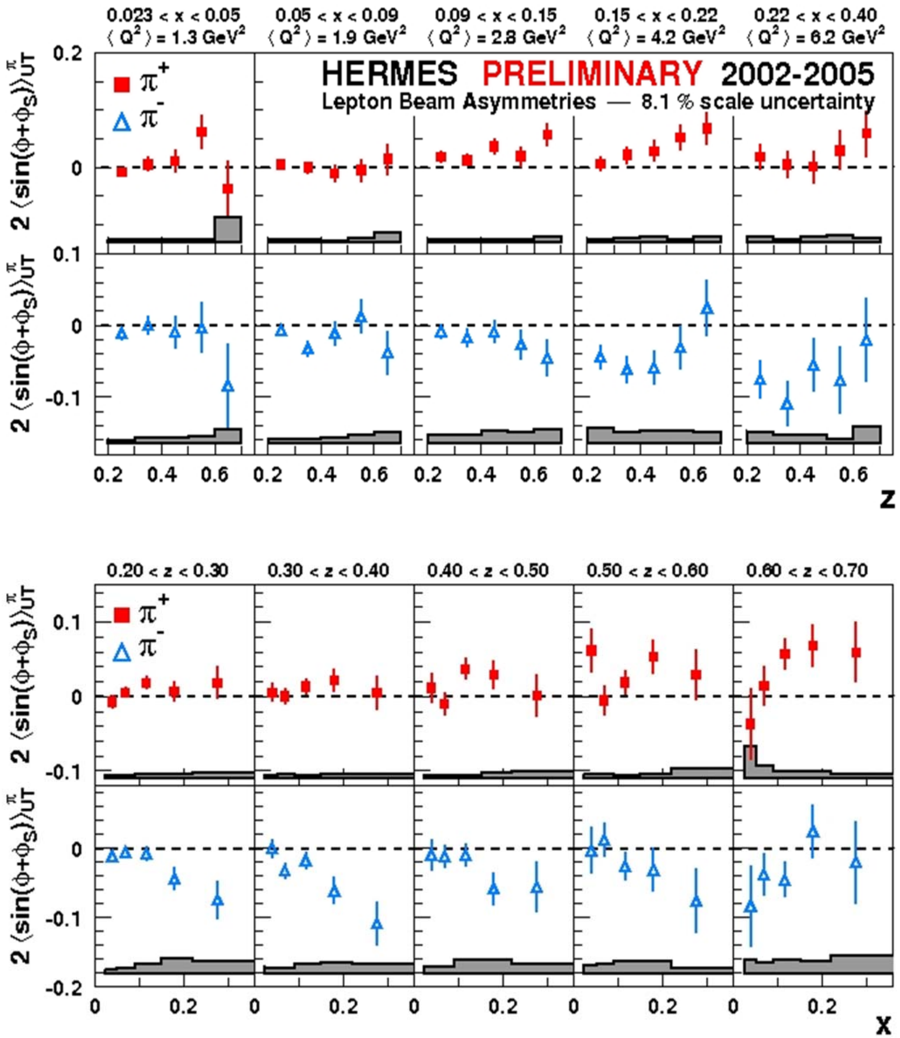
provides access to Sivers valence quarks distribution!

2-D Collins pions amplitudes

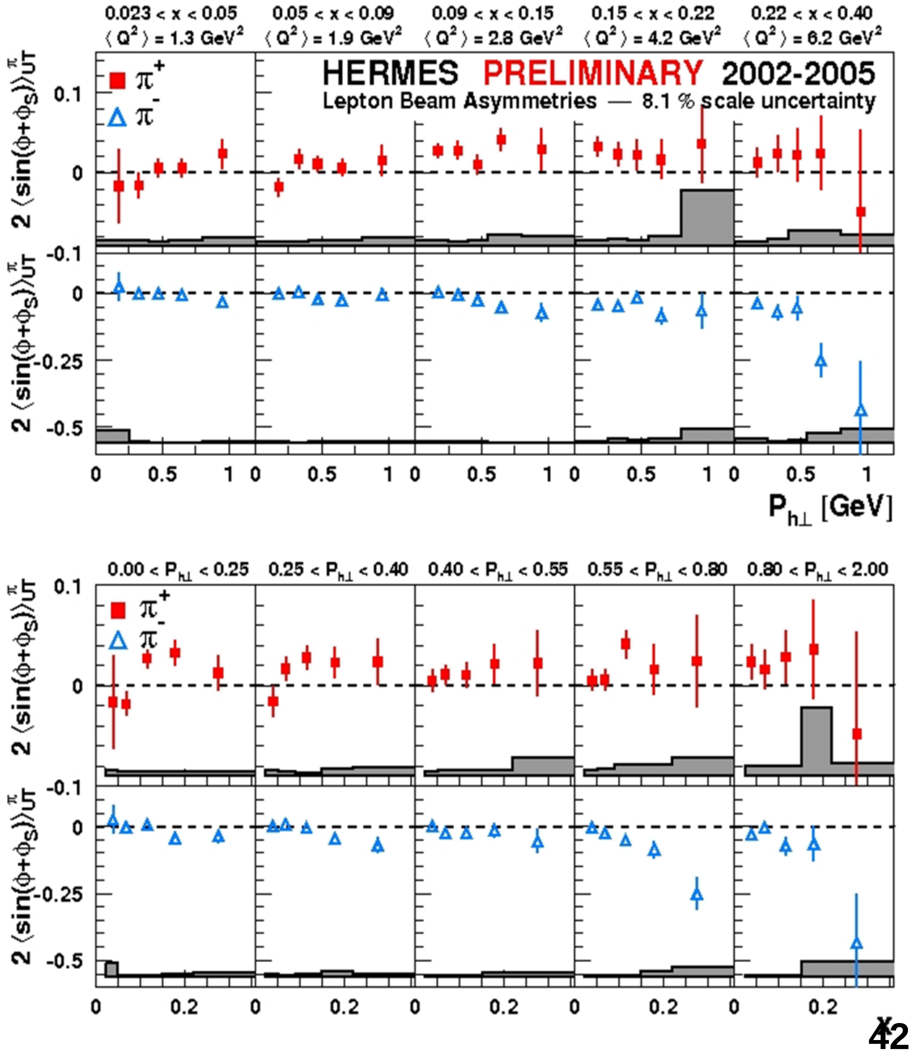
Kinematic dependencies often don't factorize → correlations among variables

⇒ **bin in as many independent variables as possibles (multidim. analysis)**

X vs. Z



X vs. $P_{h\perp}$

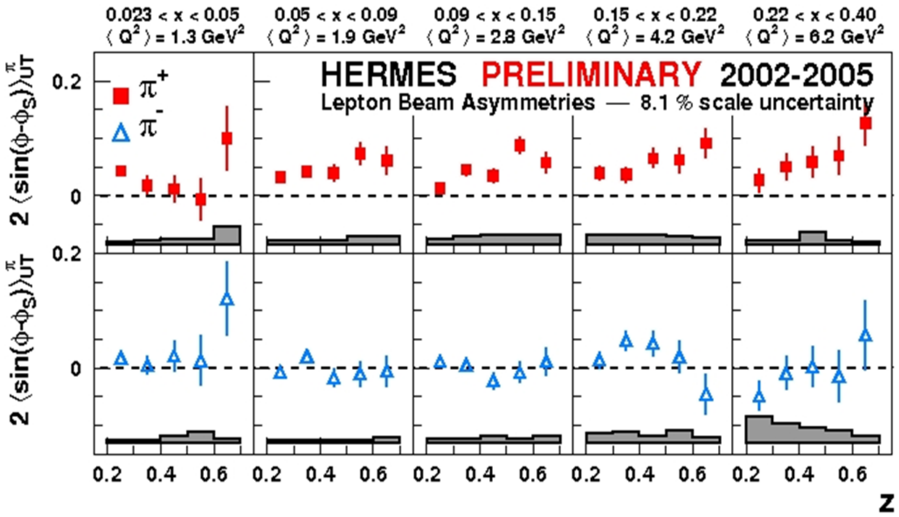


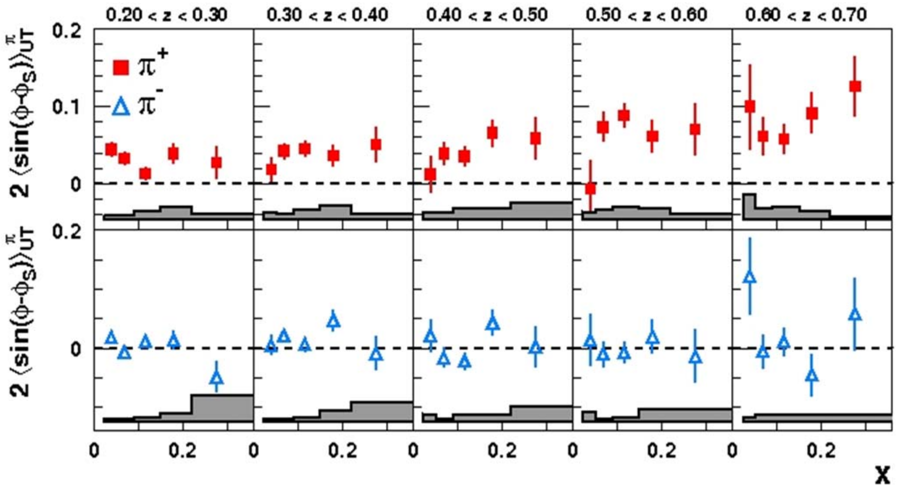
2-D Sivers pions amplitudes

Kinematic dependencies often don't factorize → correlations among variables

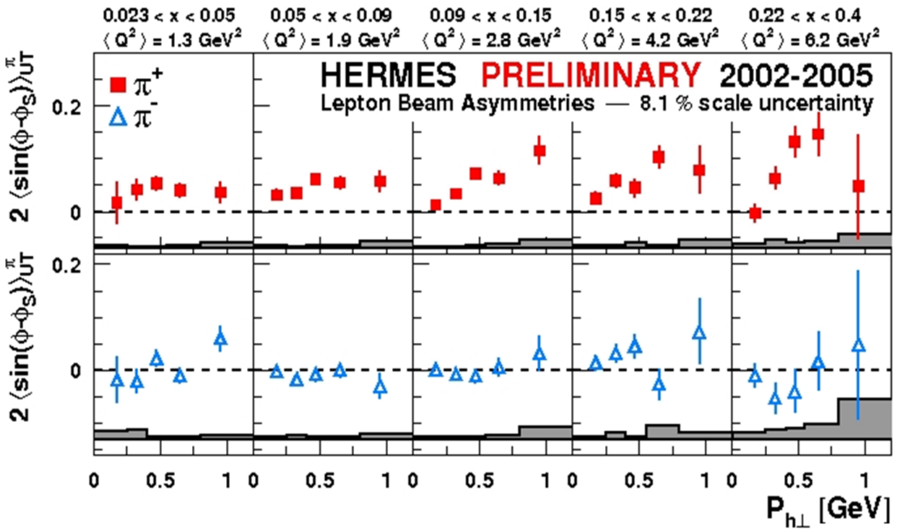
→ **bin in as many independent variables as possibles (multidim. analysis)**

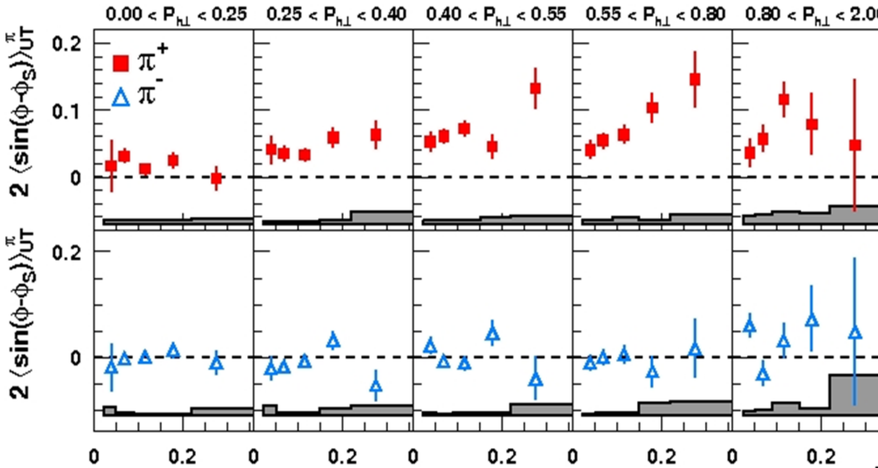
X vs. Z





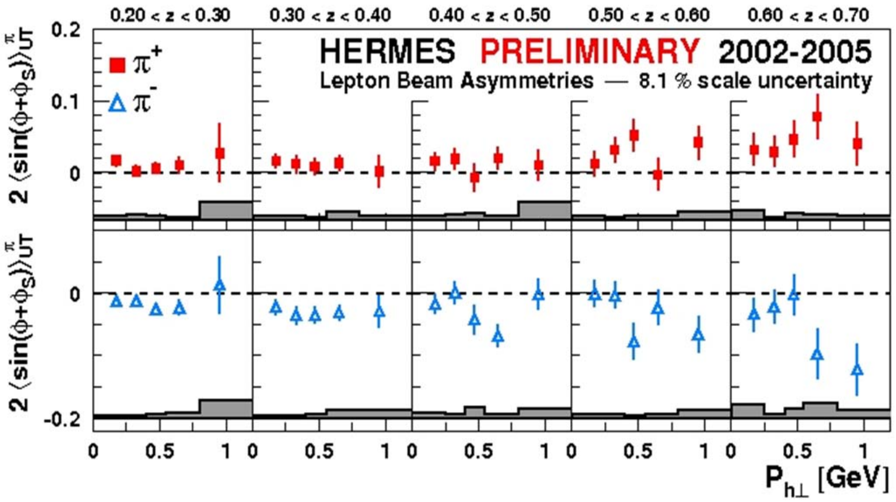
X vs. $P_{h\perp}$

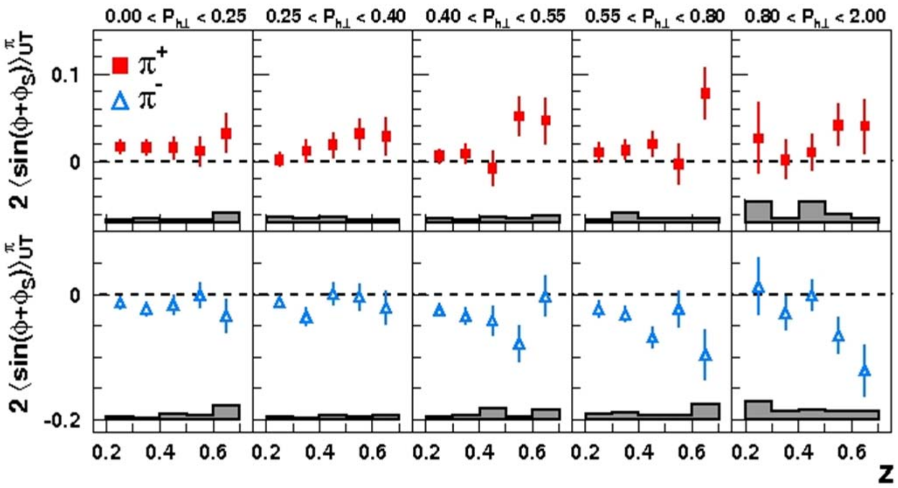




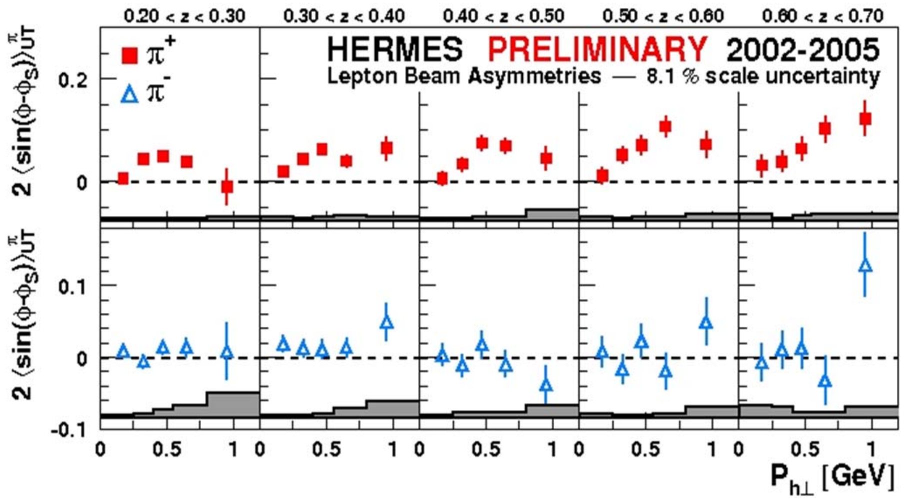
2-D moments for $\pi^{\pm}$: z vs. $P_{h\perp}$

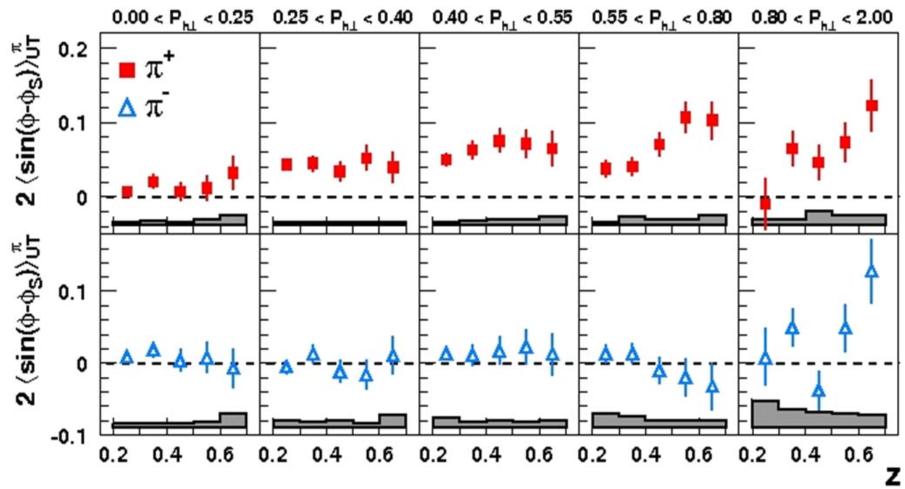
Collins: Z vs. $P_{h\perp}$





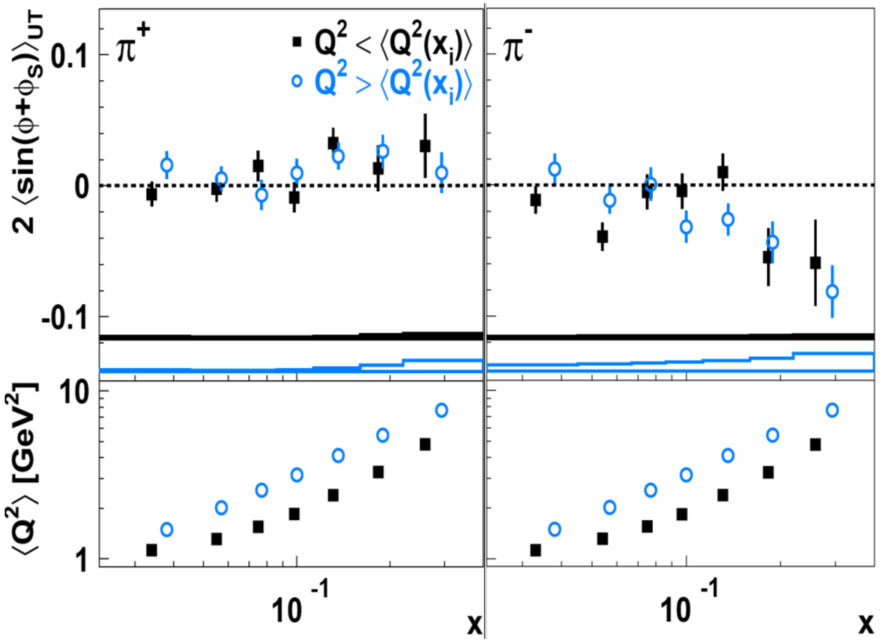
Sivers: Z vs. Ph⊥



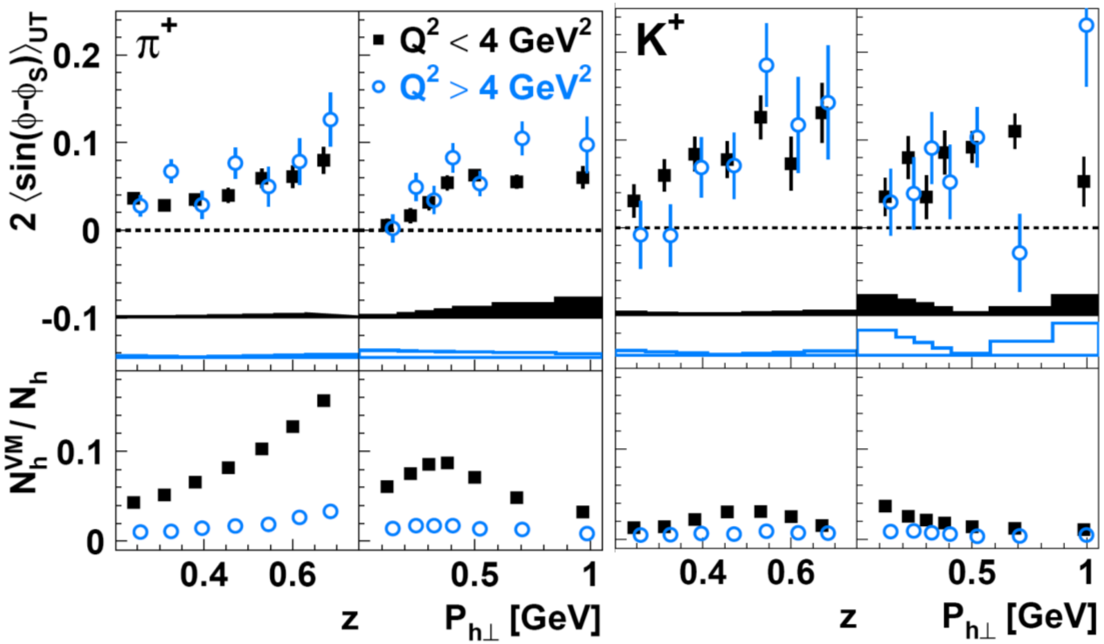


Collins amplitudes:

twist-4 contrib ?

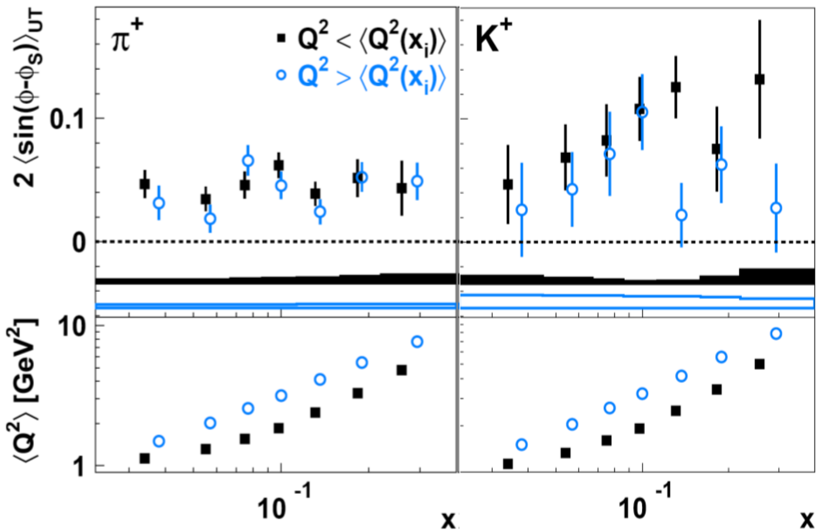


Siver amplitudes: additional studies



- No systematic shifts observed between high and low Q^2 amplitudes for both π^+ and K^+

  No indication of important contributions from exclusive VM



- test presence of $1/Q^2$-suppressed contributions

  separate each x-bin in two Q^2 bins

  hint of higher-twist contributions to the K^+ amplitude

Probing $g_{1T}^{\perp}$ through Double Spin Asymmetries

$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} g_{1T} D_1\right]$$

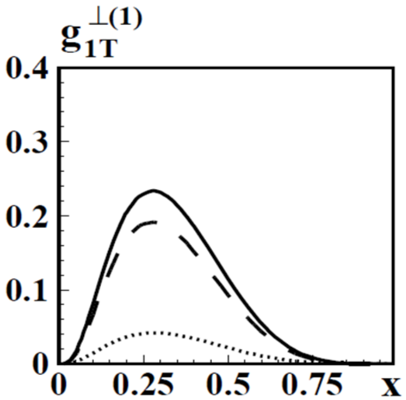
$$F_{LT}^{\cos\phi_S} = \frac{2M}{Q}\,\mathcal{C}\left\{-\left(x g_T D_1 + \frac{M_h}{M}\, h_1 \frac{\tilde{E}}{z}\right) + \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2M M_h}\left[\left(x e_T H_1^{\perp} - \frac{M_h}{M} g_{1T} \frac{\tilde{D}^{\perp}}{z}\right) + \left(x e_T^{\perp} H_1^{\perp} + \frac{M_h}{M} f_{1T}^{\perp} \frac{\tilde{G}^{\perp}}{z}\right)\right]\right\}$$

$$F_{LT}^{\cos(2\phi_h-\phi_S)} = \frac{2M}{Q}\,\mathcal{C}\left\{-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{2M^2}\left(x g_T^{\perp} D_1 + \frac{M_h}{M}\, h_{1T}^{\perp} \frac{\tilde{E}}{z}\right) + \frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2M M_h}\left[\left(x e_T H_1^{\perp} - \frac{M_h}{M} g_{1T} \frac{\tilde{D}^{\perp}}{z}\right) - \left(x e_T^{\perp} H_1^{\perp} + \frac{M_h}{M} f_{1T}^{\perp} \frac{\tilde{G}^{\perp}}{z}\right)\right]\right\}$$

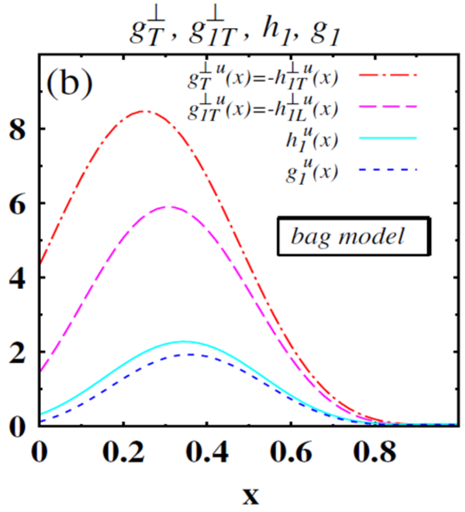
The simplest way to probe worm-gear $g_{1T}^{\perp}$ is through the $\cos(\phi - \phi_S)$ Fourier component

$$2\left\langle \cos(\phi - \phi_S)\right\rangle_{\mathrm{LT}}^{h} \equiv \sqrt{1-\varepsilon^2}\,\frac{F_{LT}^{\cos(\phi_h-\phi_S)}}{F_{UU,T}} = \frac{\mathcal{C}\left[-\frac{\hat{\mathrm{h}}\cdot\mathrm{p}_T}{M}\, g_{1\mathrm{T}}^{\perp,q}\left(x,\mathrm{p}_T^2\right) D_1^q\left(z, z^2\mathrm{k}_T^2\right)\right]}{\mathcal{C}\left[f_1^q\left(x,\mathrm{p}_T^2\right) D_1^q\left(z, z^2\mathrm{k}_T^2\right)\right]}$$

Model calculations

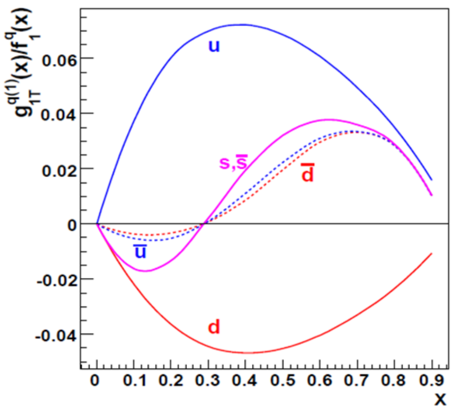


S. Boffi et al. (2009)
Phys. Rev. D 79 094012
Light cone constituent quark model
dashed line: interf. L=0, L=1
dotted line: interf L=1, L=2



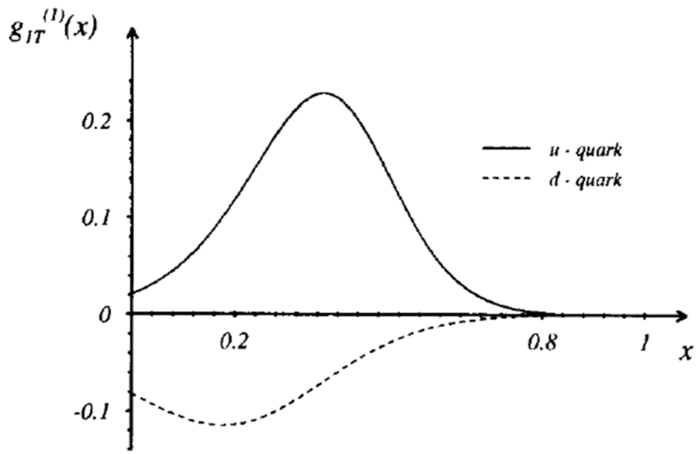
H. Avakian et al. (2010)
Phys. Rev. D 81 074035
Bag model

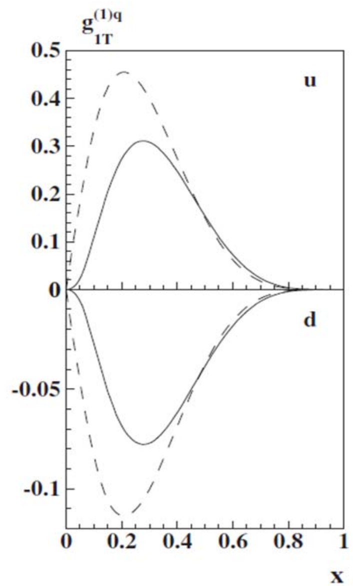
B. Pasquini et al. (2008)
Phys. Rev. D 78 034025
Light cone constituent quark model
dashed line:
Wandzura-Wilczek app.



A. Kotzinian et al. (2006)
arXiv:hep-ph/0603194v5
- Wandzura-Wilczek app.
- LO GRV98 (unpol. DFs)
- LO GRV2000 (pol. DFs)

R. Jakob et al.
Nucl. Phys. A 626 937 (1997)
Spectator model



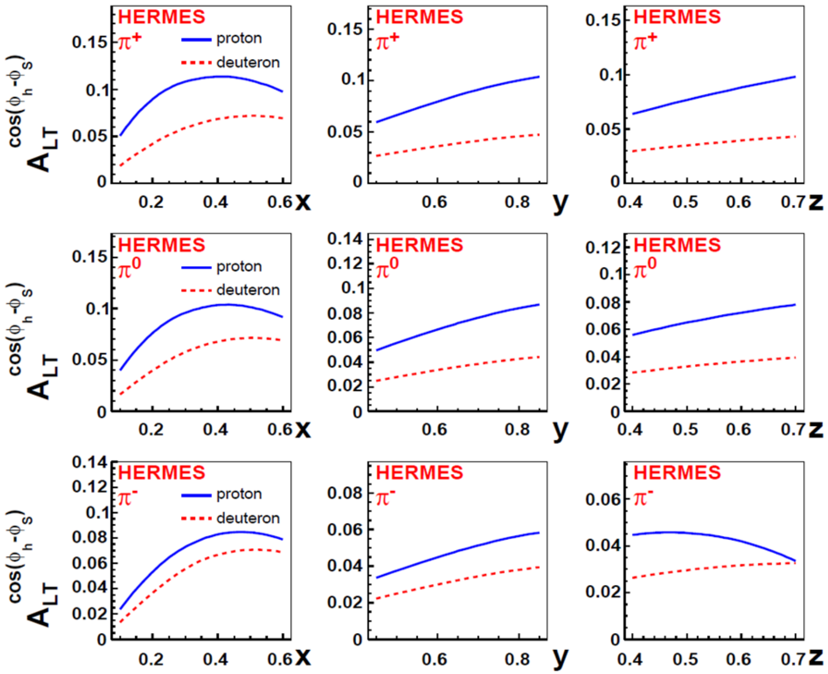


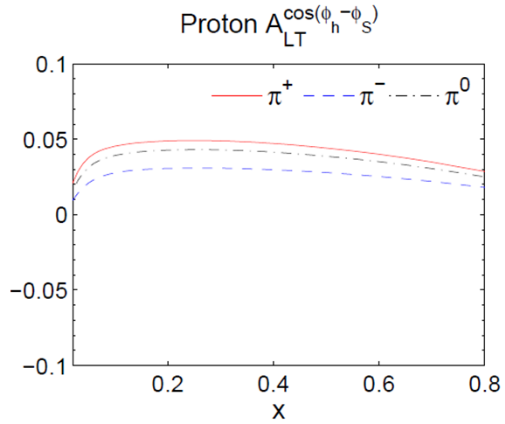
Model predictions for $A_{LT}^{\cos(\phi-\phi_S)}$

A. Kotzinian et al. (2006)
arXiv:hep-ph/0603194v5

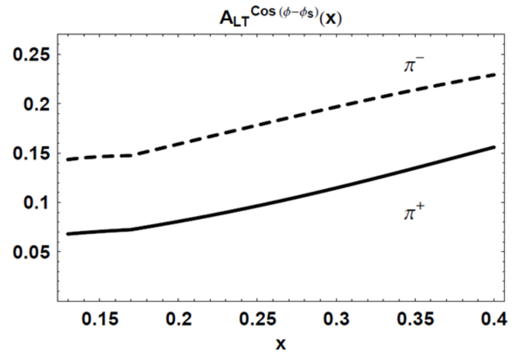
- Wandzura-Wilczek app.
- LO GRV98 (unpol. DFs)
- LO GRV2000 (pol. DFs)
- Kretzer FFs

Proton and deuterium targets
Similar predictions for COMPASS and JLAB

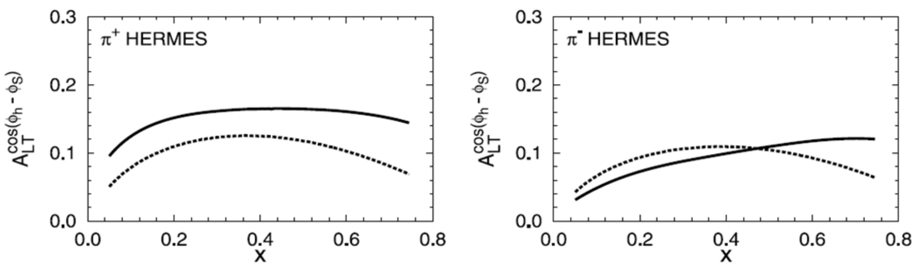




S. Boffi et al. (2009)
Phys. Rev. D 79 094012
Light cone constituent quark model

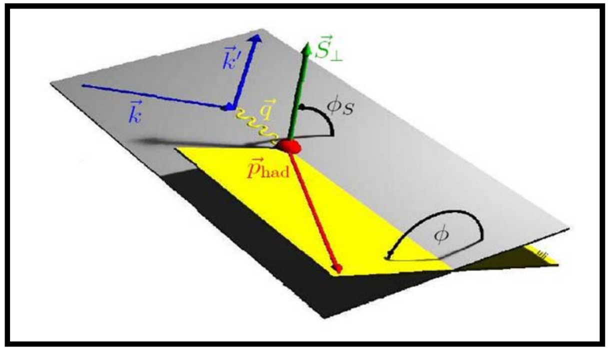


A. Bacchetta et al. (2010)
Eur.Phys.J. A45 373-388
diquark spectator model
Pt-weighted asymmetry



J. Zhu and B0-Qiang Ma , Phys. Let. B 696 (2011) 246
Light-cone quark-diquark model
Two different prescriprions
Similar predictions for n and d targets and for COMPASS and JLAB

		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$ -
	L		g_1 -	$h_{1L}^\perp$ -
	T	$f_{1T}^\perp$ - -	$g_{1T}^\perp$ - -	h_1 - - $h_{1T}^\perp$ - -



$$d\sigma = d\sigma_{UU}^{0} + \cos 2\phi\, d\sigma_{U}^{1} \ldots$$

$$+ S_L \{ \sin 2\phi\, d\sigma_{UL}^{4} + \ldots$$

$$+ S_T \{ \sin(\phi - \phi_S)\; d\sigma_{UT}^{8} + \sin(\ldots$$

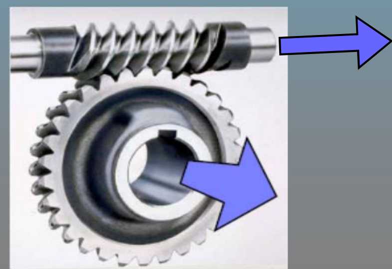
$$+ \frac{1}{Q} \ldots$$

$$+ \lambda_e \left[\cos(\phi - \phi_S)\; d\sigma_{LT}^{13} + \frac{1}{Q} \ldots \right.$$

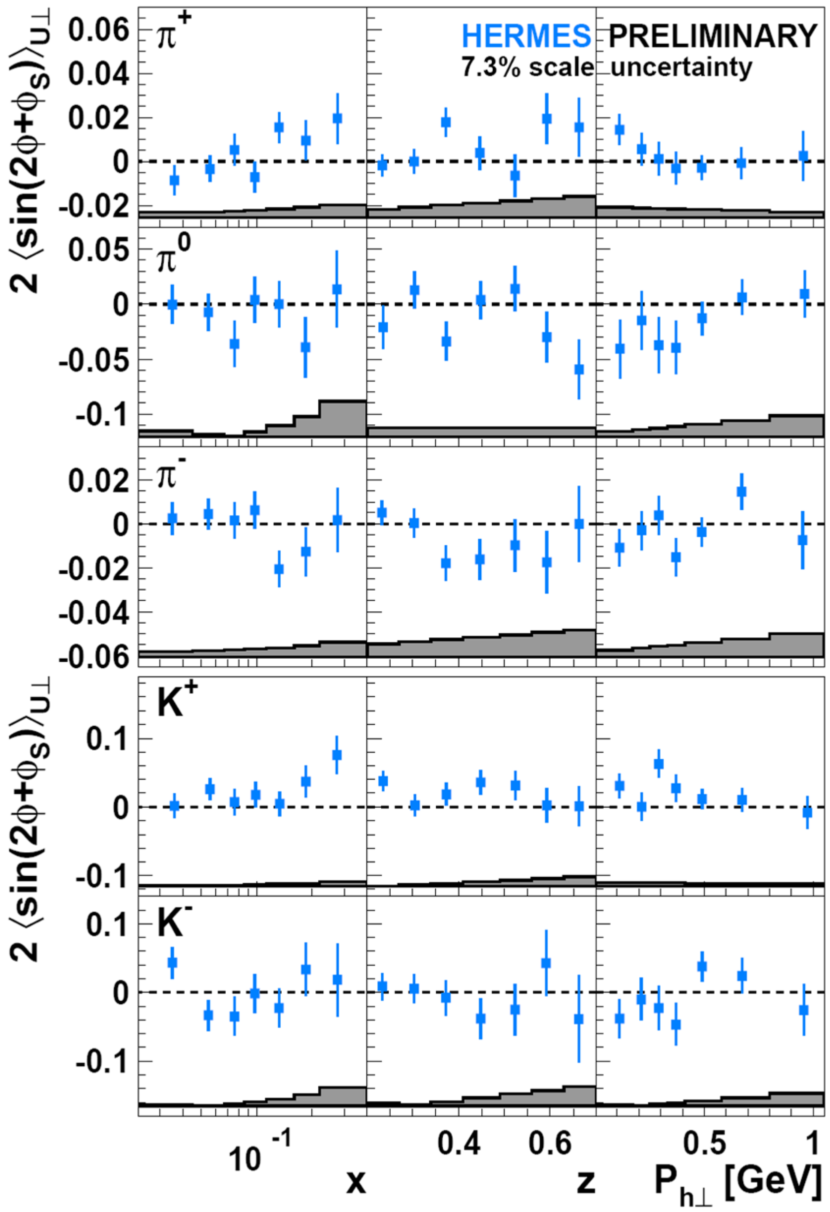
Worm-gear (UL)

(Kotzinian-Mulders)

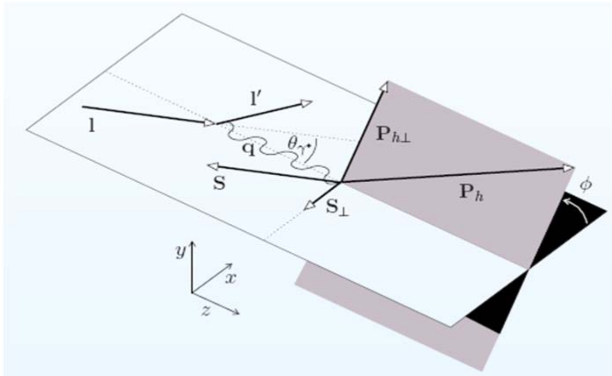
- $\propto h_{1L}^\perp(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$
- describes the probability to find transversely polarized quarks in a longitudinally polarized nucleon
- accessible in UT measurements through sin(2ϕ+ϕ_S) Fourier component



The sin(2ϕ+ϕ$_S$) Fourier component



- arises solely from longitudinal (w.r.t. virtual photon direction) component of the target spin

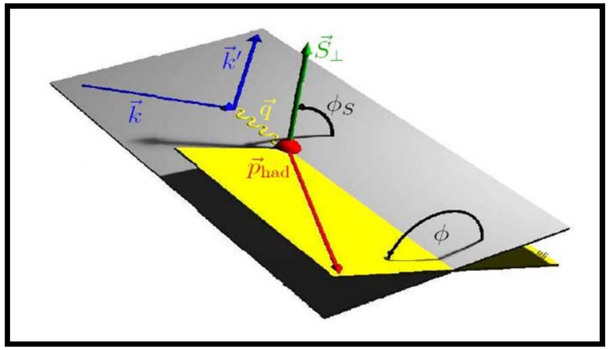


- related to <sin(2ϕ)>$_{UL}$ Fourier comp:

$$2\left\langle \sin(2\phi+\phi_S)\right\rangle_{UT}^{h} \propto \frac{1}{2}\sin(\vartheta_{l\gamma^*})2\left\langle \sin(2\phi)\right\rangle_{UL}^{h}$$

- sensitive to **worm-gear** $h_{1L}^{\perp}$
- suppressed by one power of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes
- **no significant signal observed (except maybe for K+)**

		quark		
		U	**L**	**T**
nucleon	**U**	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$



$$d\sigma = d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} \ldots$$

$$+S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \ldots \right.$$

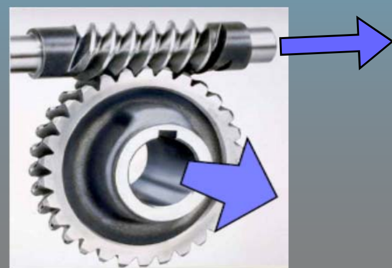
$$+S_T \left\{ \sin(\phi - \phi_S) \; d\sigma^8_{UT} + \sin(\phi \ldots \right.$$

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

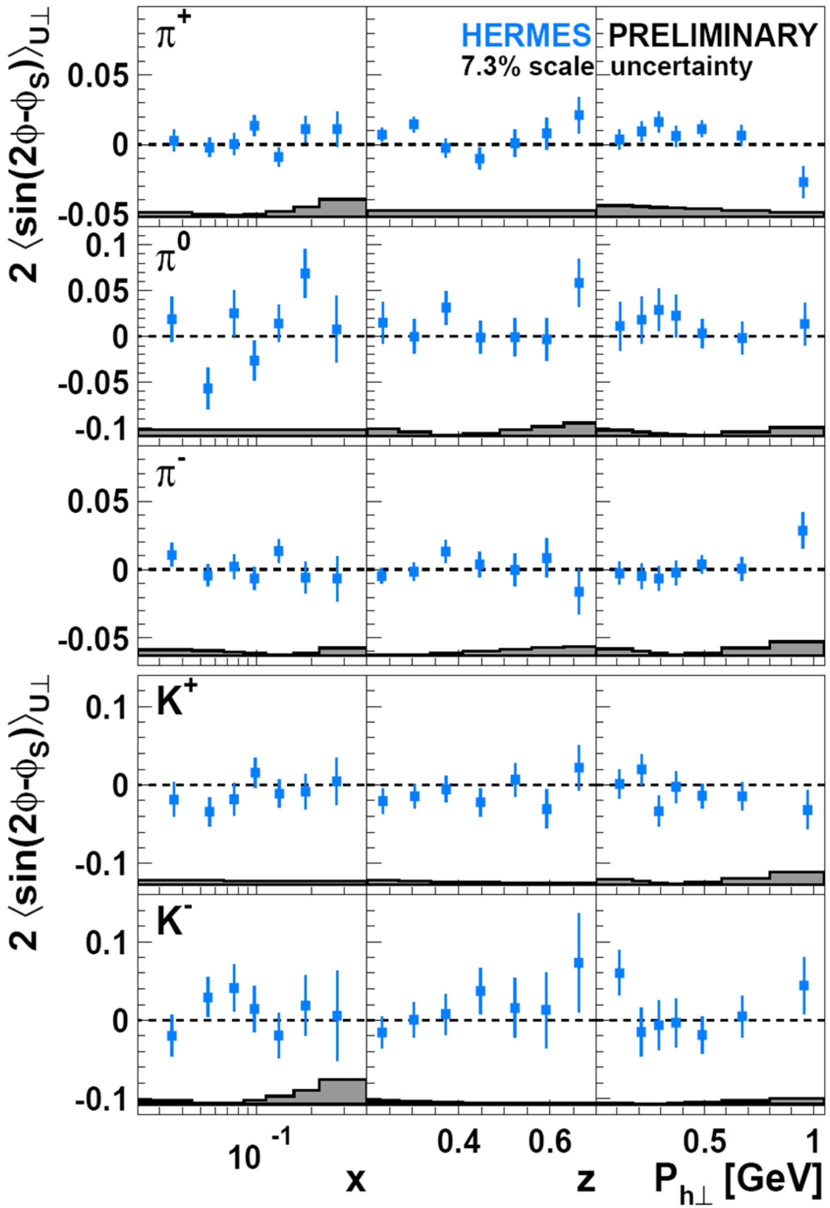
$$+\lambda_e \left[\cos(\phi - \phi_S) \; d\sigma^{13}_{LT} + \frac{1}{Q} \ldots \right.$$

Worm-gear (LT)

- $\propto g_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$
- describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon
- accessible in UT measurements through sub-leading sin(2ϕ-ϕ$_S$) Fourier comp.



The subleading-twist sin(2ϕ-ϕ$_S$) Fourier component



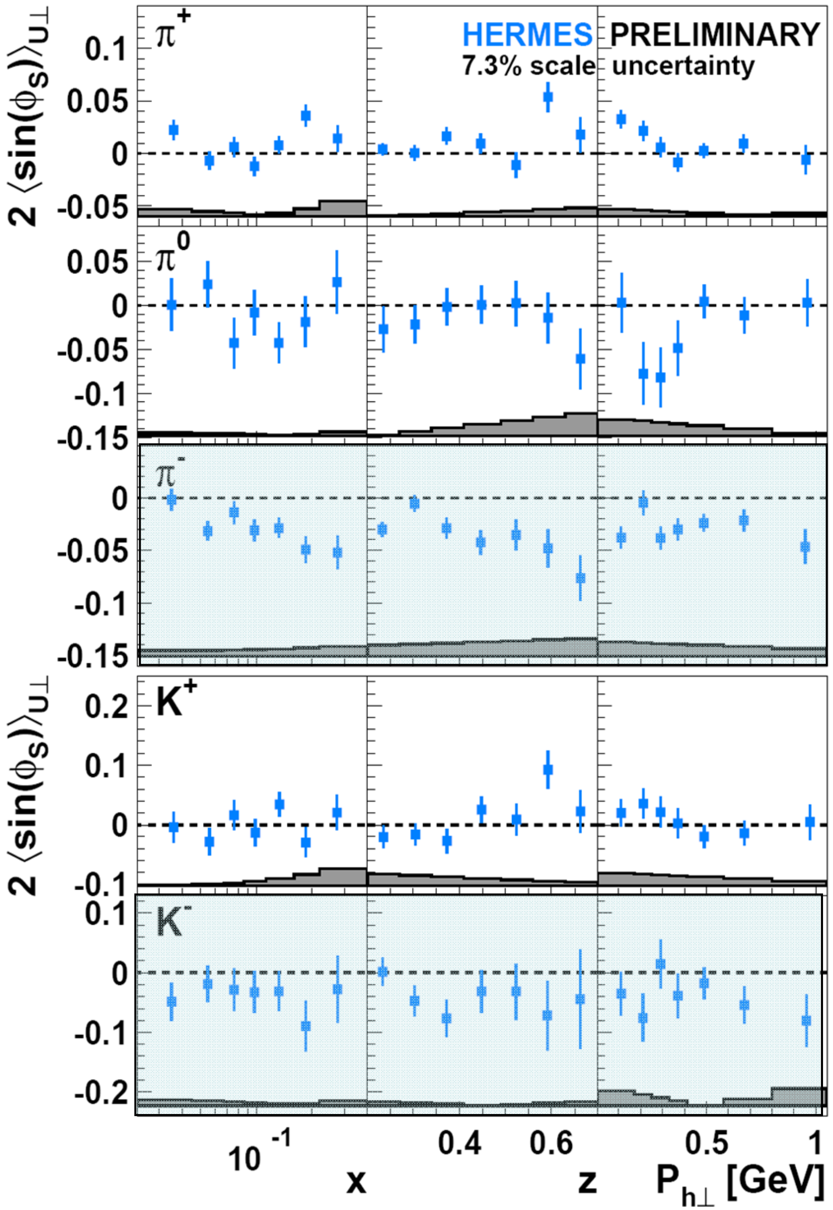
• sensitive to **worm-gear** $g_{1T}^{\perp}$, **Pretzelosity** and **Sivers function**:

$$\propto \mathcal{W}_1(p_T, k_T, P_{h\perp}) \left(x f_T^{\perp} D_1 - \frac{M_h}{M} h_{1T}^{\perp} \frac{\tilde{H}}{z} \right) - \mathcal{W}_2(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^{\perp}}{z} \right) + \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp} \frac{\tilde{D}^{\perp}}{z} \right) \right]$$

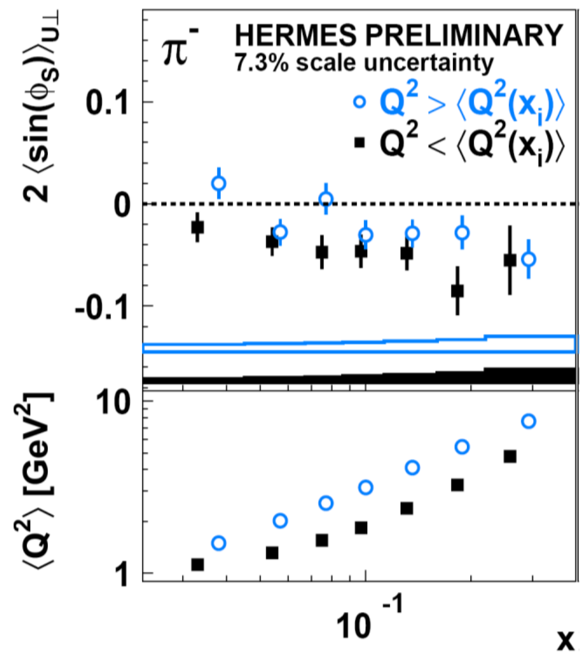
• suppressed by one power of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

• **no significant non-zero signal observed**

The subleading-twist sin(ϕ_S) Fourier component



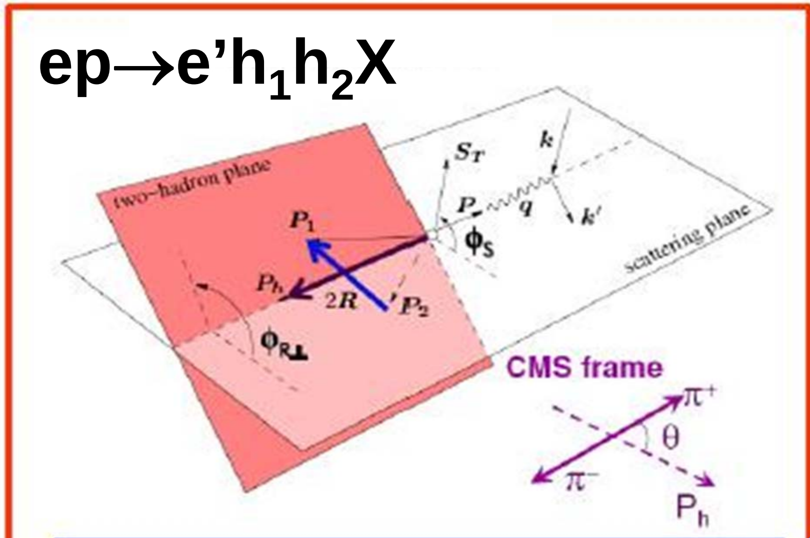
- sensitive to **worm-gear** $g_{1T}^{\perp}$, **Sivers function**, **Transversity**, etc
- **significant non-zero signal observed for π^- and K^- !**



- low-Q^2 amplitude larger
- hint of Q^2 dependence for π^-

An alternative access to transversity: the di-hadron SSA

$ep \rightarrow e'h_1h_2X$



$$\sigma_{UT} \propto S_T \sin\theta \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 h_1 H_{1,q}^{\sphericalangle}$$

azimuthal orientation of relative transv. momentum of the 2 had.

Di-hadron FF

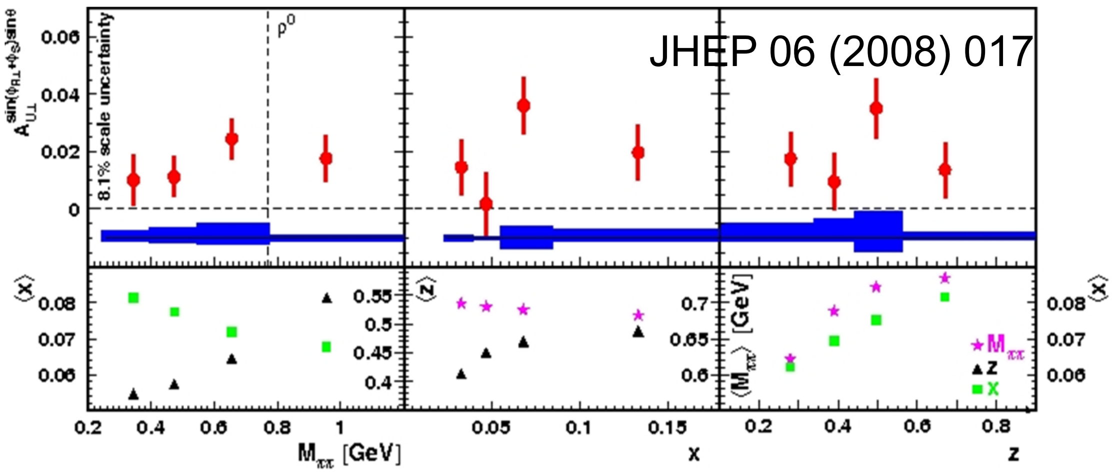
(does not depend on quark transv. momentum)

Chiral-odd   T- odd

Correlation between transverse spin of the fragmenting quark and the relative orbital angular momentum of the hadron pair.

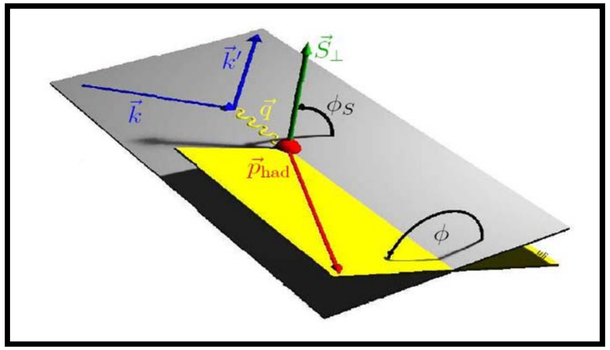
Describes Spin-orbit correlation in fragmentation

azimuthal asymmetries in the direction of the outgoing hadron pairs.



- significantly positive amplitudes
- 1st evidence of non zero dihadron FF
  (can be measured at e^+e^- colliders)
- independent way to access transversity
- no convolution integral involved
- limited statistical power (v.r.t. 1 hadron)

		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$



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

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

$$\ldots + \phi_S)\; d\sigma^9_{UT} + \sin(3\phi - \phi_S)\; d\sigma^{10}_{UT}$$

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

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

Boer-Mulders effect

- $\propto h_1^\perp(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$
- correlation between parton transverse momentum and parton transverse polarization in an unpolarized nucleon

The Boer-Mulders effect

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h dP_{h\perp}} \propto \left\{ F_{UU,T} + \varepsilon F_{UU,L} + 2\sqrt{\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos 2\phi_h F_{UU}^{\cos 2\phi_h} \right\}$$

Twist-2: $d\sigma_{UU}^{Cos2\phi} \propto \cos 2\phi \cdot \sum_q e_q^2 I\left[\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T) - \vec{k}_T\cdot\vec{p}_T}{MM_h} h_1^\perp H_1^{\perp q} \right]$

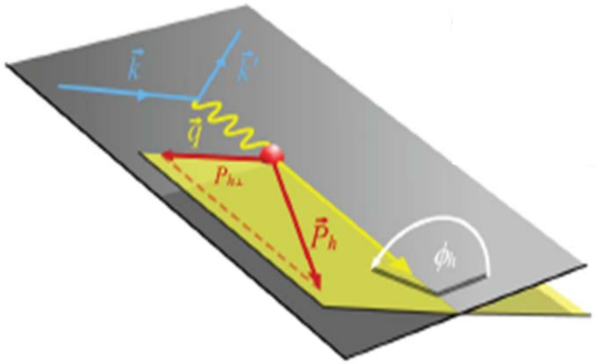
Boer-Mulders effect

Cahn effect

Twist-3: $d\sigma_{UU}^{Cos\phi} \propto \cos\phi \cdot \sum_q e_q^2 \frac{2M}{Q} I\left[-\frac{(\hat{P}_{h\perp}\cdot\vec{p}_T)}{M_h} x\, h_1^\perp H_1^{\perp q} - \frac{(\hat{P}_{h\perp}\cdot\vec{k}_T)}{M} x\, f_1 D_1 + \ldots \right]$

Accessed through azimuthal modulations in SIDIS with unpol. H and D targets

$$\langle\cos n\phi\rangle(x,y,z,P_{h\perp}) = \frac{\int \cos n\phi\ \sigma^{(5)} d\phi}{\int \sigma^{(5)}\, d\phi} \propto \frac{F_{UU}^{\cos n\phi}}{F_{UU,T} + \varepsilon F_{UU,L}}$$



Analysis

Full-differential unfolding of detector and radiative effects

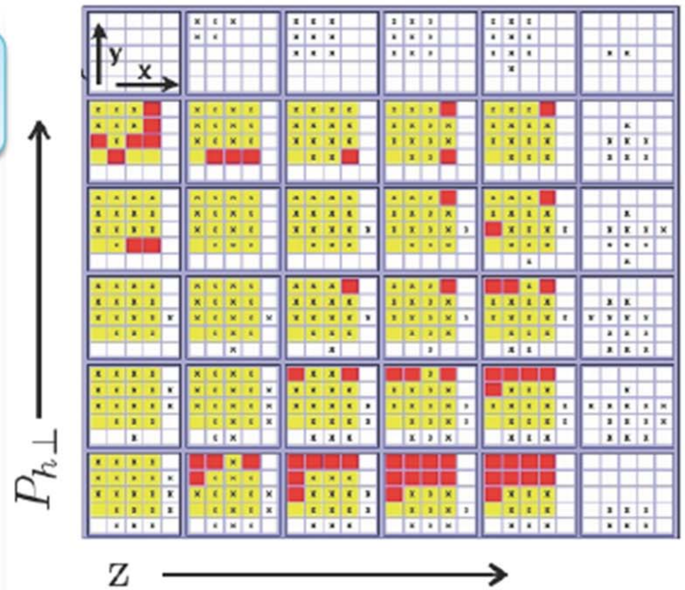
$$n_{born} = S^{-1}[n - B]$$

Bin-by-bin acceptance and smearing effects

Background events smeared into acceptance

Binning 900 kinematic bins x 12 ϕ_h-bins								
Variable	Bin limits							#
x	0.023	0.04	0.078	0.145	0.27	0.6		5
y	0.2	0.3	0.45	0.6	0.7	0.85		5
z	0.2	0.3	0.4	0.5	0.6	0.75	1	6
$P_{h\perp}$	0.05	0.2	0.35	0.5	0.7	1	1.3	6

Full differential result !



Extraction method checks:

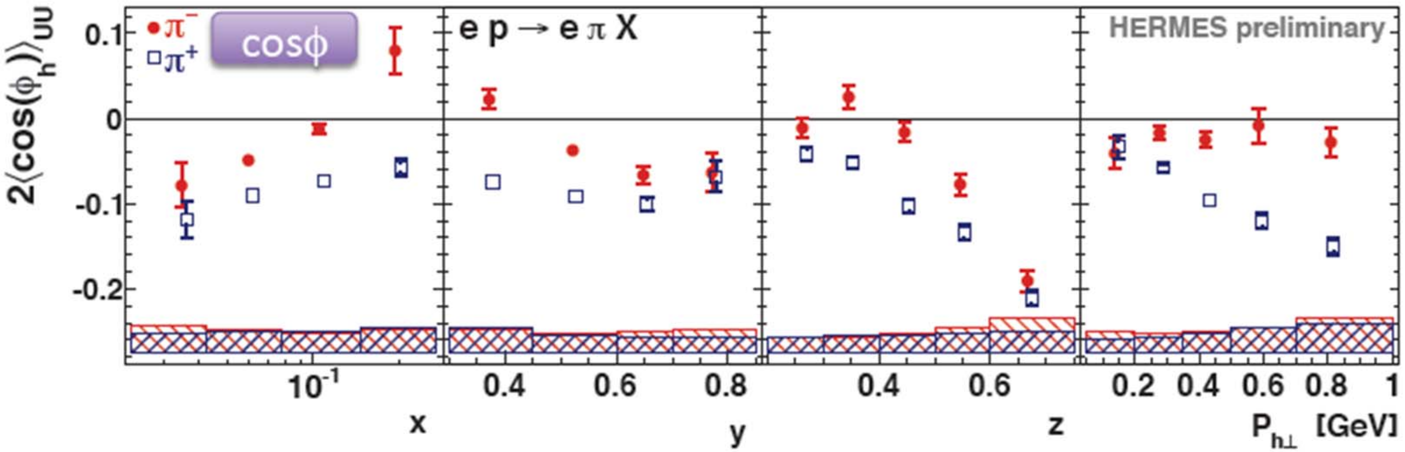
- Stable versus time and major target magnet and IP geometry variations
- Stable versus beam charge and misalignment
- Unphysical cos(3ϕ) and cos(4ϕ) terms consistent with zero
- Stable with different xsec models and binning schemes

Unpolarized cross-section

cosϕ large and negative !

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

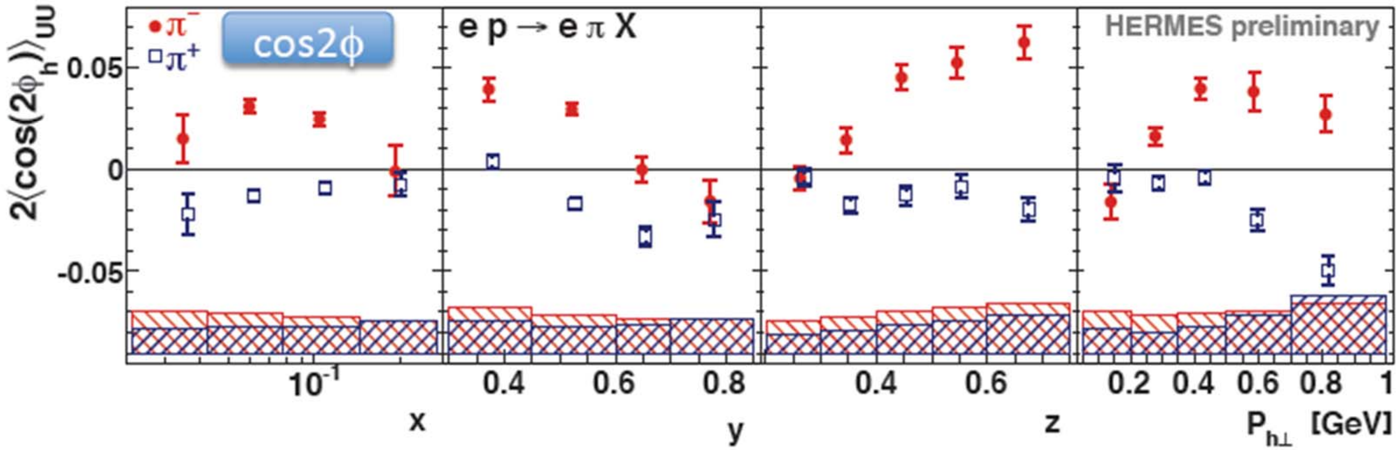
- Increasing with z and P_h
- Large difference in hadron charge !
- Larger in magnitude for π+



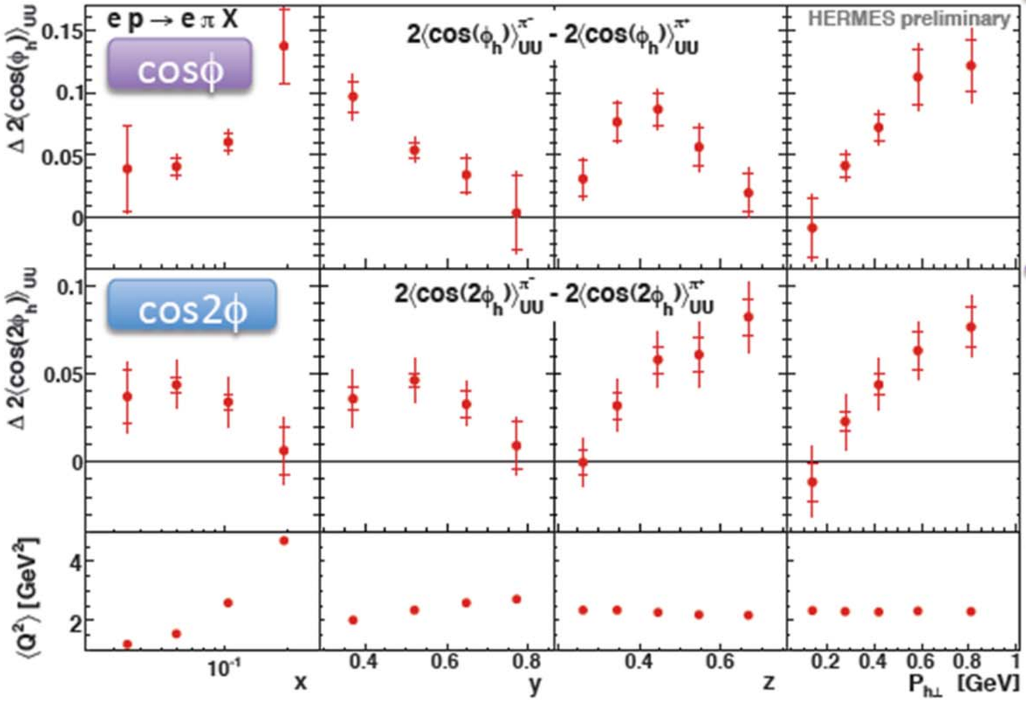
cos2ϕ non-zero !

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

- Difference in hadron charge !
- Positive for π-
- Negative for π+



Difference in pion charge



$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

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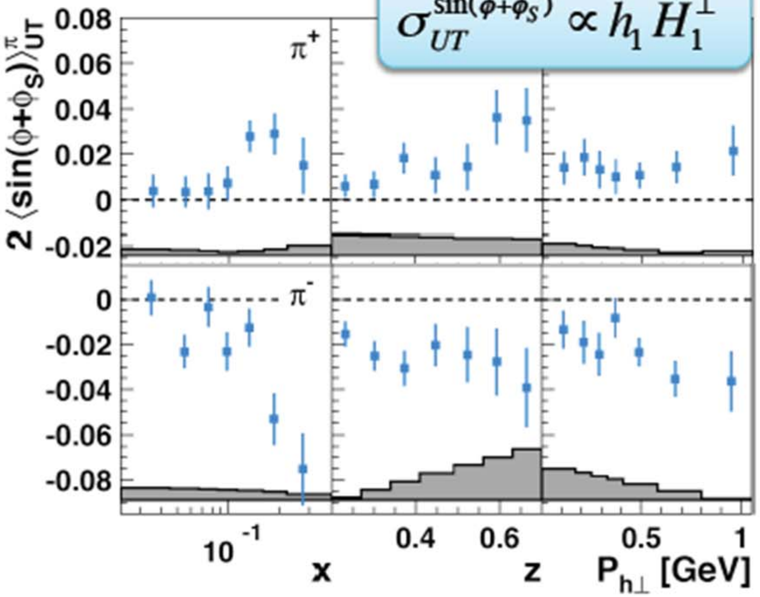
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^{\perp}$$

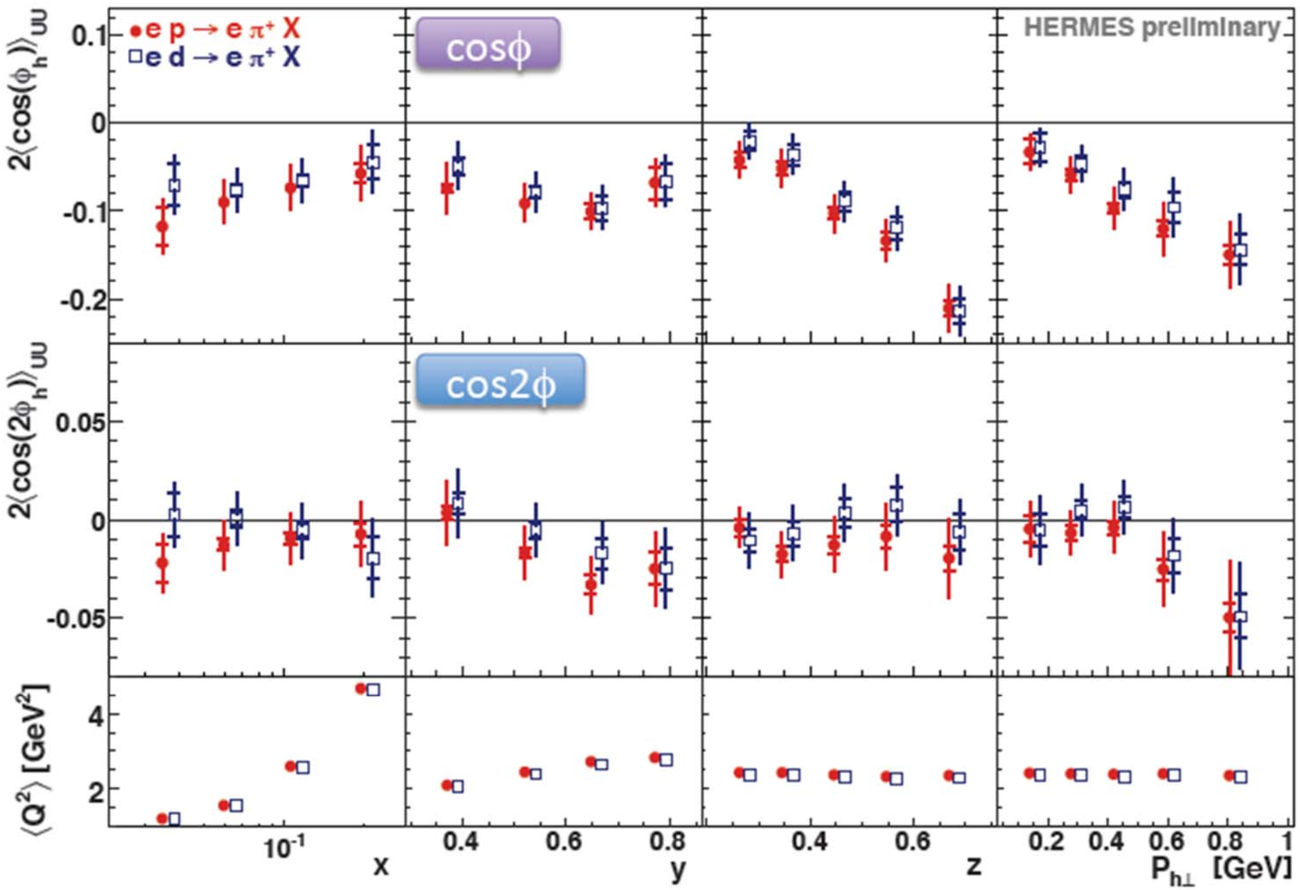


Mild flavor dependendence of k_T expected

From A_{UT}: Collins favored ($u \rightarrow \pi+$) and unfavored ($u \rightarrow \pi-$) fragmentation opposite in sign

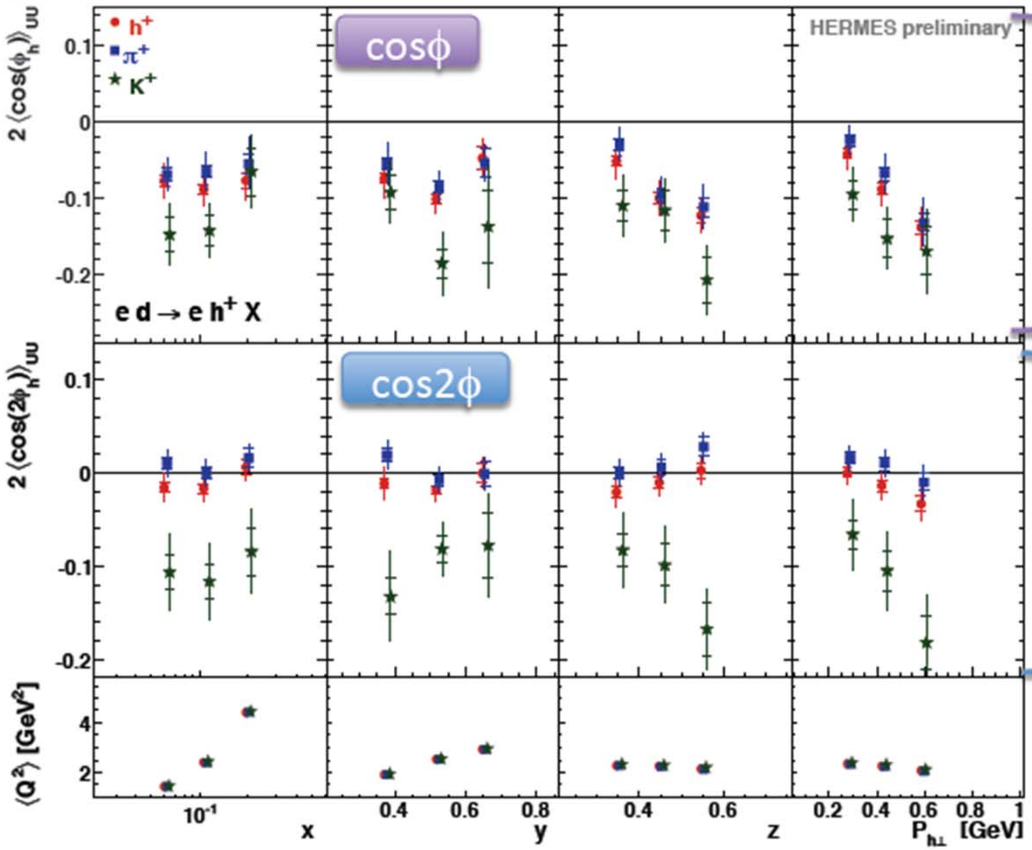
With u-dominance
Collins makes the difference !
Hint of non-zero Boer-Mulders

Proton vs Deuteron Target



Quark d vs u contribution ?
DATA support Boer-Mulders of same sign for u and d

The kaon signal



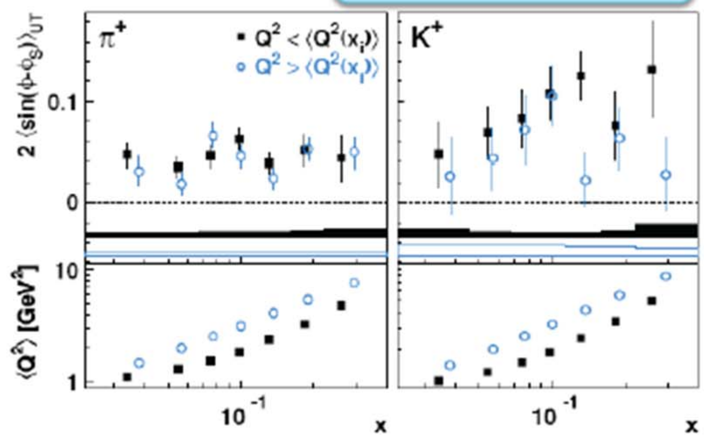
$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots\right]/Q$$

NEW !!

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots\right]/Q^2$$

Phys. Rev. Lett. 103 (2009) 152002

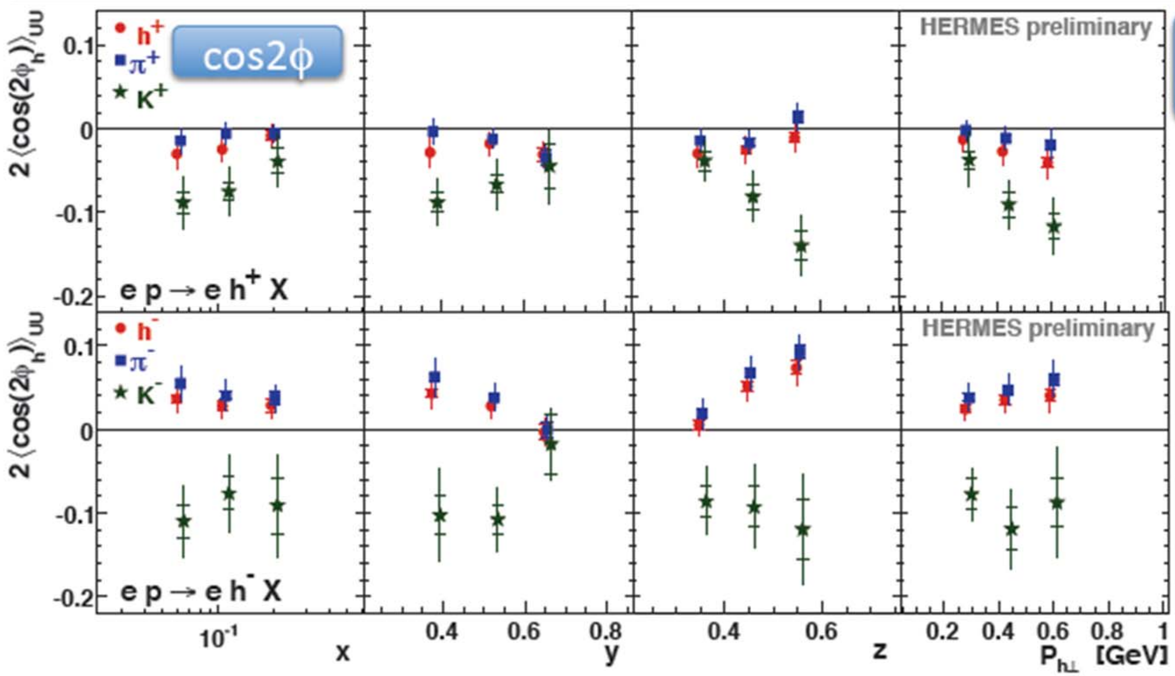
$$\sigma_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^\perp D_1^\perp$$



Striking difference versus pions !

- ❖ Role of the sea
- ❖ Strange Collins
- ❖ Sub-leading twists

The kaon signal



$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

NEW !!

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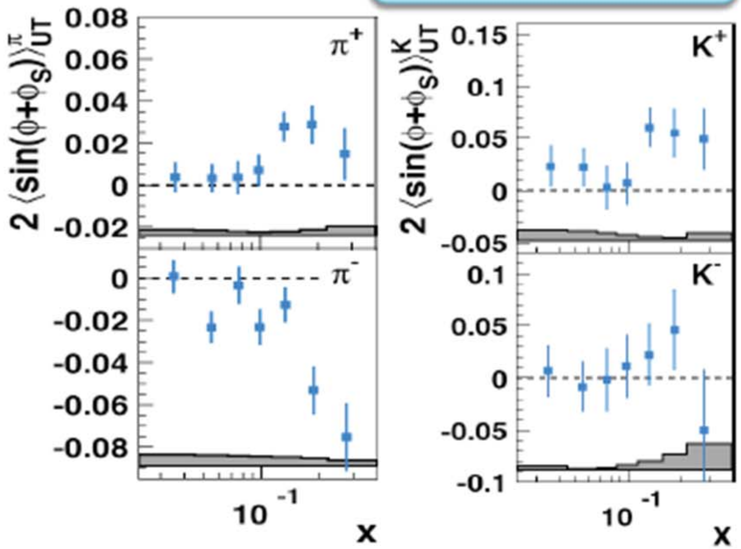
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^\perp$$



The kaon puzzle

Already found in A_{UT}: Collins+Transversity

Role of the sea in
distribution and fragmentation functions