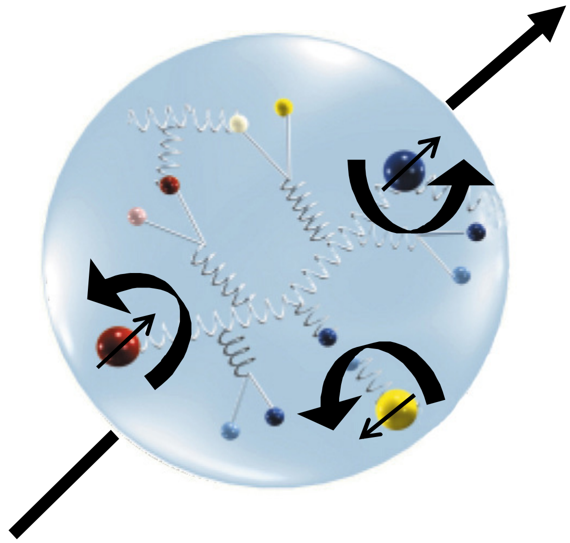
Study of TMDs with polarized beam and/or targets

Luciano L. Pappalardo

INFN & University of Ferrara

Looking deeply into the proton

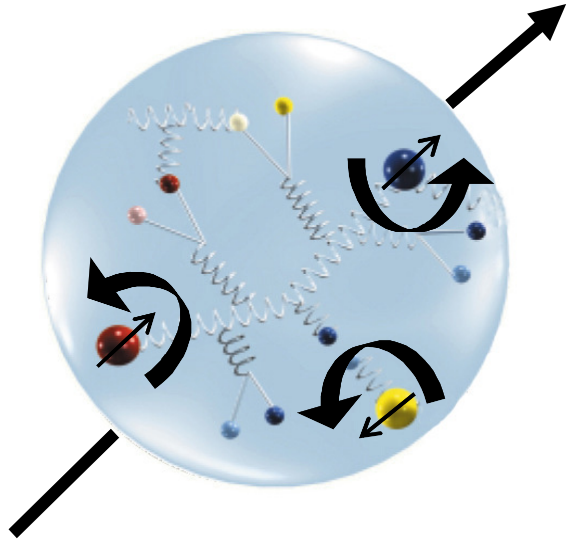


What is our final goal?

Understanding the **full phase-space distribution of the partons: Wigner function**

$$W(x, p_T, r)$$

Looking deeply into the proton



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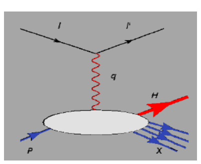
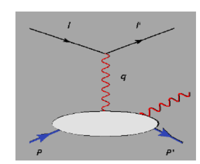
...but $\Delta x \Delta p \geq \frac{\hbar}{2}$ $\rightarrow$ no simultaneous knowledge of momentum and position!

$$W(x, p_T, r)$$

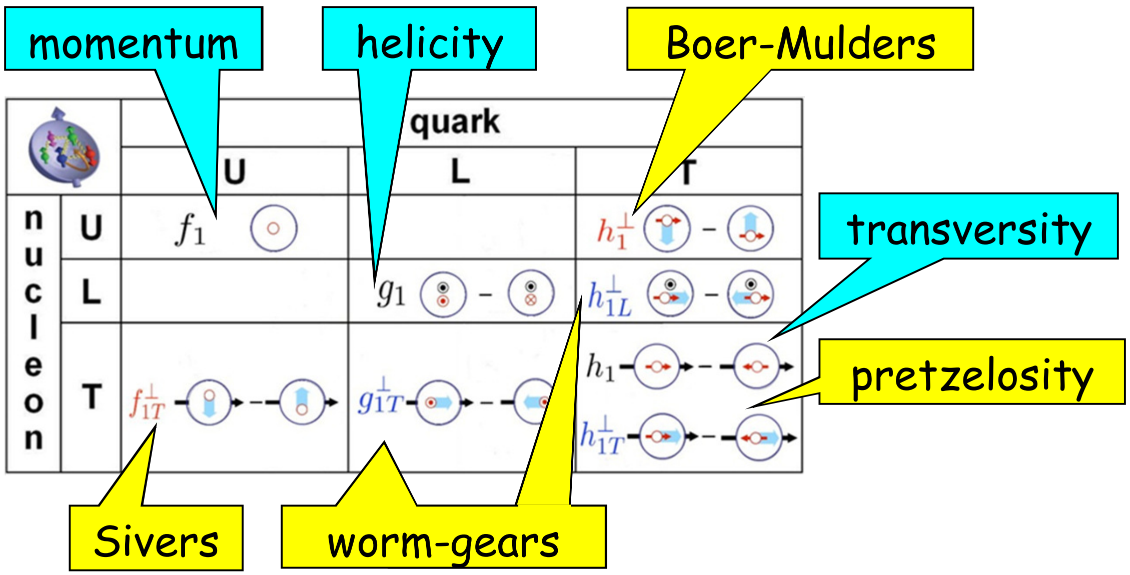
$\int d^3r$ → TMDs: $f(x, p_T)$

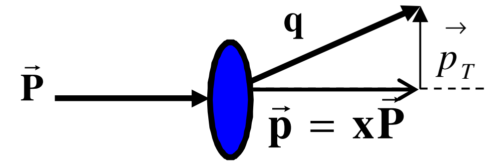
$\int d^2p_T$ → GPDs: $\mathrm{H}(x, \xi, t)$


TMDs $f(x, p_T)$

$\mathrm{H}(x, \xi, t)$ GPDs


The **non-collinear** structure of the nucleon





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- Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)

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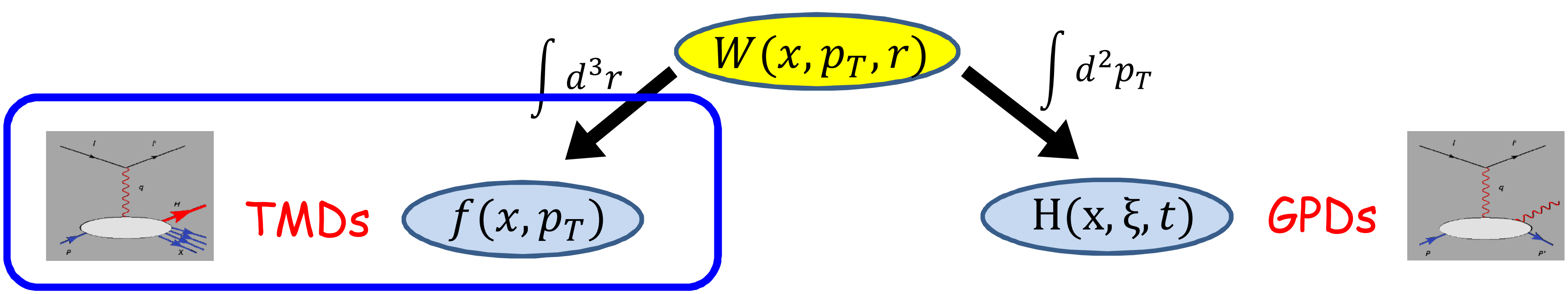

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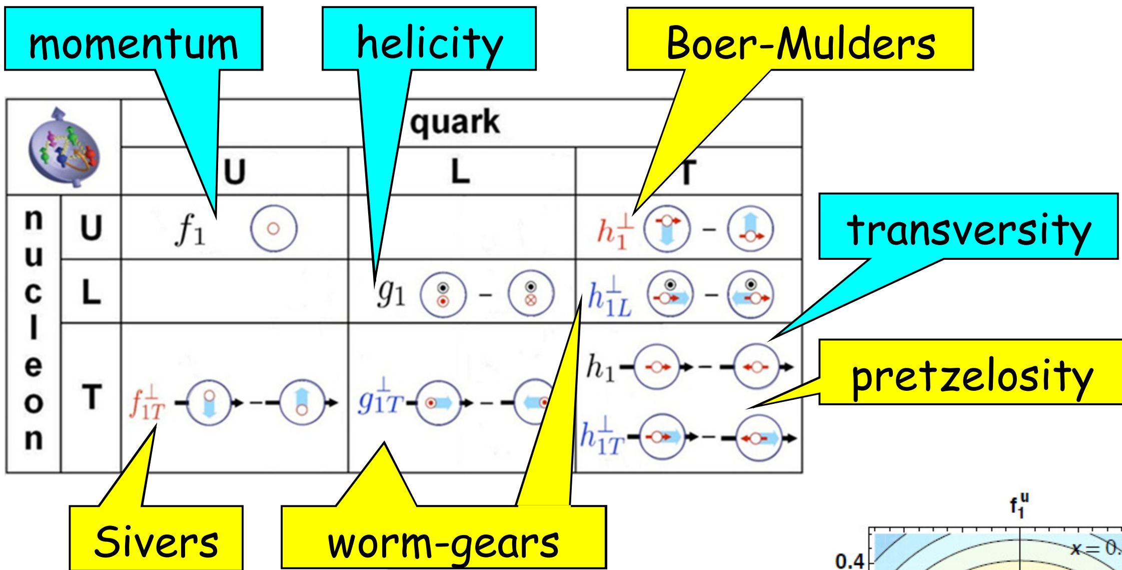

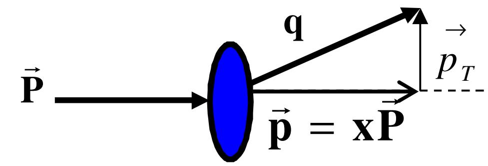

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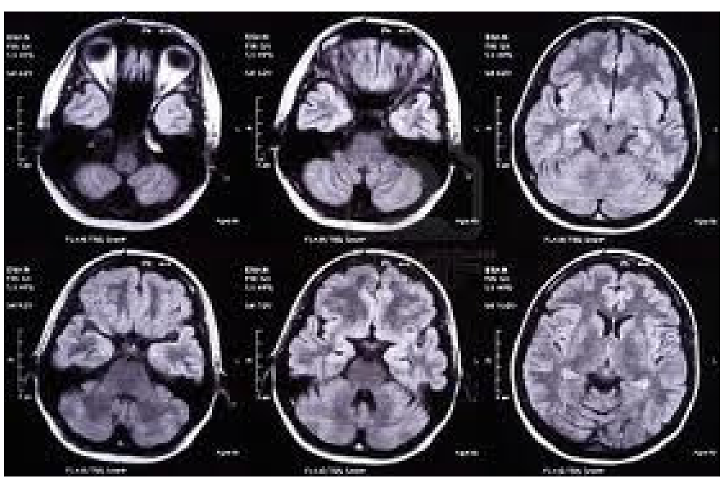
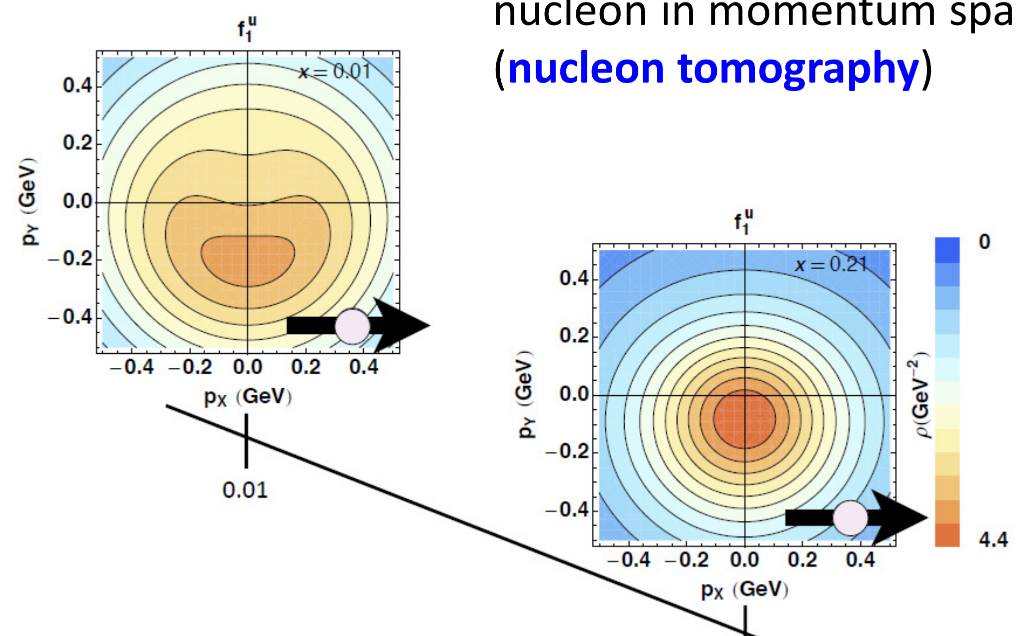
- Provide **a 3-dim picture** of the nucleon in momentum space (**nucleon tomography**)





Based on model calculation
A.B., Conti, Guagnelli, Radici, arXiv:1003.1328

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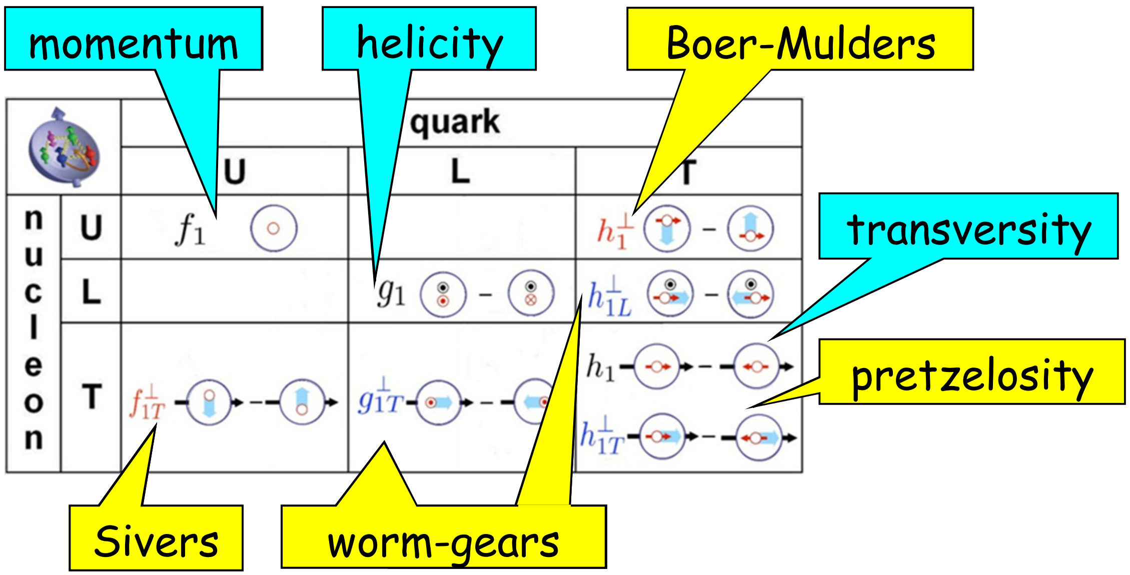

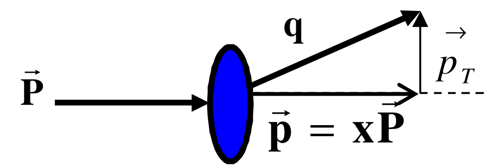

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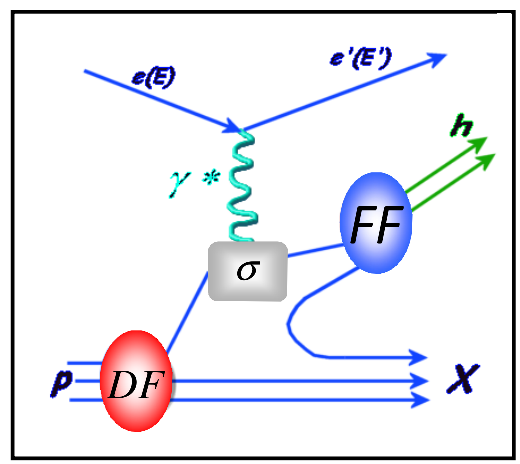
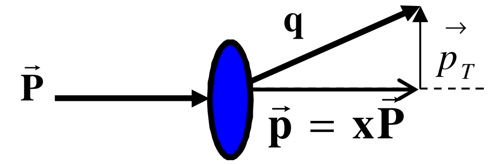
Mostly investigated in **SIDIS**: detection of transverse momentum of produced hadrons gives access to p_T



The **non-collinear** structure of the nucleon

momentum | helicity | Boer-Mulders | transversity | pretzelosity | Sivers | worm-gears

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



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Fragmentation Functions (FF)

		quark U	quark L	quark T
hadron	U	D_1		$H_1^{\perp}$
	L		G_{1L}	$H_{1L}^{\perp}$
	T	$D_{1T}^{\perp}$	G_{1T}	H_1, $H_{1T}^{\perp}$

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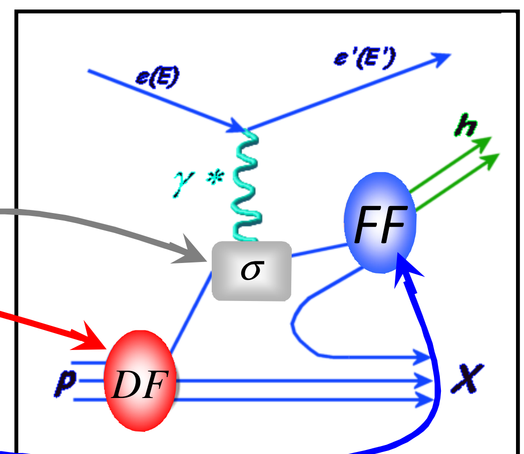
Factorization → (key result of QCD!)

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



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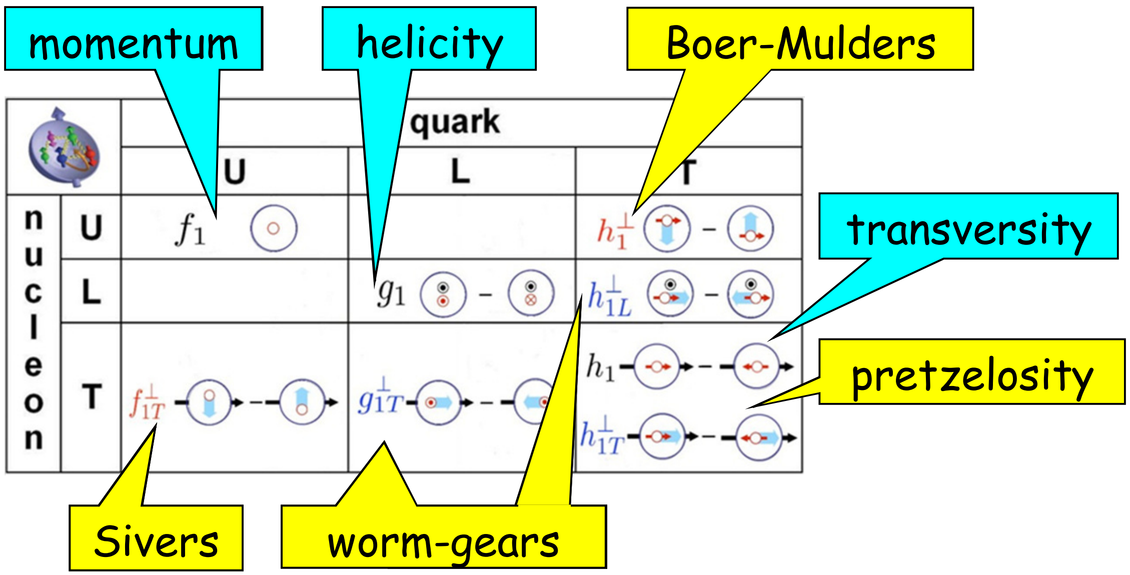

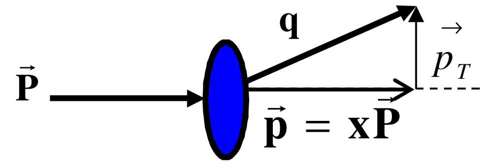

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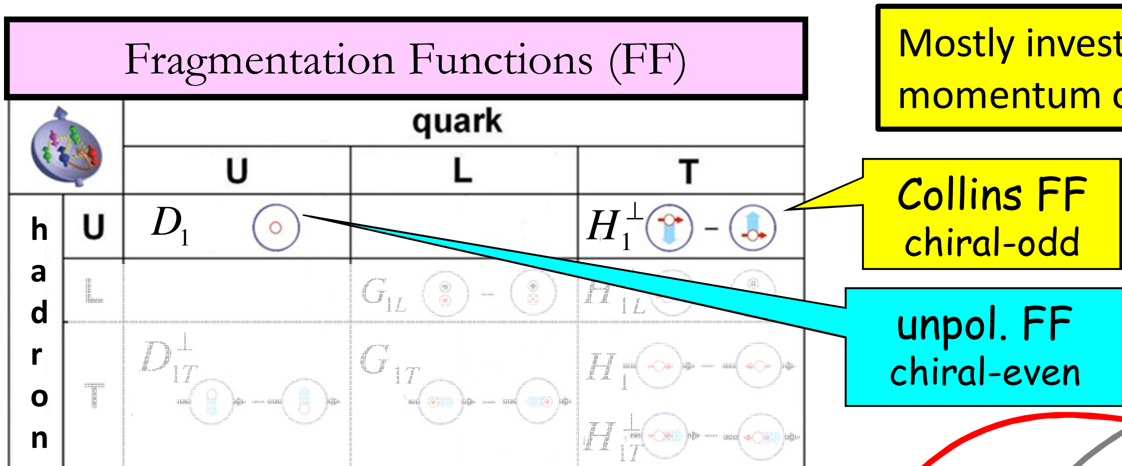

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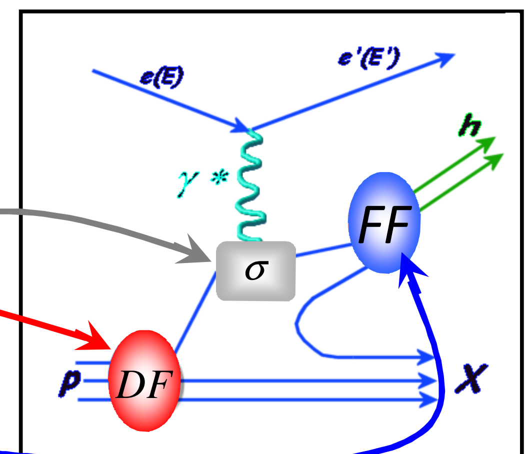

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$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

The SIDIS cross-section

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \quad \lambda_l & \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ S_L \quad & \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ S_L\;\lambda_l & \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
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& + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
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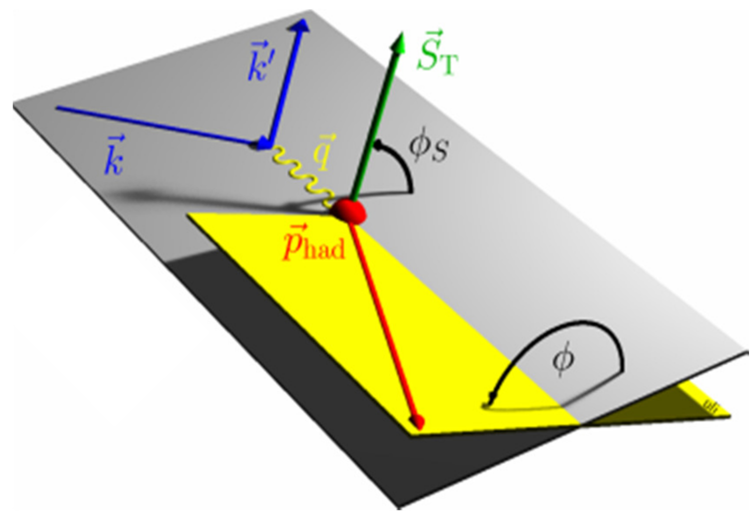
\end{aligned}
$$



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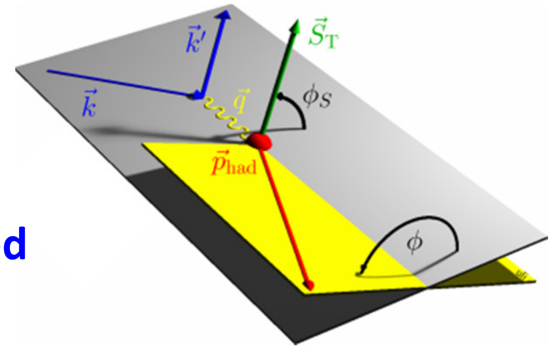

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$$

unpolarized

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

beam polarization

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

target polarization

$$
+ 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]
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beam and target polarization

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$$
\begin{aligned}
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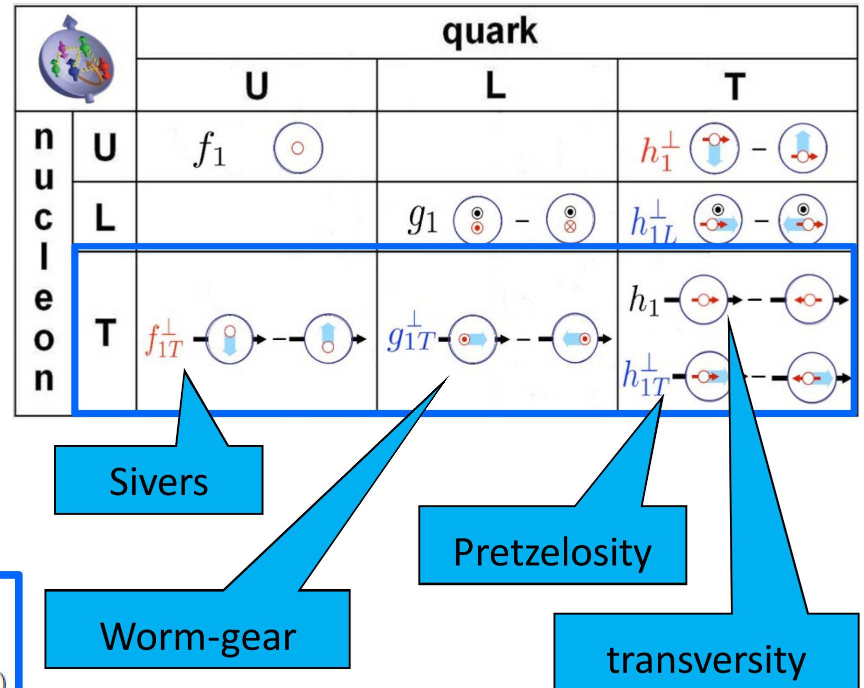
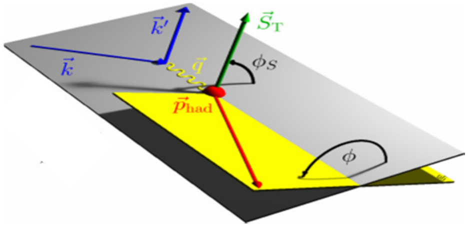


This talk

Selected results from A_{UT} SSAs

The Sivers effect



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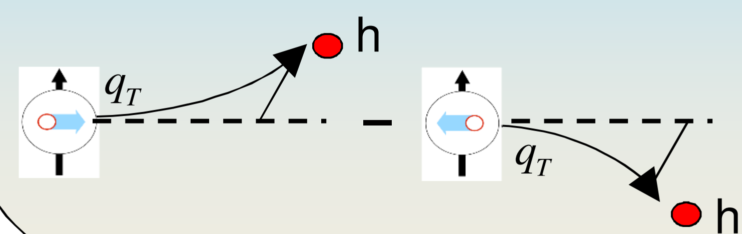
nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers effect

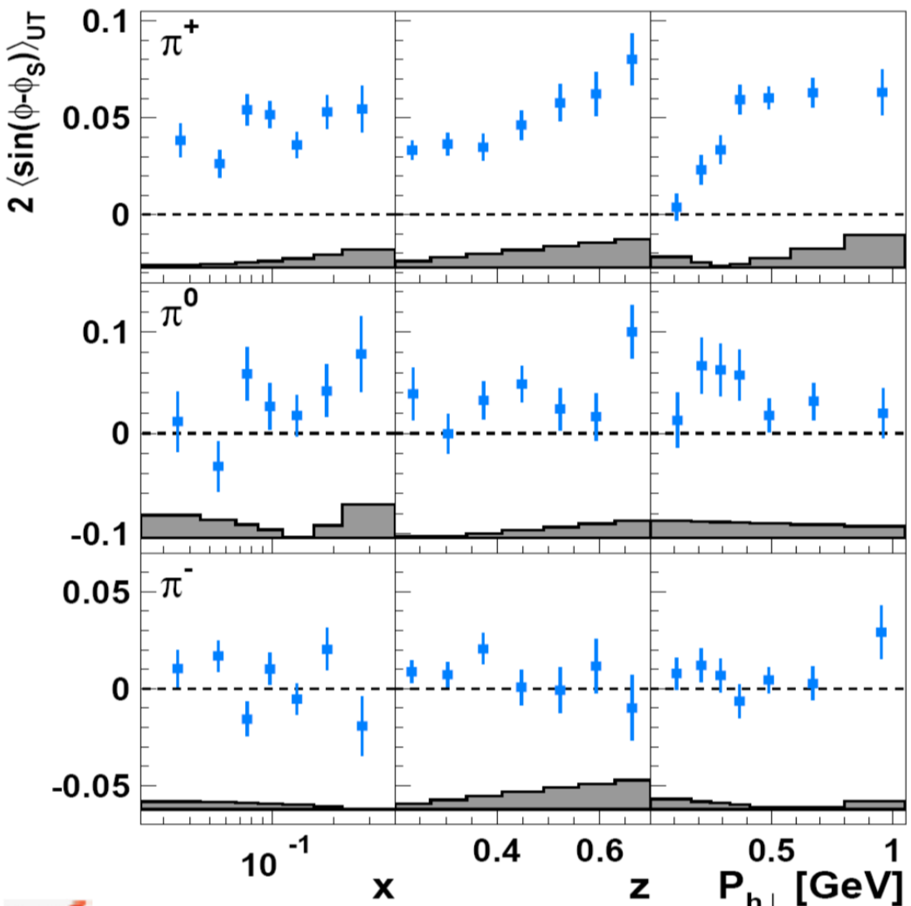
$$\propto f_{1T}^\perp(x, p_T^2) \otimes D_1(z, k_T^2)$$

- 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

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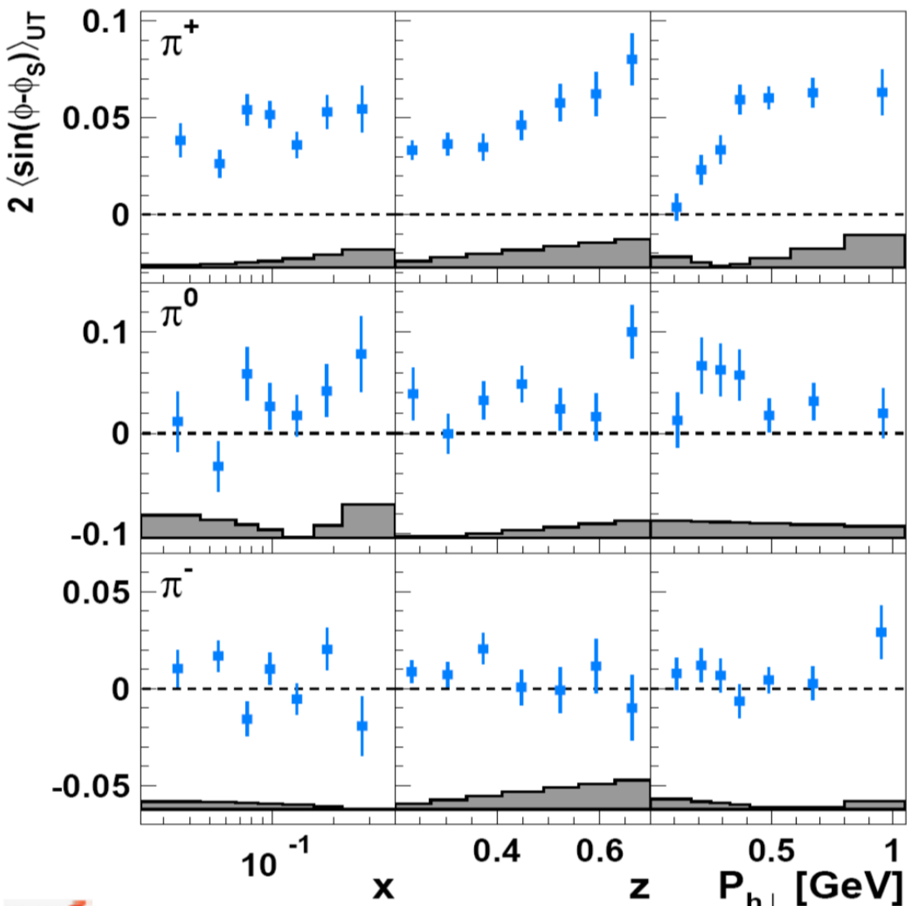

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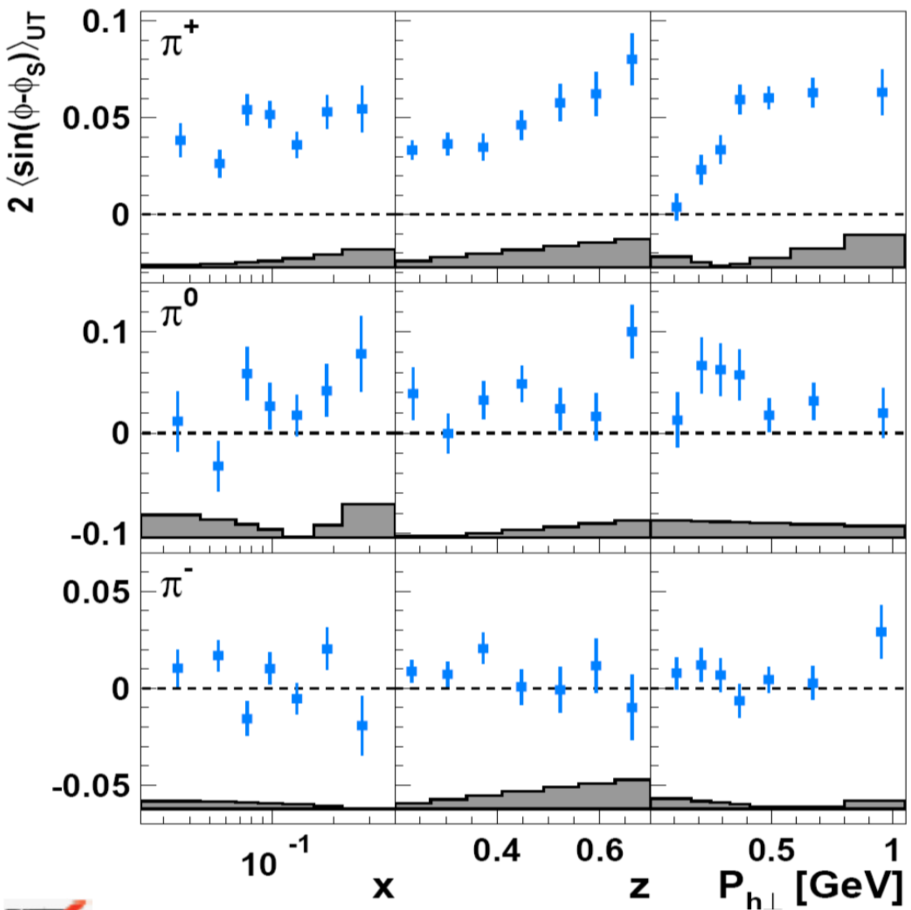

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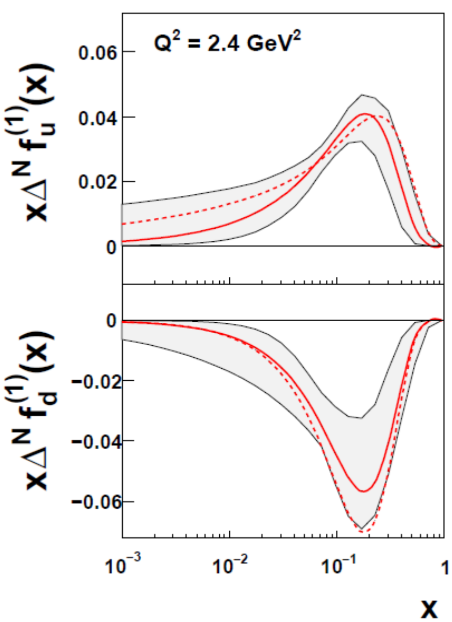
Data consistent with Sivers function of opposite signs for u and d quarks



Consistent with ***u*** and ***d*** quarks with **opposite OAM** in a transversely polarized nucleon

[Anselmino *et al.*, Eur.Phys.J.A39:89-100,2009]

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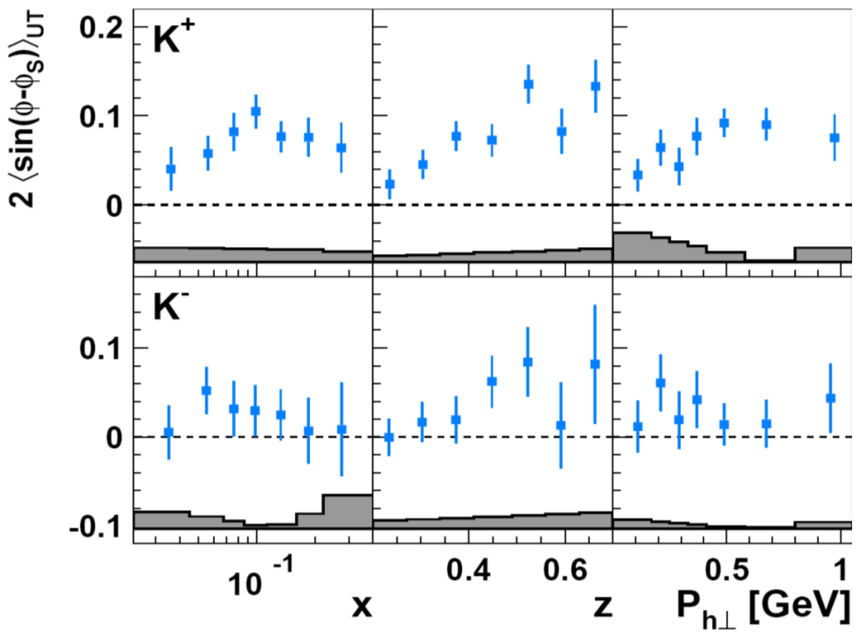
Sivers kaons amplitudes [Airapetian *et al.*, Phys. Rev. Lett. 103 (2009) 152002]



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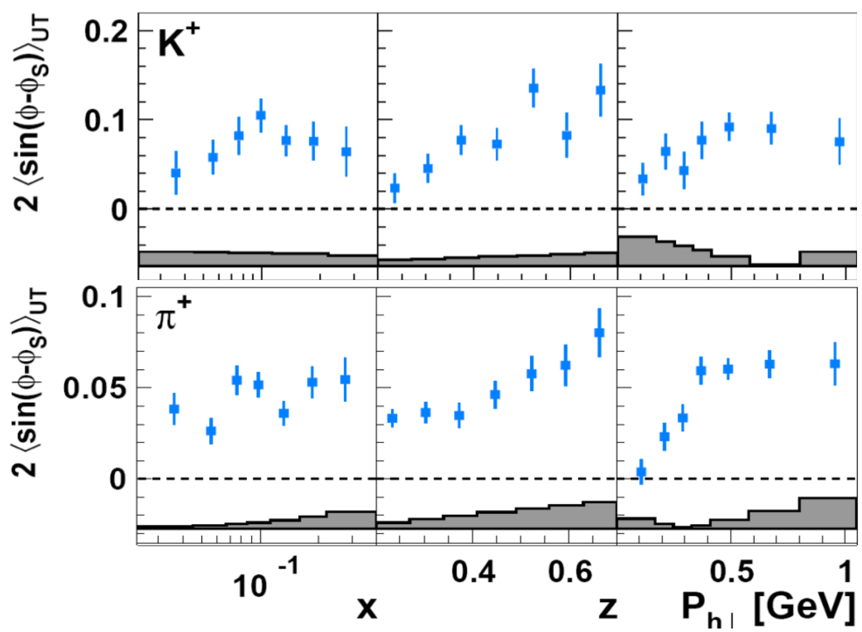
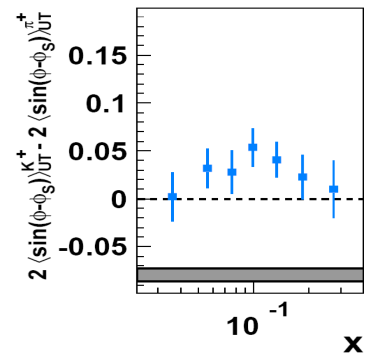
Sivers kaons amplitudes: open questions

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





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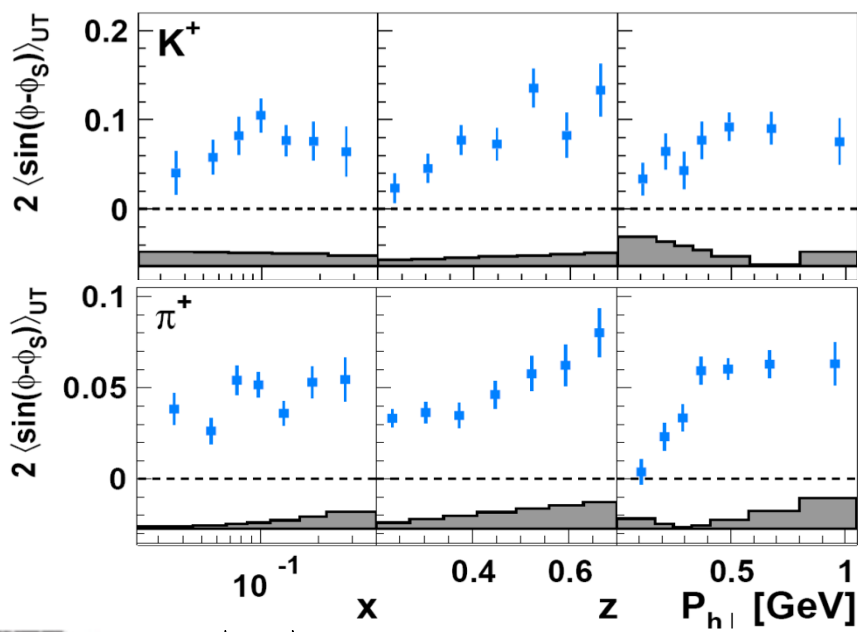
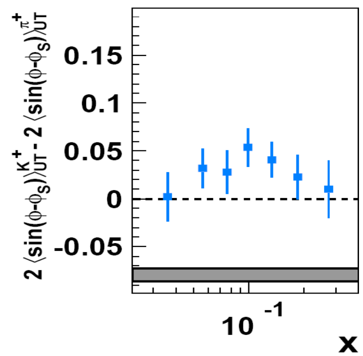
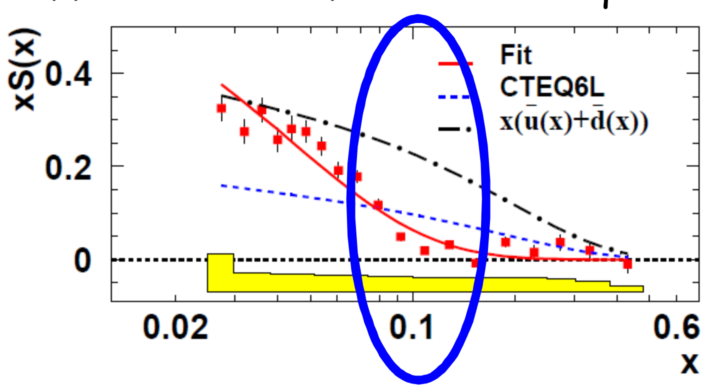




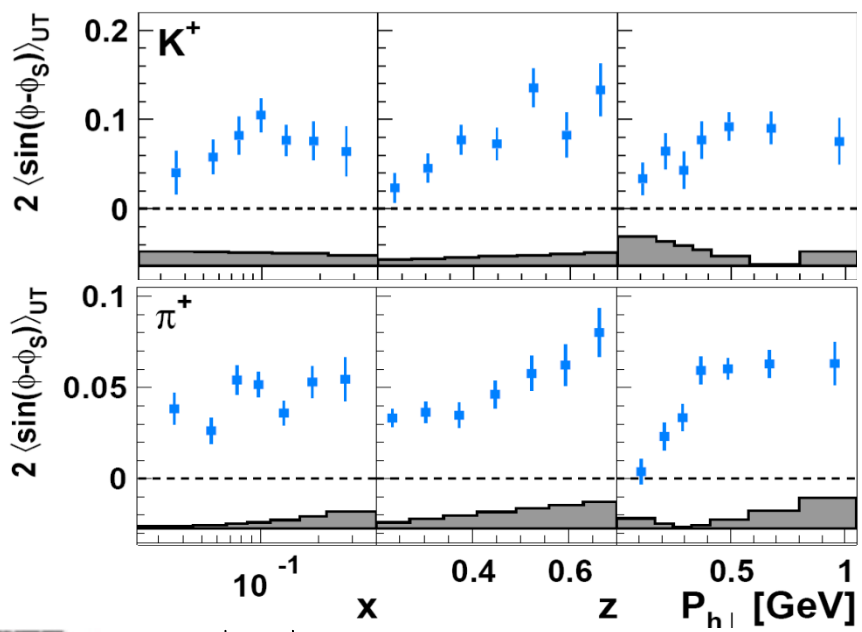
$\pi^+ \equiv |u\bar{d}\rangle, \;\; K^+ \equiv |u\bar{s}\rangle \;\; \rightarrow$

different role of various sea quarks ?



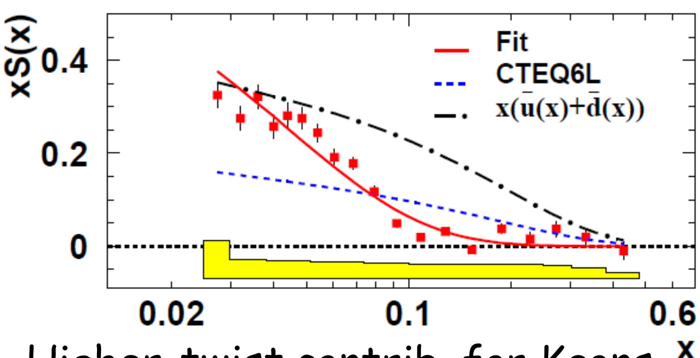
Sivers kaons amplitudes: open questions

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

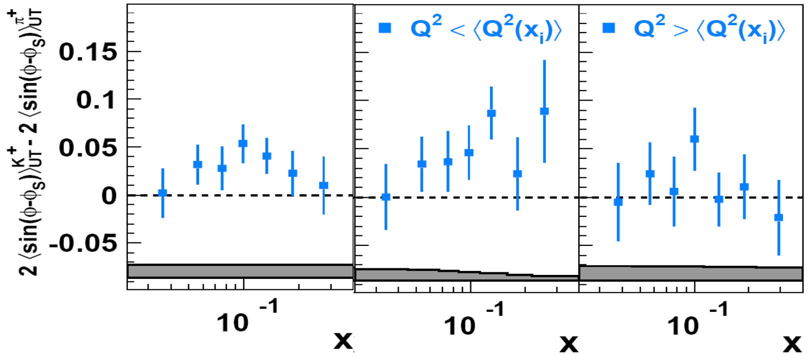


$\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle \rightarrow$

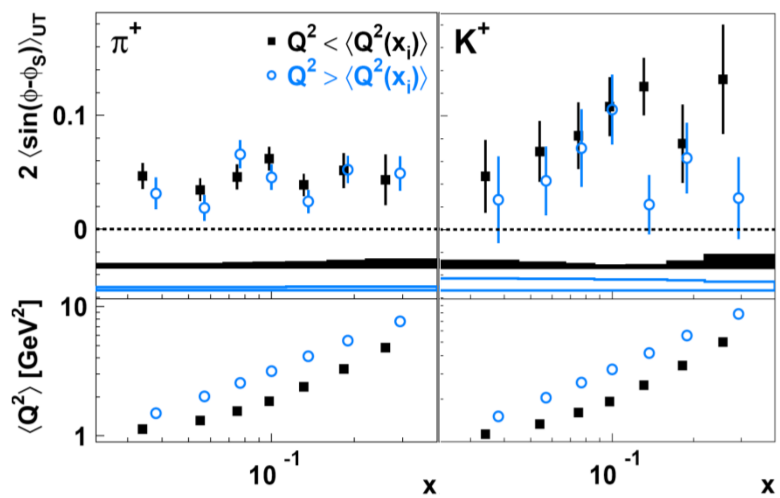
different role of various sea quarks ?



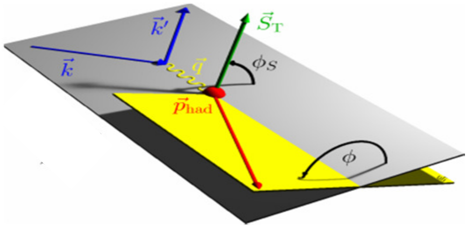
Higher-twist contrib. for Kaons



- only in low-Q^2 region significant (90% C.L.) deviation is observed



- each x-bin divided into two Q^2 bins
- no effect for pions, but hint of a systematic shifts for kaons



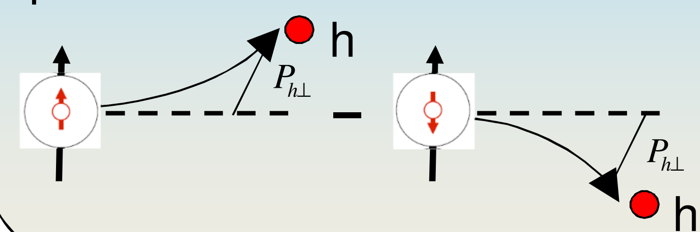
The Collins effect

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,dP^2_{h\perp}} = {} & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \ & \lambda_l \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ \ & S_L \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ \ & S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ \ & S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \boxed{\epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)}} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \ & S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$

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

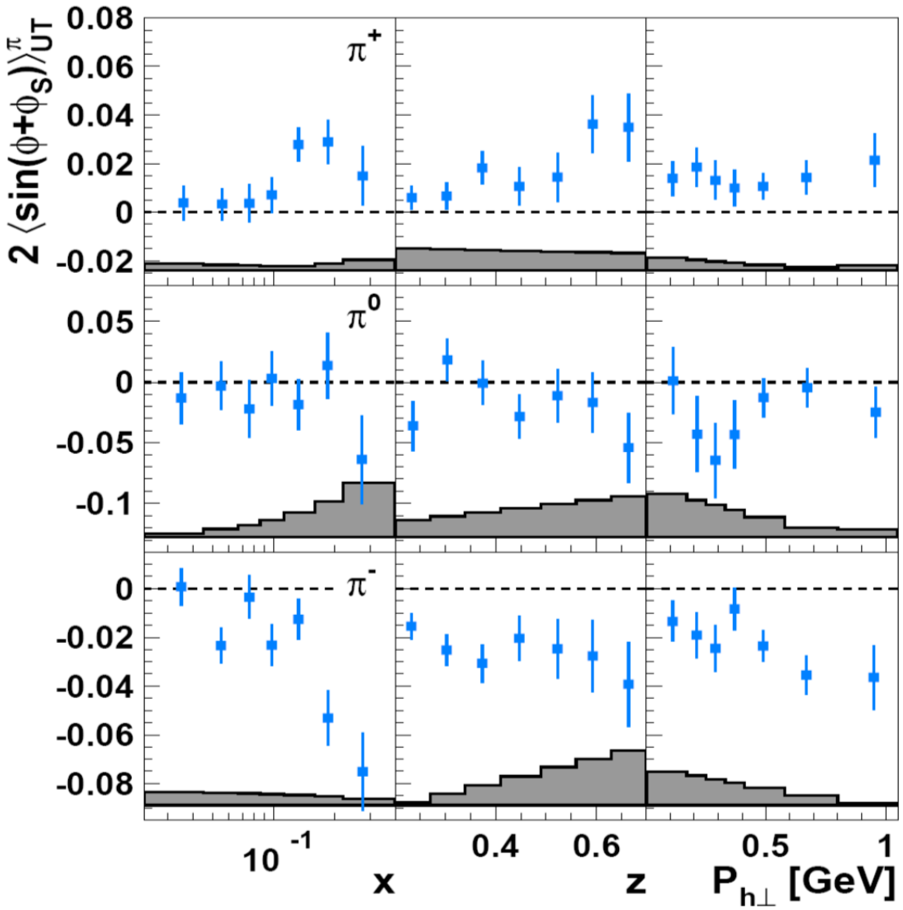
Collins effect

- $\propto h_1(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$
- correlation between quark transverse polarization 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!

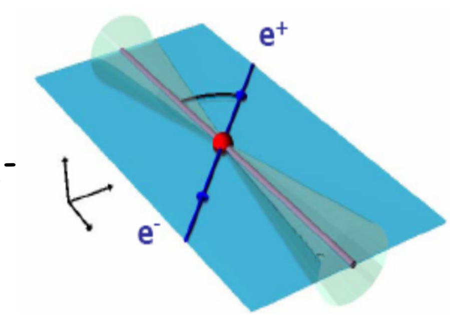
$$\begin{cases} u \rightarrow \pi^- \\ d \rightarrow \pi^+ \end{cases} \qquad \begin{cases} u \rightarrow \pi^+ \\ d \rightarrow \pi^- \end{cases}$$

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

- ☑ Non-zero Collins effect observed
- ☑ Both transversity and Collins function sizeable!

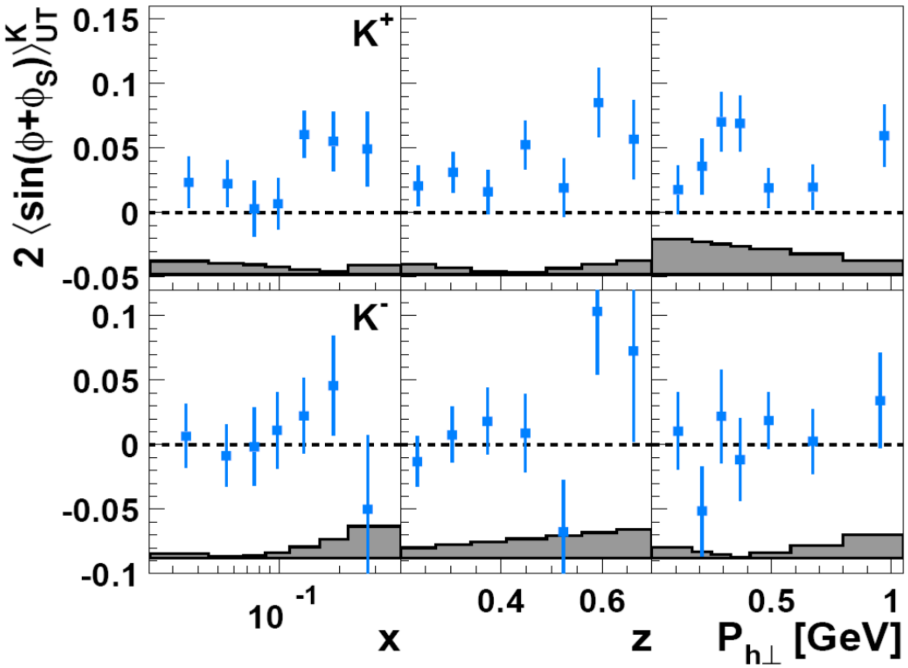
Consistent with Belle/BaBar measurements at e^+e^- collider machines

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



Collins kaons amplitudes

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



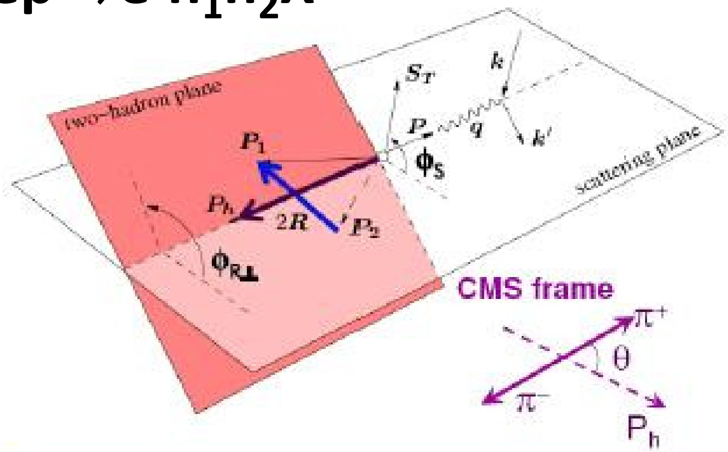
- significantly positive
- rise with x and z
- consistent with zero

☑ Non-zero Collins effect observed

☑ Both transversity and Collins function sizeable!

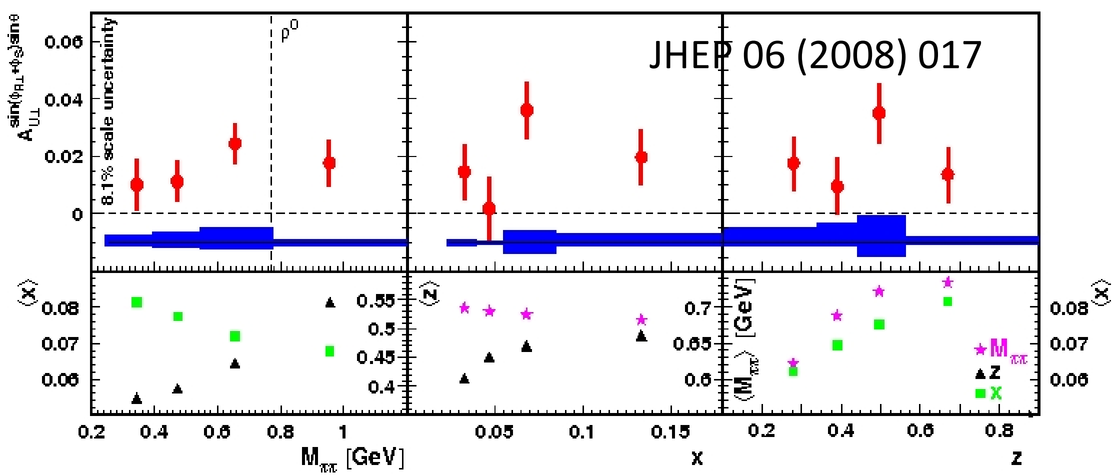
An alternative access to transversity: the di-hadron SSA

$ep \to e'h_1h_2X$



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

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



Di-hadron FF

(does not depend on quark transv. momentum)

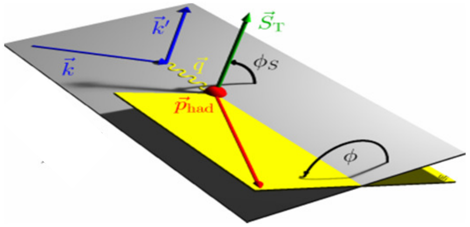
Chiral-odd T- odd

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 (eventually measured at e^+e^- colliders)
- independent way to access transversity
- no convolution integral involved
- limited statistical power (v.r.t. 1 hadron)



The "pretzelosity"

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathrm{P}_{h\perp}^2} = \; & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ \; & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \; \lambda_l \; & \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ \; S_L \; & \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ \; S_L\,\lambda_l \; & \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ \; S_T \; & \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \boxed{\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \; S_T\,\lambda_l \; & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$

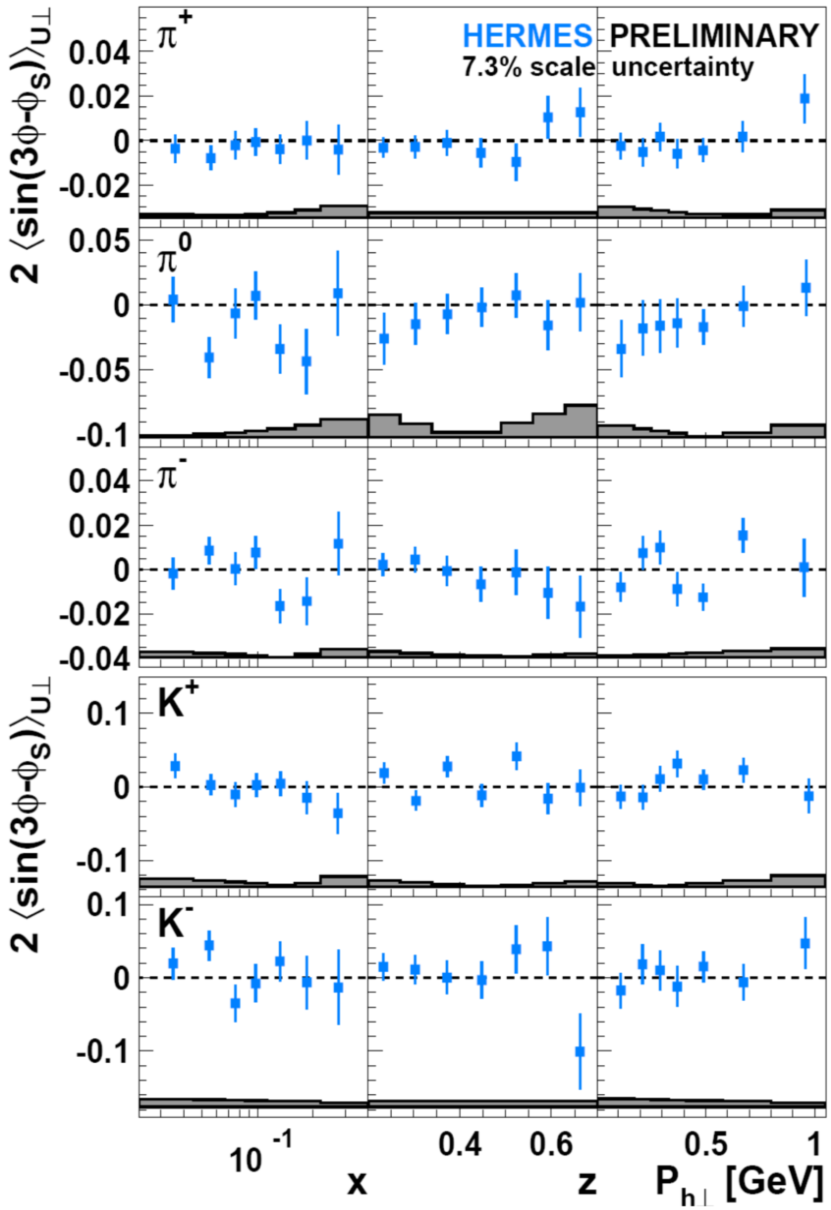
nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

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

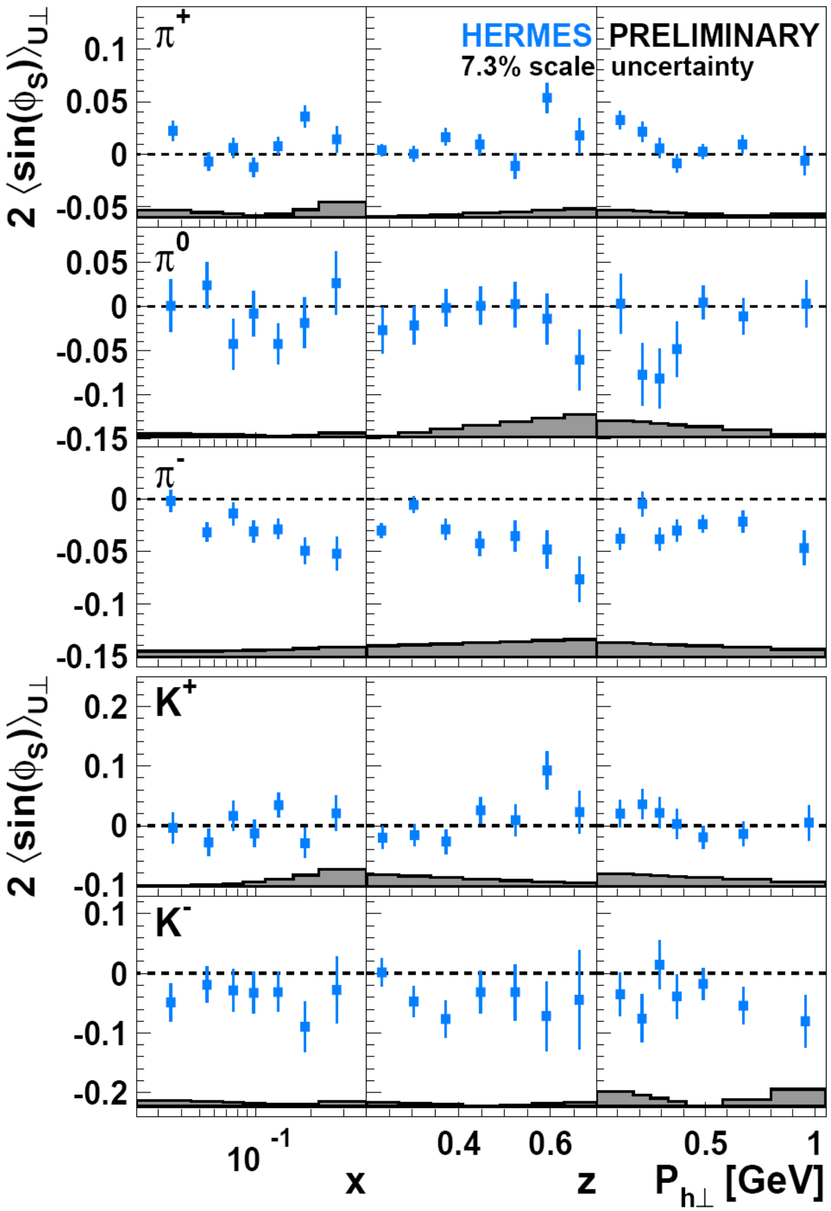
The sin(3ϕ-ϕ_S) Fourier component



All amplitudes consistent with zero

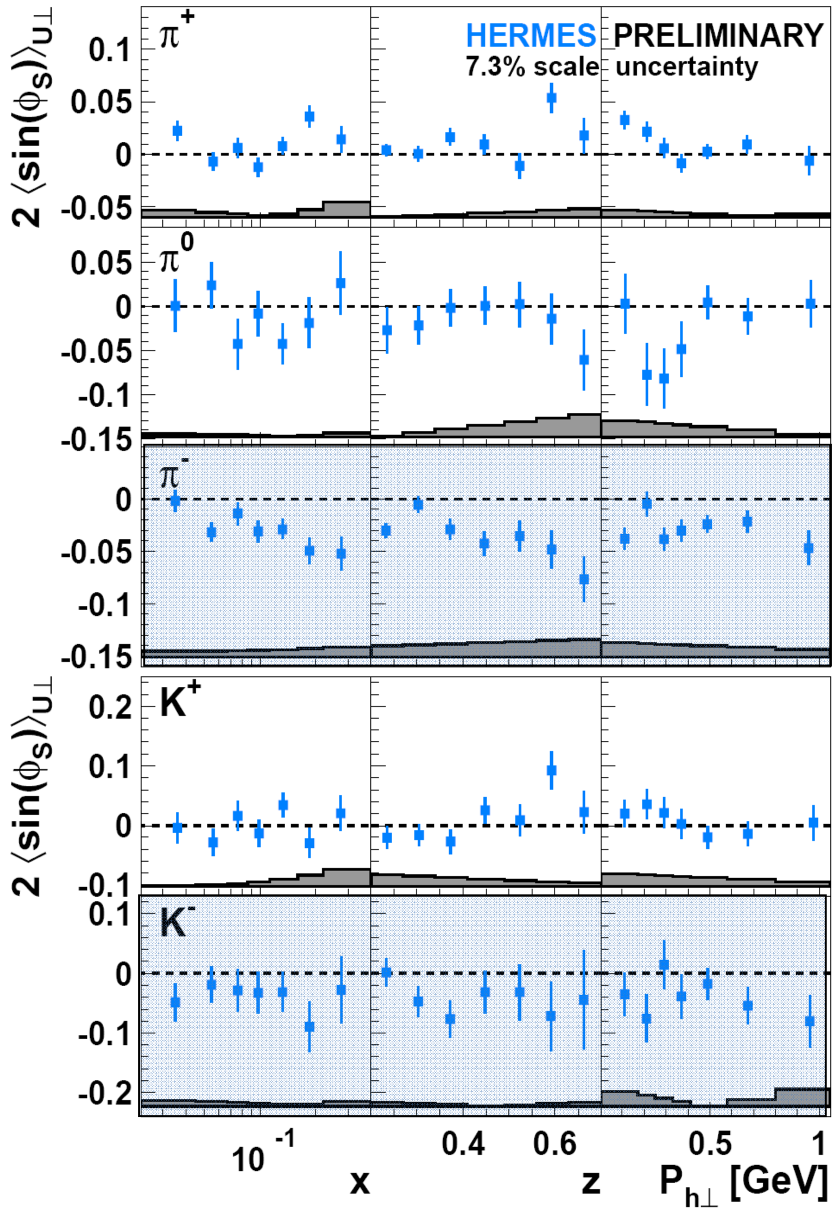
…suppressed by two powers of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

The subleading-twist $\sin(\phi_S)$ Fourier component

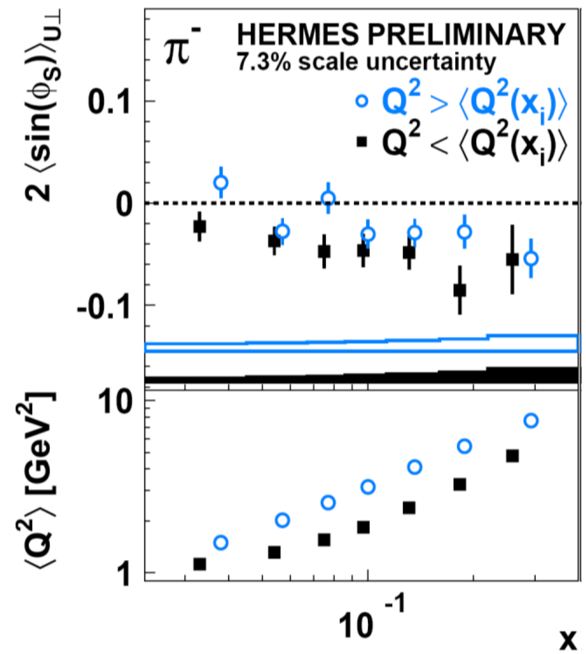


- sensitive to **worm-gear** $g_{1T}^{\perp}$, **Sivers function**, **Transversity**, etc

The subleading-twist sin(ϕ_S) Fourier component

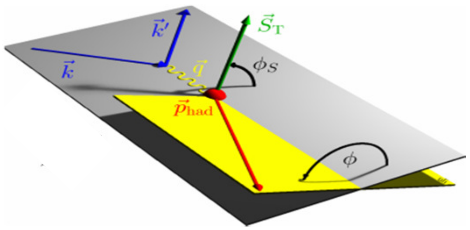


- sensitive to **worm-gear** $g_{1T}^{\perp}$, **Sivers function**, **Transversity**, etc
- **significant non-zero signal for π^- and K^- !**
- ***similar observations at COMPASS***



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

Recent results from A_{LT} DSAs



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

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

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

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

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

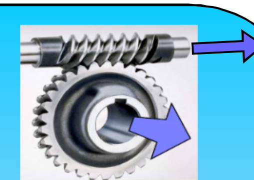
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F^{\cos(\phi)}_{\mathrm{LL}}\Big]$$

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

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

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

Worm-gear

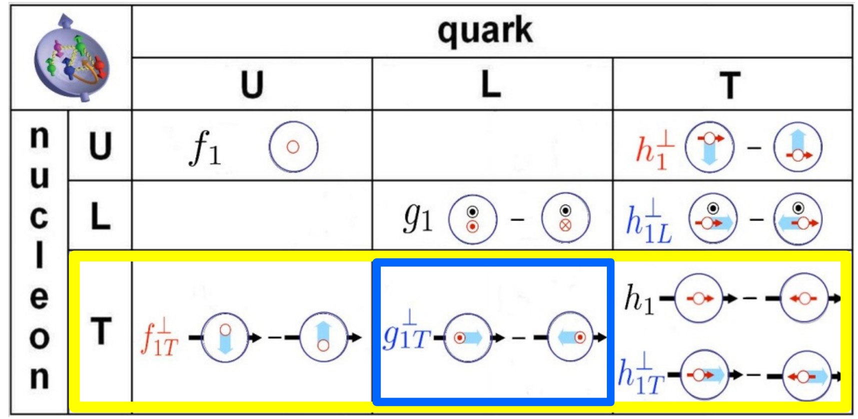


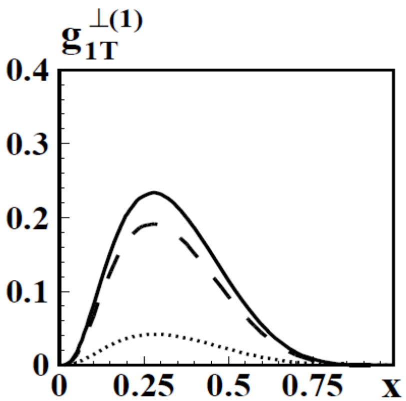
$$\propto g_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$$

- describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon (→ "**trans-helicity**")
- accessible in LT DSAs through the leading-twist cos(ϕ-ϕ_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.)

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

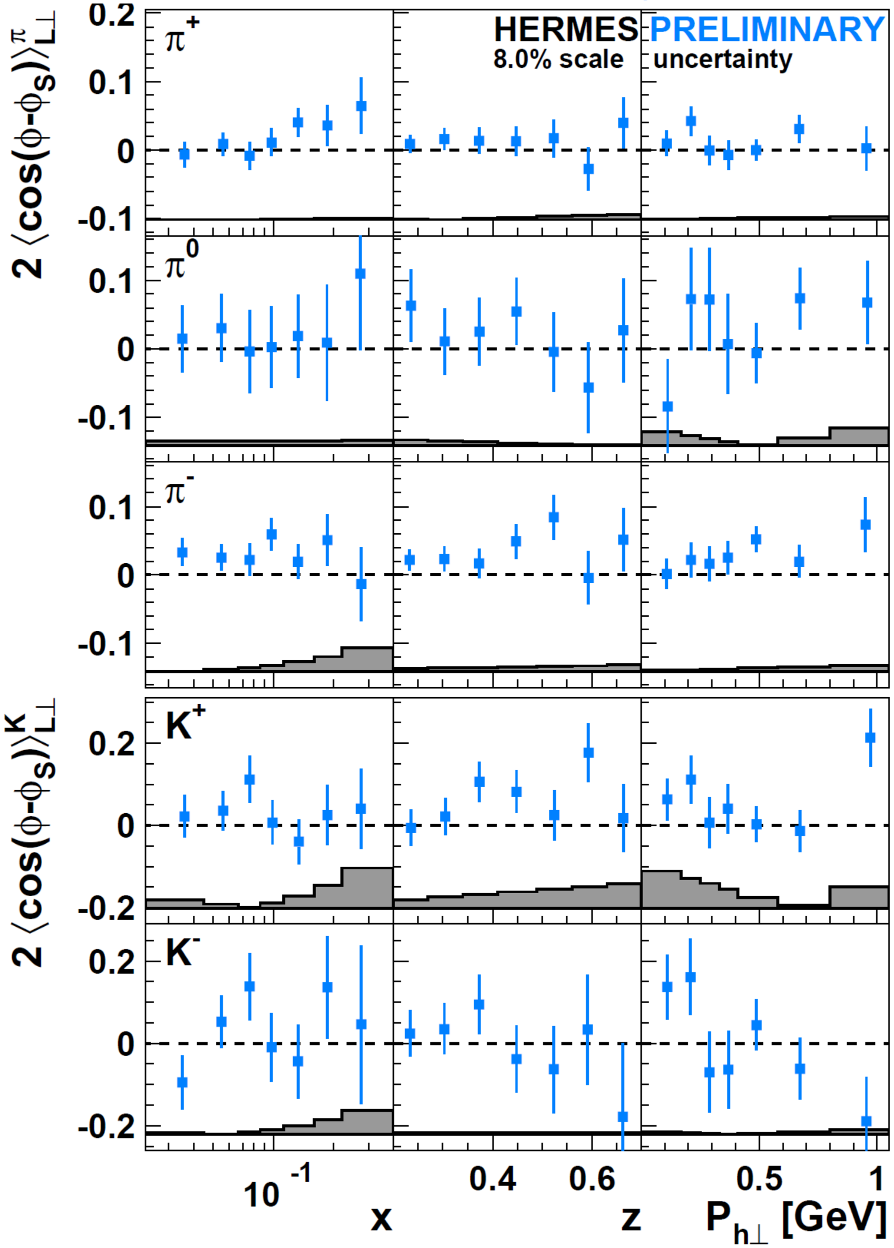
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\, g_{1T} D_1\right]$$

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

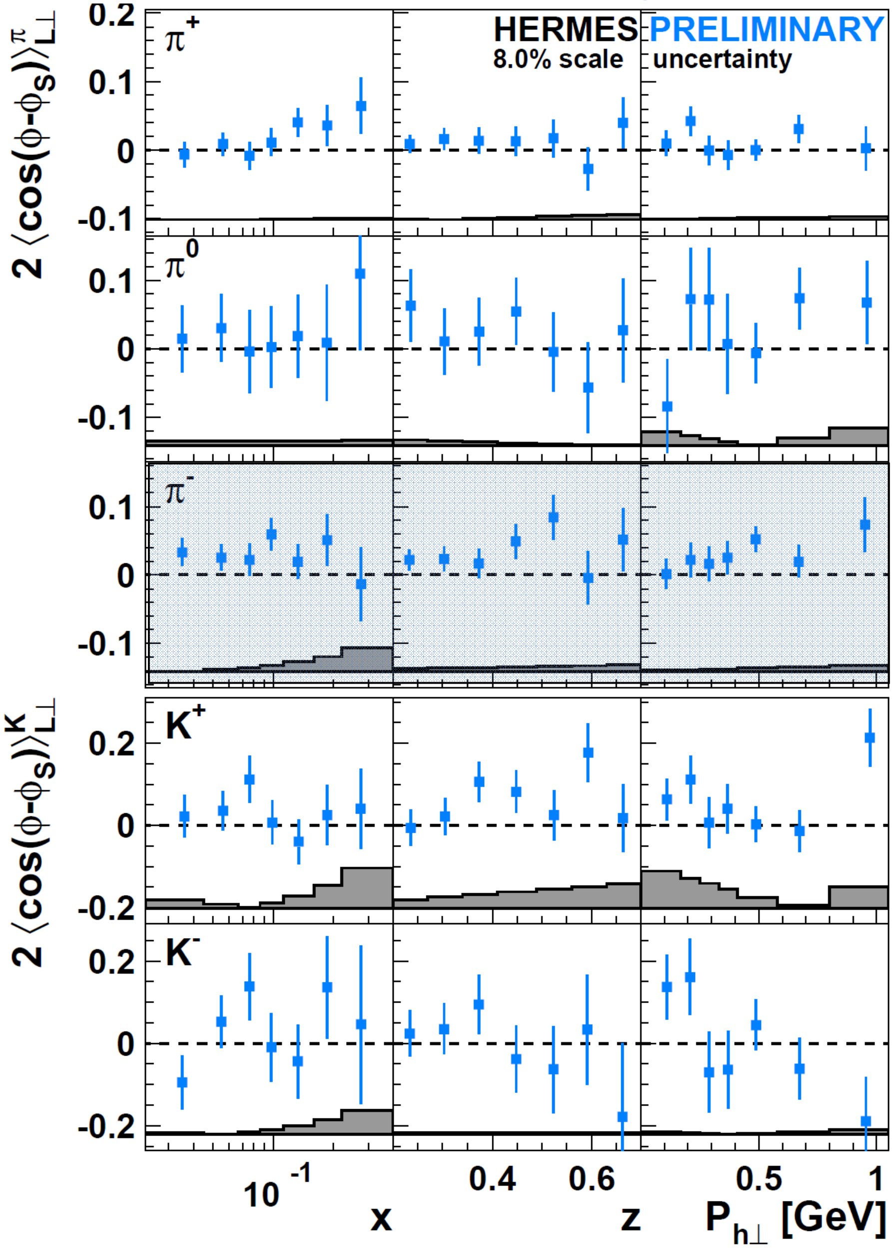
$$F_{LT}^{\cos(2\phi_h-\phi_S)} = \frac{2M}{Q}\,\mathcal{C}\Big\{-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{2M^2}\Big(x g_T^{\perp} D_1 + \frac{M_h}{M}\, h_{1T}^{\perp} \frac{\tilde{E}}{z}\Big) + \frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)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

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

The cos(ϕ-ϕ$_S$) Fourier component



The cos(ϕ-ϕ$_S$) Fourier component



slightly positive ?

≈ 0

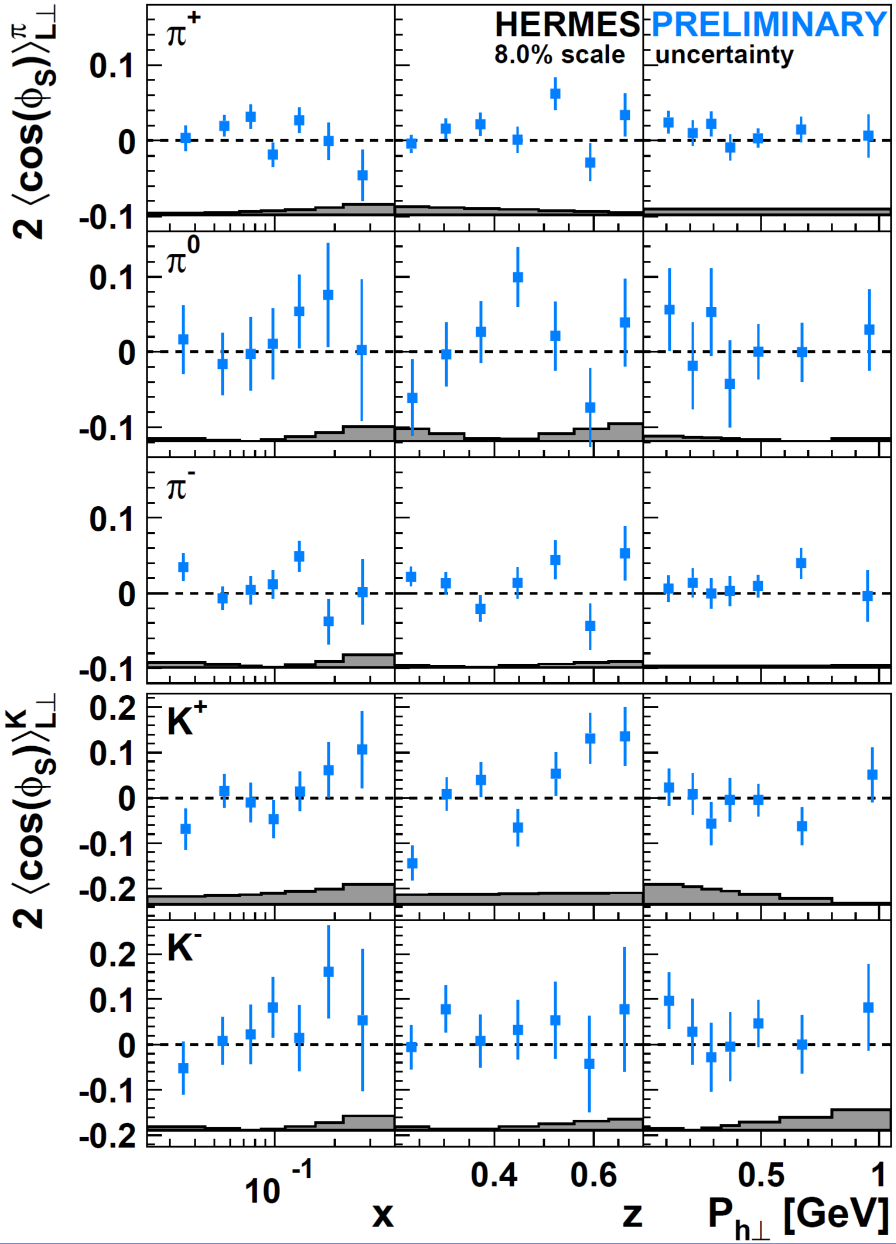
positive!

Similar observations from Hall-A and COMPASS

slightly positive ?

≈ 0

The cos(ϕ_S) Fourier component



≈ 0

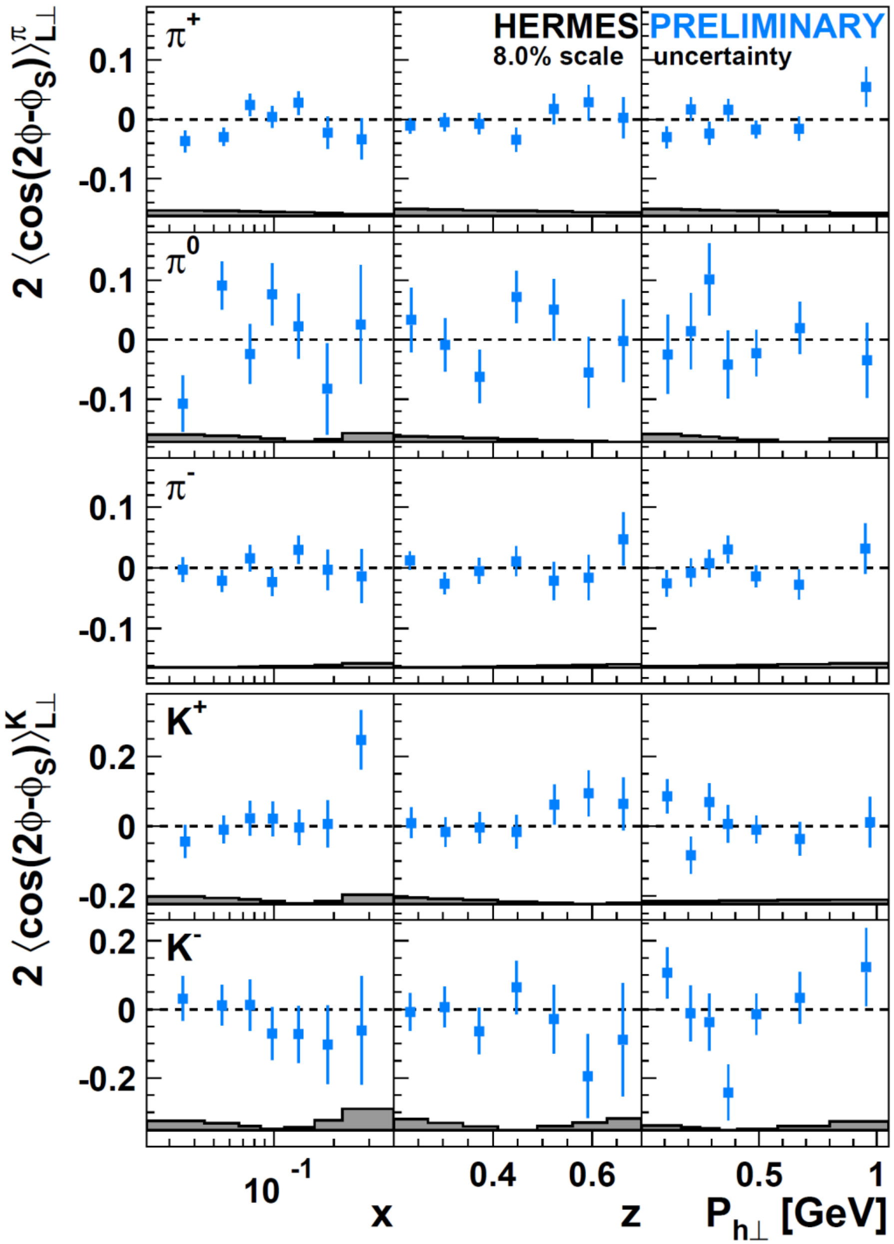
≈ 0

≈ 0

≈ 0
sign change?

≈ 0

The cos(2ϕ-ϕ$_S$) Fourier component



≈ 0

≈ 0

≈ 0

≈ 0

≈ 0

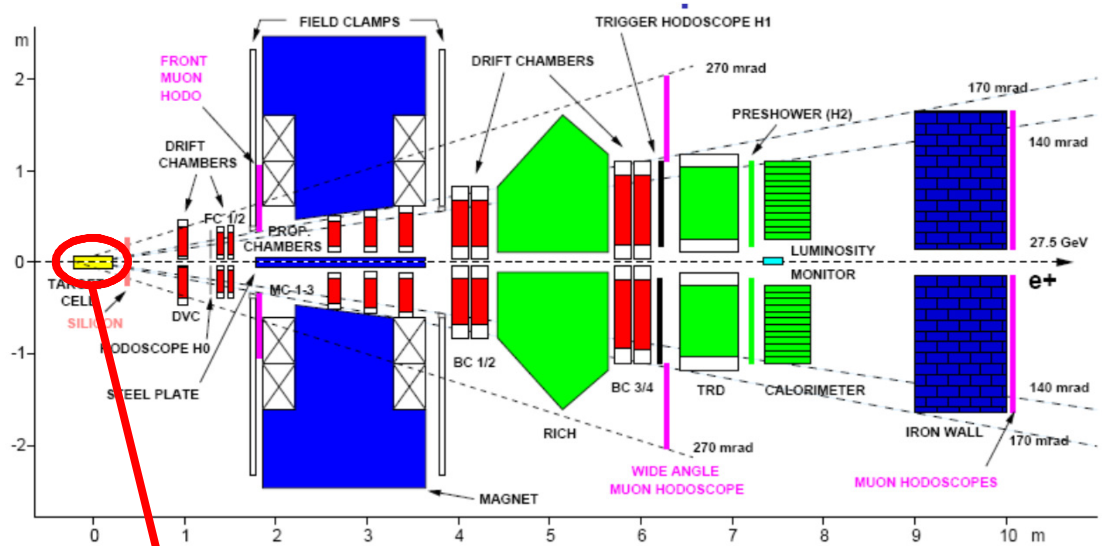
Conclusions

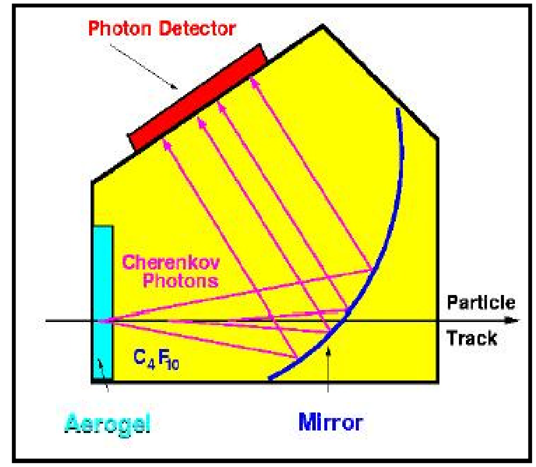
- Orbital motion of partons is now considered as a key ingredient for a complete picture of the nucleon
- rich phenomenology and surprising effects when parton transverse momentum is not integrated out
- The HERMES experiment has played a major role in these studies:
  - **significant Collins amplitudes observed for charged pions and K^+**
  - **significant Sivers amplitudes observed for π^+ and K^+**
  - **recent 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^-

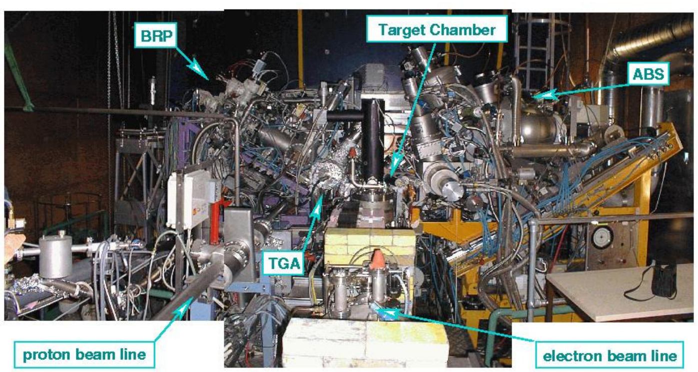
- Impressive progresses in last decade, but still lots of open issues and quest for new high-precision data

Back-up

The HERMES experiment at HERA

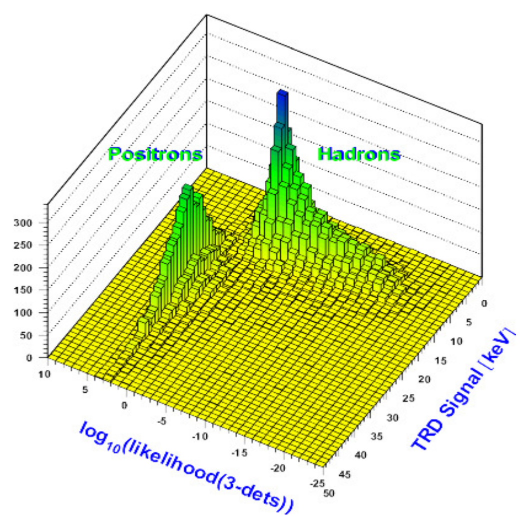




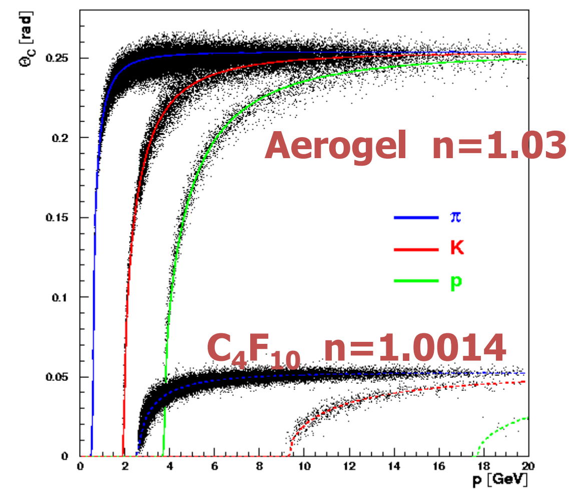


TRD, Calorimeter, preshower, RICH:

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 $\langle P_T \rangle \approx 73\%$)**

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

The relevant Fourier components are 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)

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

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

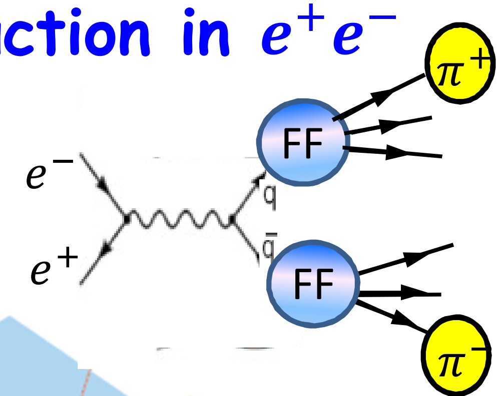
$$A_{UT}^h(\phi,\phi_S) = \frac{1}{|P_T|}\frac{d\sigma^h(\phi,\phi_S) - d\sigma^h(\phi,\phi_S+\pi)}{d\sigma^h(\phi,\phi_S) + d\sigma^h(\phi,\phi_S+\pi)}$$

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

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

$\mathcal{I}$ [...]: convolution integral over initial (p_T) and final (k_T) quark transverse momenta

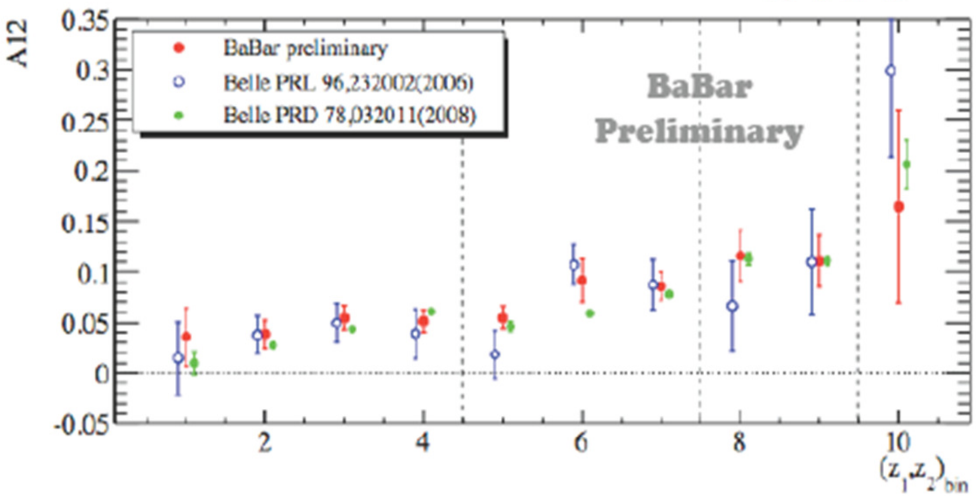
Collins FF from inclusive hadron-pair production in e^+e^-

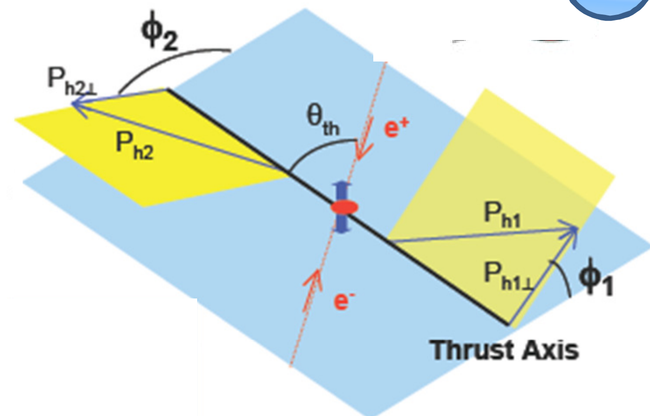


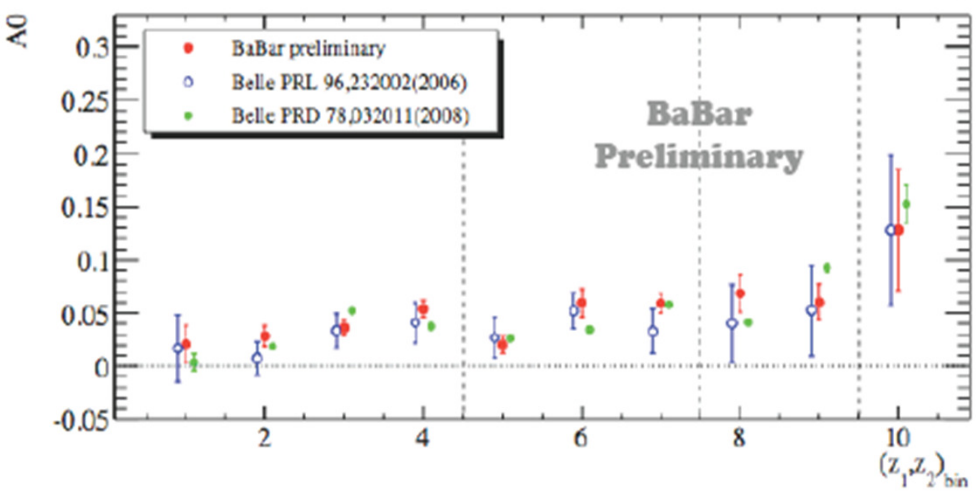
BaBar preliminary: $\mathcal{L}\approx 45$ fb^{-1}

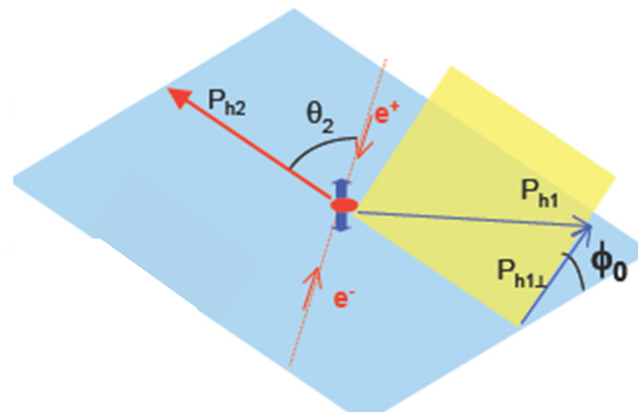
Belle Off-peak: $\mathcal{L}\approx 29$ fb^{-1}

Belle full statistics (supersede previous results) $\mathcal{L}\approx 547$ fb^{-1}

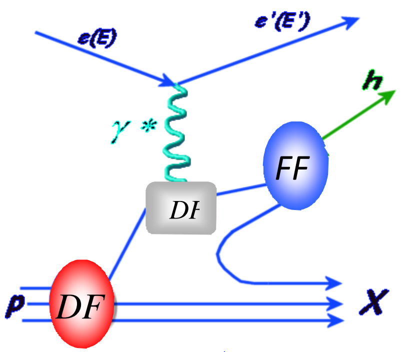




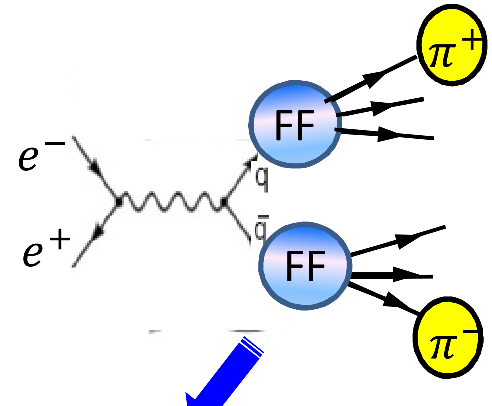




First extraction of Transversity



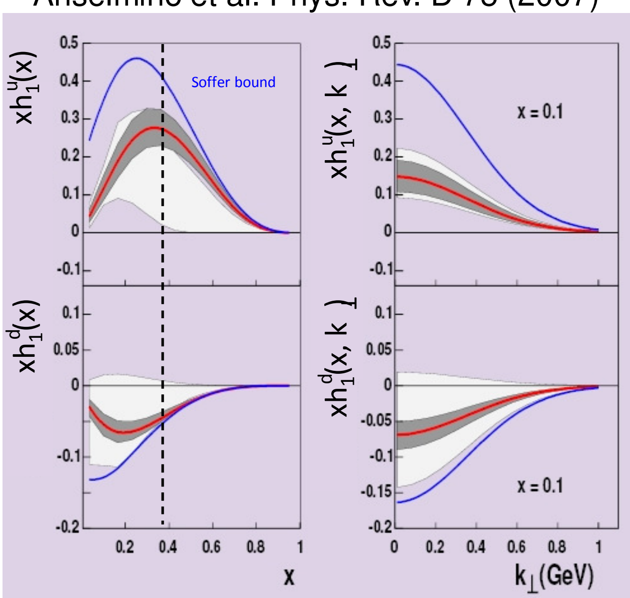
+



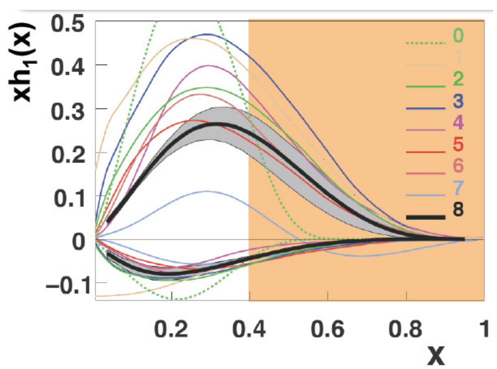
hermes COMPASS BELLE

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

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

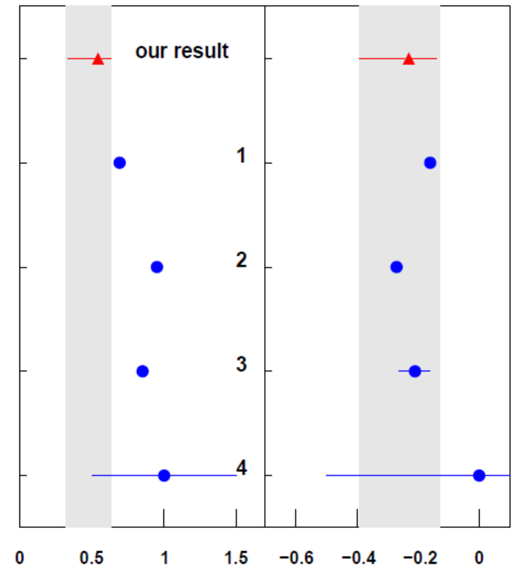


0. chiral color-dielectric model [Barone et al. ,PLB 390 (97)]
1. Soffer bound [Soffer et al., PRD 65 (02)]
2. $h_1 = g_1$ [Korotov et al.., EPJC 18 (01)]
3. Chiral quark-soliton model [Schweitzer et. al., PRD 64 (01)]
4. chiral-quark soloiton model [Wakamatsu, PLB 509 (01)]
5. light-cone constituent quark model [Pasquini et al., PRD 72 (05)]
6. quark-diquark model [Cloet, Bentz, Thomas, PLB 659 (08)]
7. quark-diquark model [Bacchetta, Conti, Radici, PRD 78 (08)]
8. Parametrization [Anselmino et al. , arXiv 0807.0173]



Tensor charge

$$\delta q = \int_0^1 dx\, \left[h_1^q(x) - \bar{h}_1^q(x)\right]$$



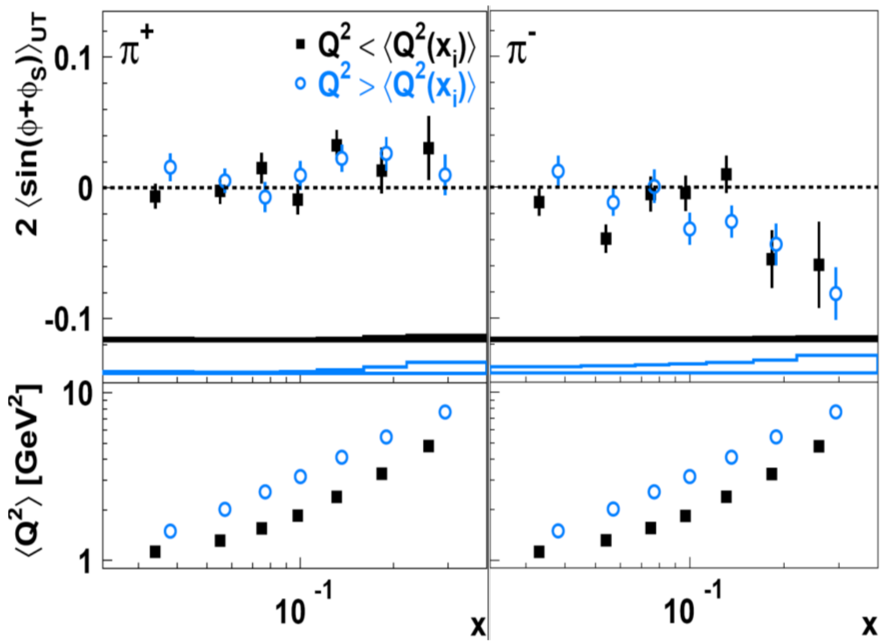
1: Quark-diquark model
2: Chiral quark soliton model
3: Lattice QCD
4: QCD sum rules

$\delta u = 0.54^{+0.09}_{-0.22}$ $\delta d = -0.23^{+0.09}_{-0.16}$

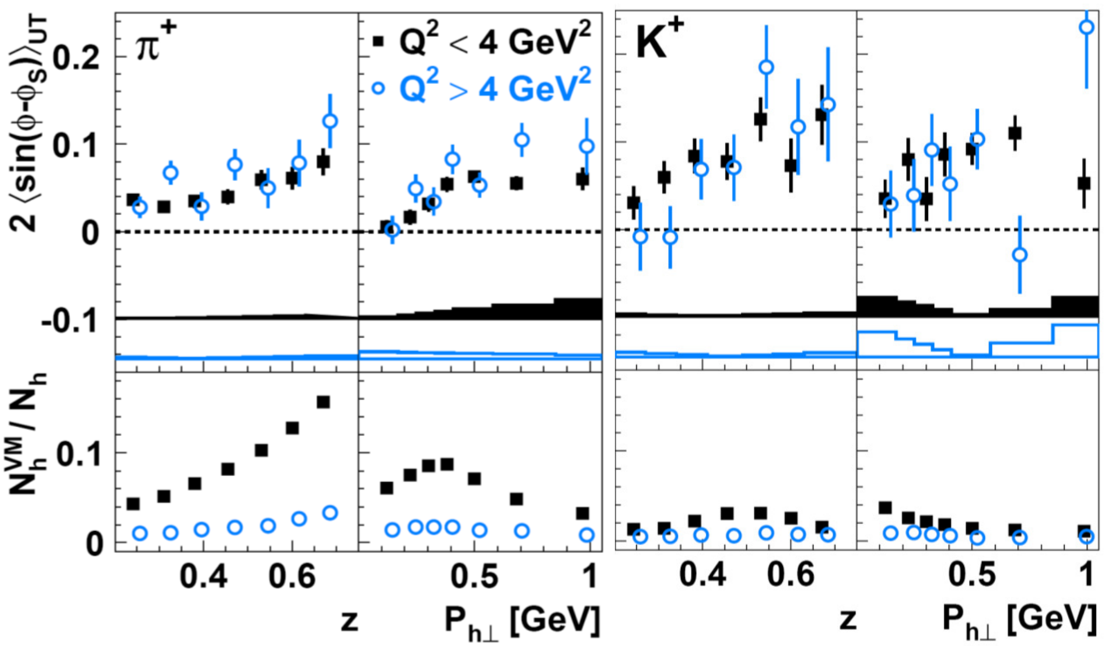
M. Anselmino et al **hep-ph:0812.4366**

Need data in valence region (x > 0.4) -> JLab @ 12 GeV

Collins amplitudes: twist-4 contrib ?



Siver amplitudes: additional studies

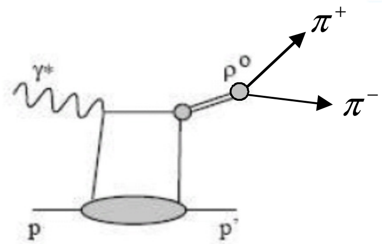


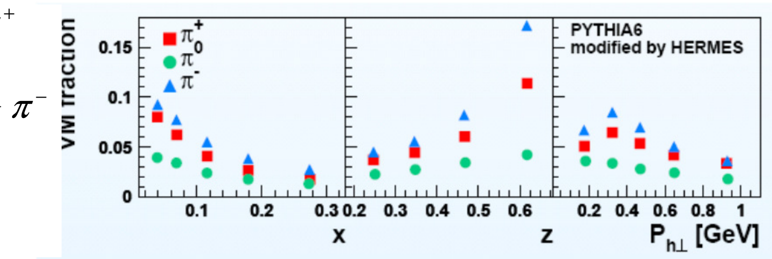
- No systematic shifts observed between high and low Q^2 amplitudes for both π^+ and K^+

  No indication of important contributions from exclusive VM

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 $z<0.7$.

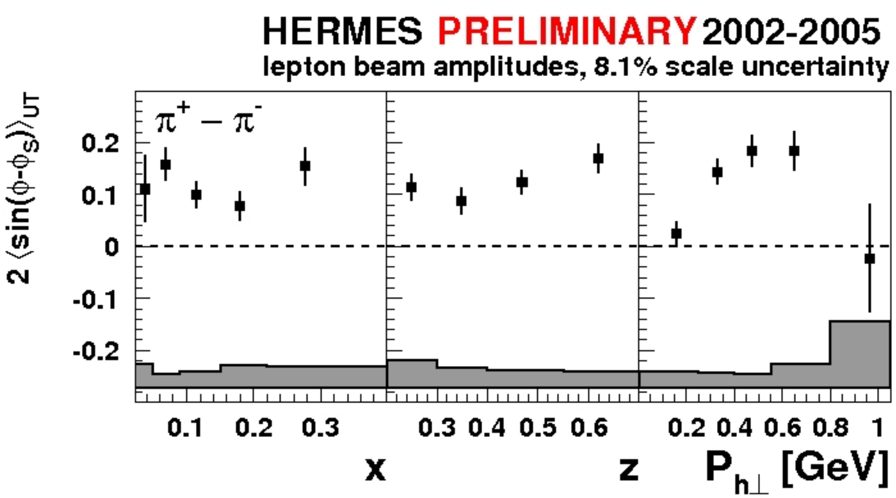


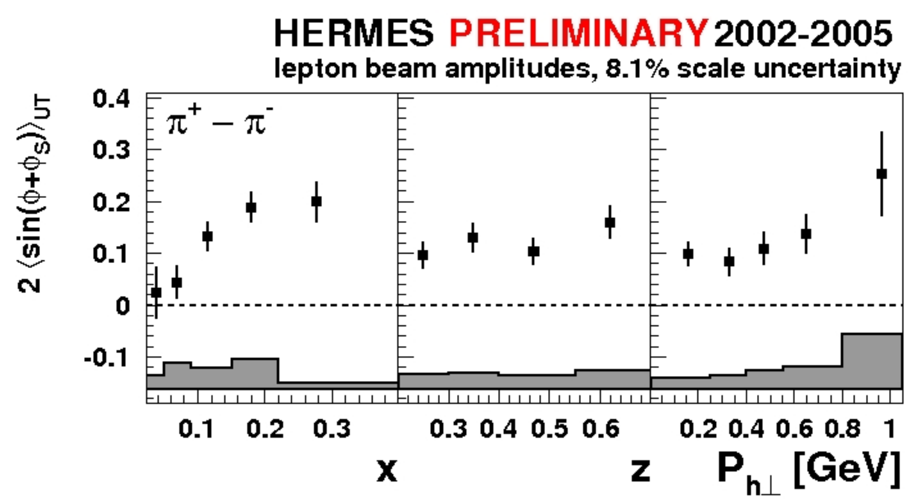


a new observable

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

Contribution from exclusive ρ^0 largely cancels out!

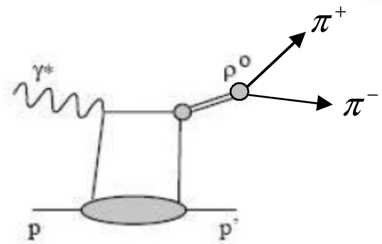


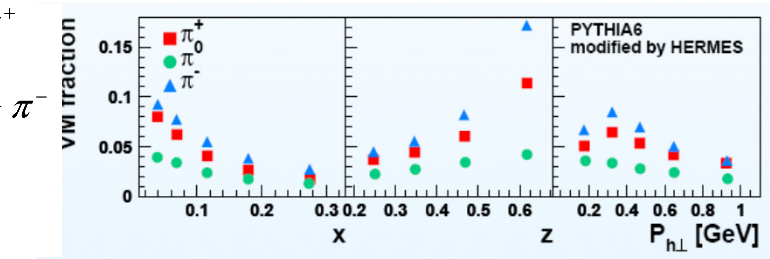


- significantly positive Sivers and Collins amplitudes are obtained
- measured amplitudes are not generated by exclusive VM contribution

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.

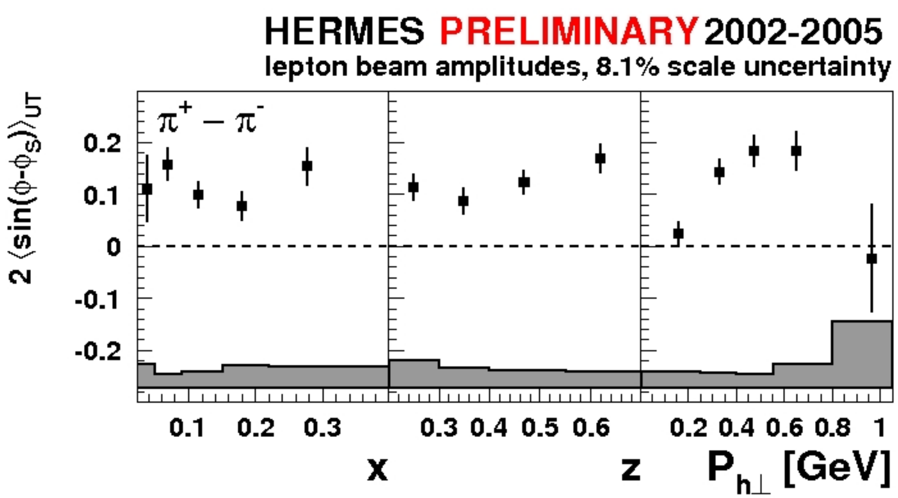




a new observable

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

Contribution from exclusive ρ^0 largely cancels out!

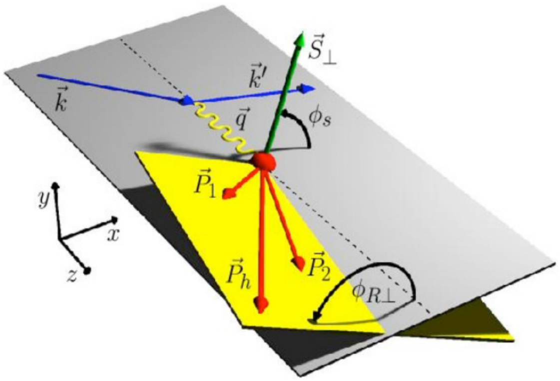


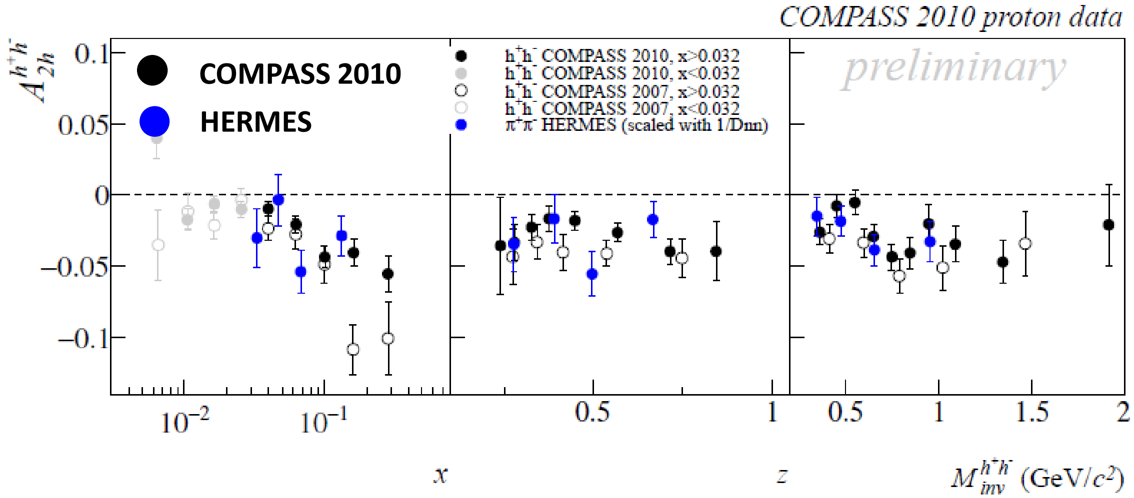
$$A_{\mathrm{UT}}^{\pi^+-\pi^-} = -\frac{4f_{1T}^{\perp,u_v}-f_{1T}^{\perp,d_v}}{4f_1^{u_v}-f_1^{d_v}}$$

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

provides access to Sivers valence quarks distribution!

Transversity

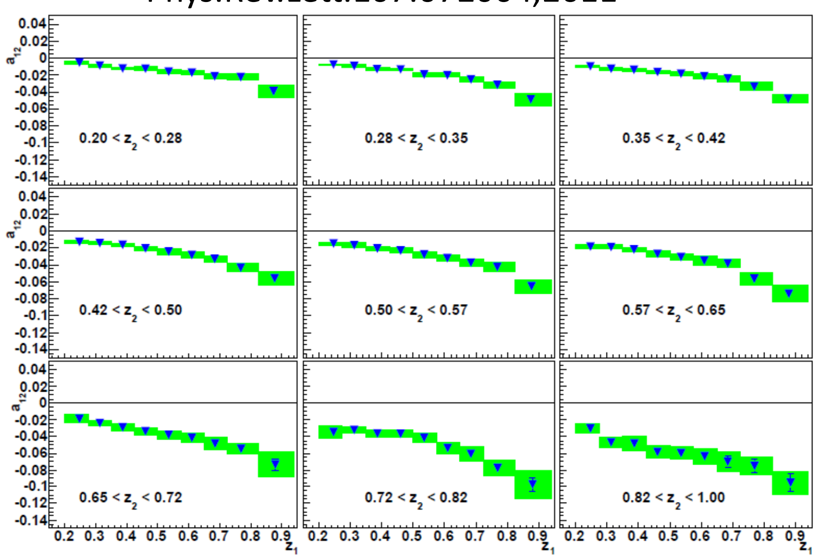




$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 h_1(x,Q^2) H_1^{\sphericalangle}(z, M_h^2, Q^2)}{\sum_q e_q^2 f_1(x,Q^2) D_1^{\sphericalangle}(z, M_h^2, Q^2)}$$

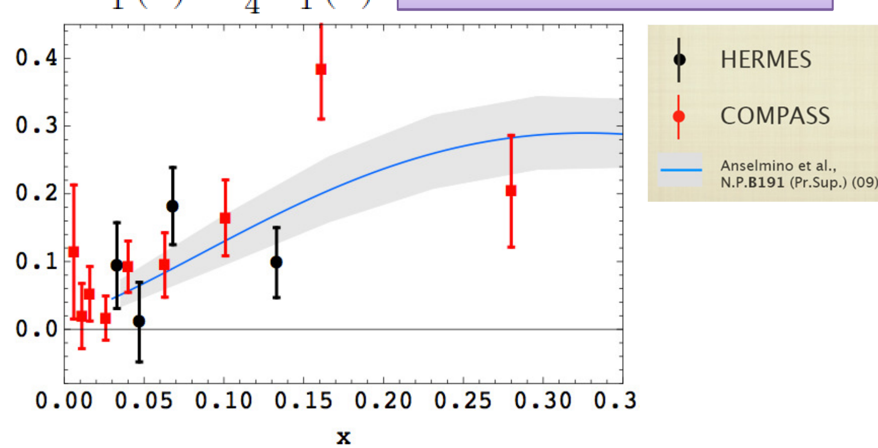
- Survives integration over transverse momentum
- Collinear factorization (simple product)
- DGLAP evolution
- **Large asymmetries @ HERMES & COMPASS**
- **$H1^{\sphericalangle}$ chiral-odd, measured at BELLE**
- **Independent extraction of transversity!**

Phys.Rev.Lett.107:072004,2011

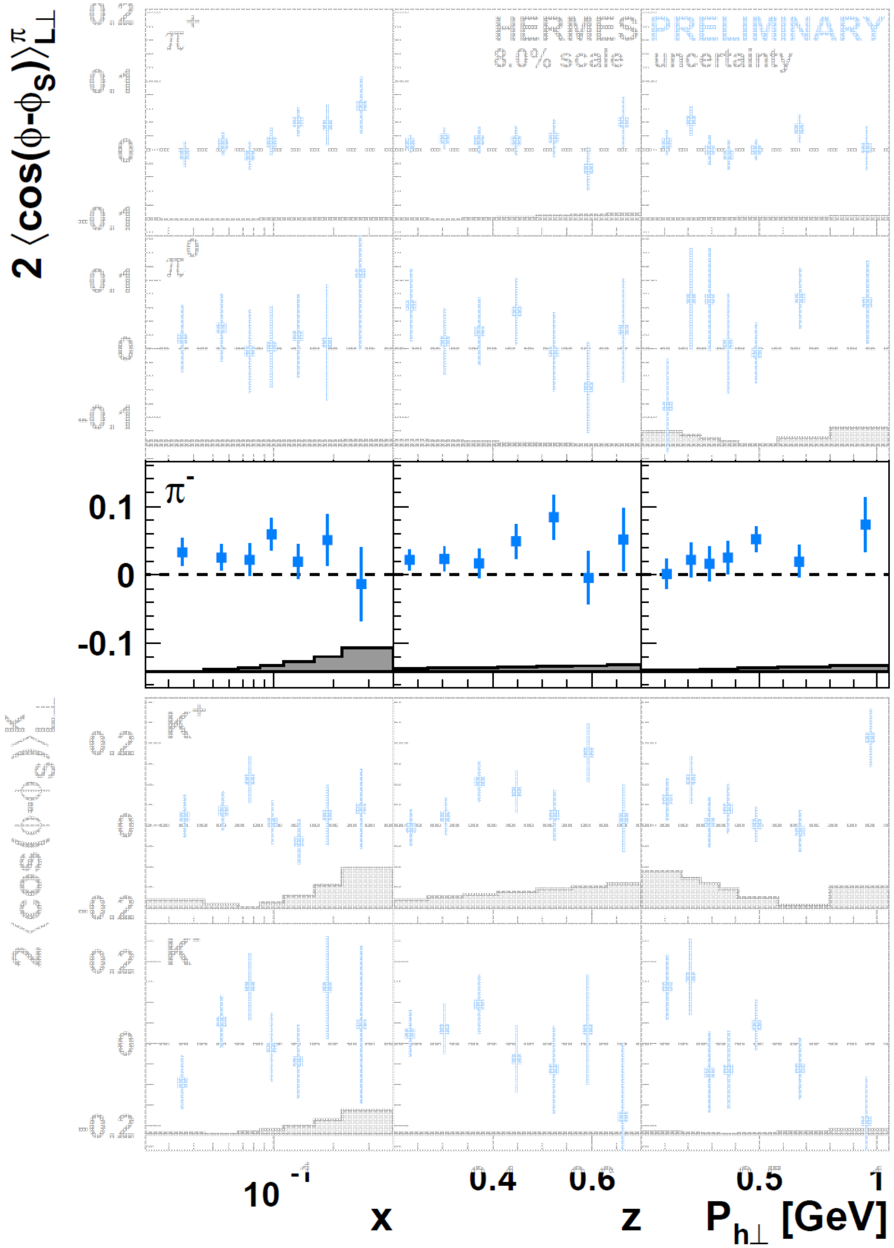


$x\ h_1^u(x) - \frac{x}{4}\ h_1^d(x)$

Bacchetta et al., PRL 107 (11)

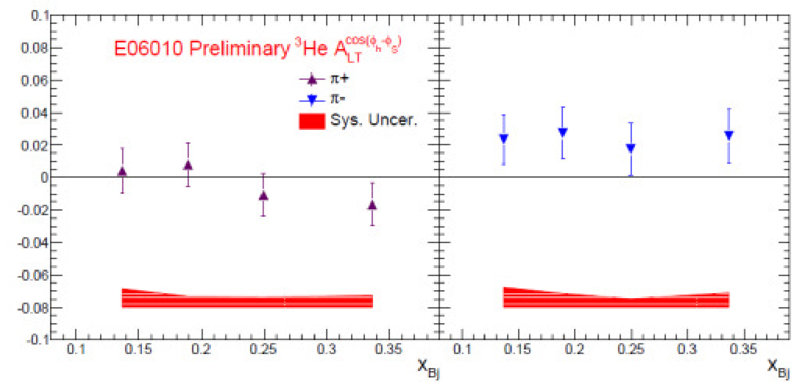


The cos(ϕ-ϕ$_S$) Fourier component

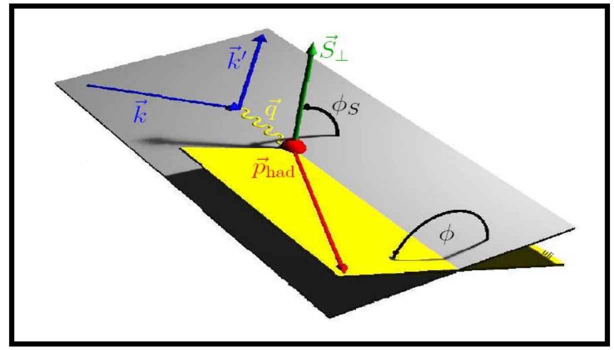


positive!

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



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



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

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

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

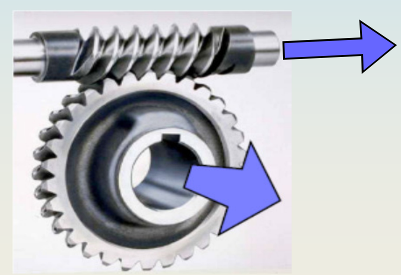
$$+ \frac{1}{Q}$$

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

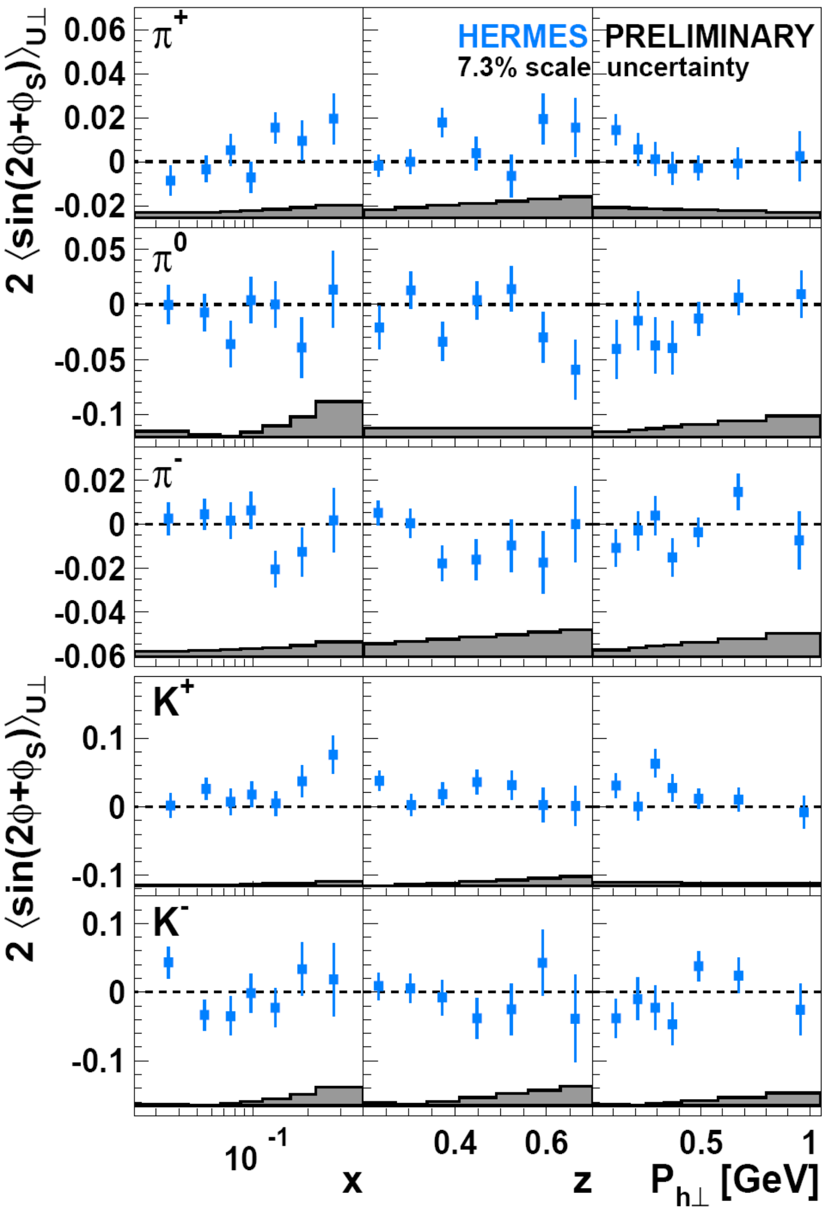
Worm-gear (UL)

(Kotzinian-Mulders)

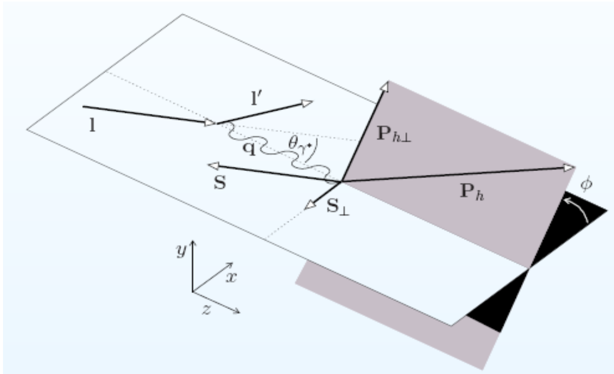
- $\propto h_{1L}^\perp(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$
- describes the probability to find transversely polarized quarks in a longitudinally polarized nucleon
- accessible in UT measurements through $\sin(2\phi+\phi_S)$ Fourier component



The sin(2ϕ+ϕ$_S$) Fourier component



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

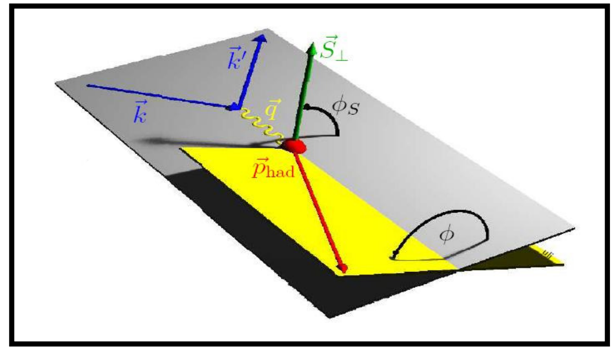


- related to <sin(2ϕ)>$_{UL}$ Fourier comp:

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

- 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 $h_{1T}^\perp$



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

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

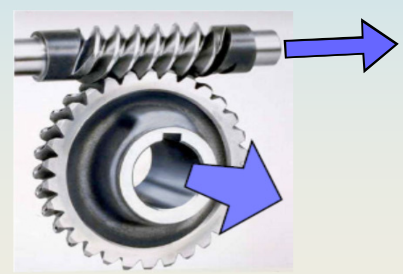
$$+S_T \left\{ \sin(\phi-\phi_S)\ d\sigma^8_{UT} + \sin(\phi \right.$$

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

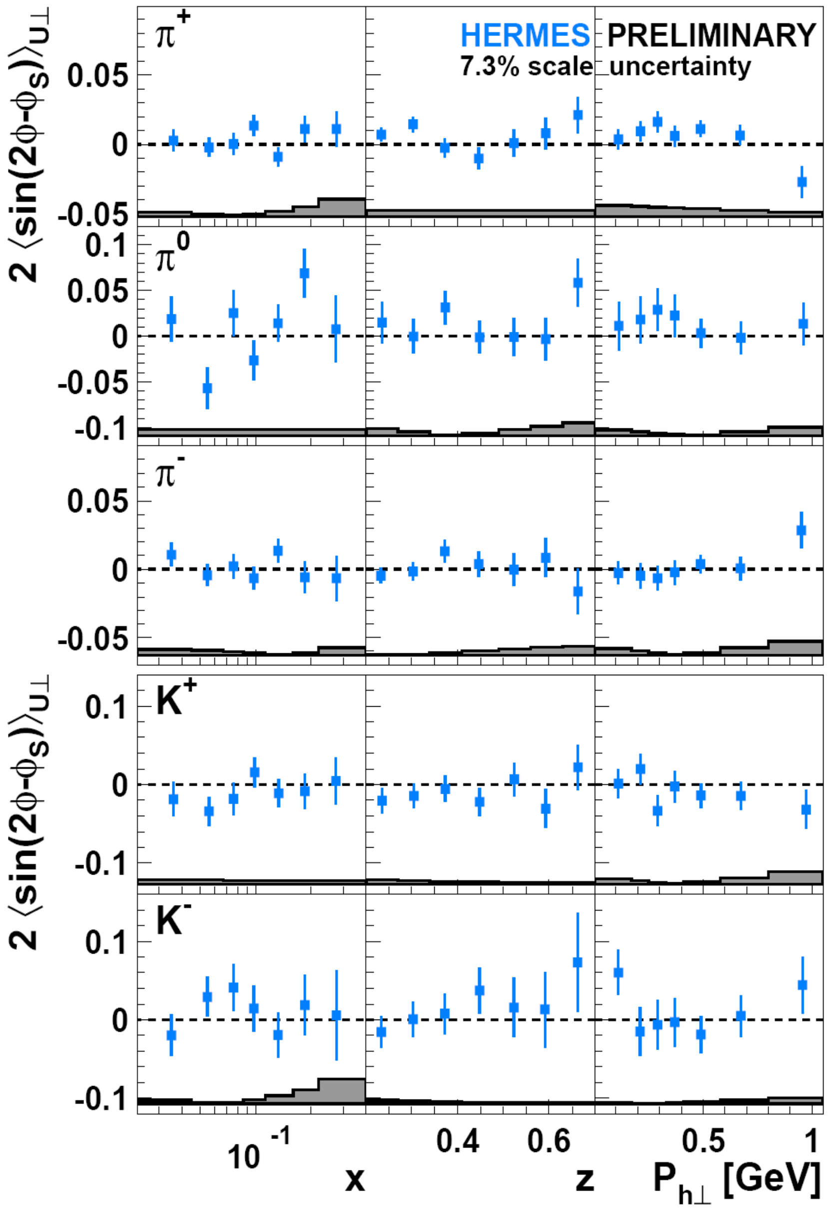
$$+\lambda_e \left[\cos(\phi-\phi_S)\ d\sigma^{13}_{LT} + \frac{1}{Q} \right.$$

Worm-gear (LT)

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



The subleading-twist $\sin(2\phi-\phi_S)$ Fourier component

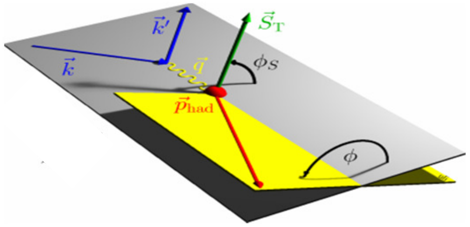


- sensitive to **worm-gear** $g_{1T}^{\perp}$, **Pretzelosity** and **Sivers function**:

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

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

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



The Helicity TMD

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

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

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

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

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

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

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

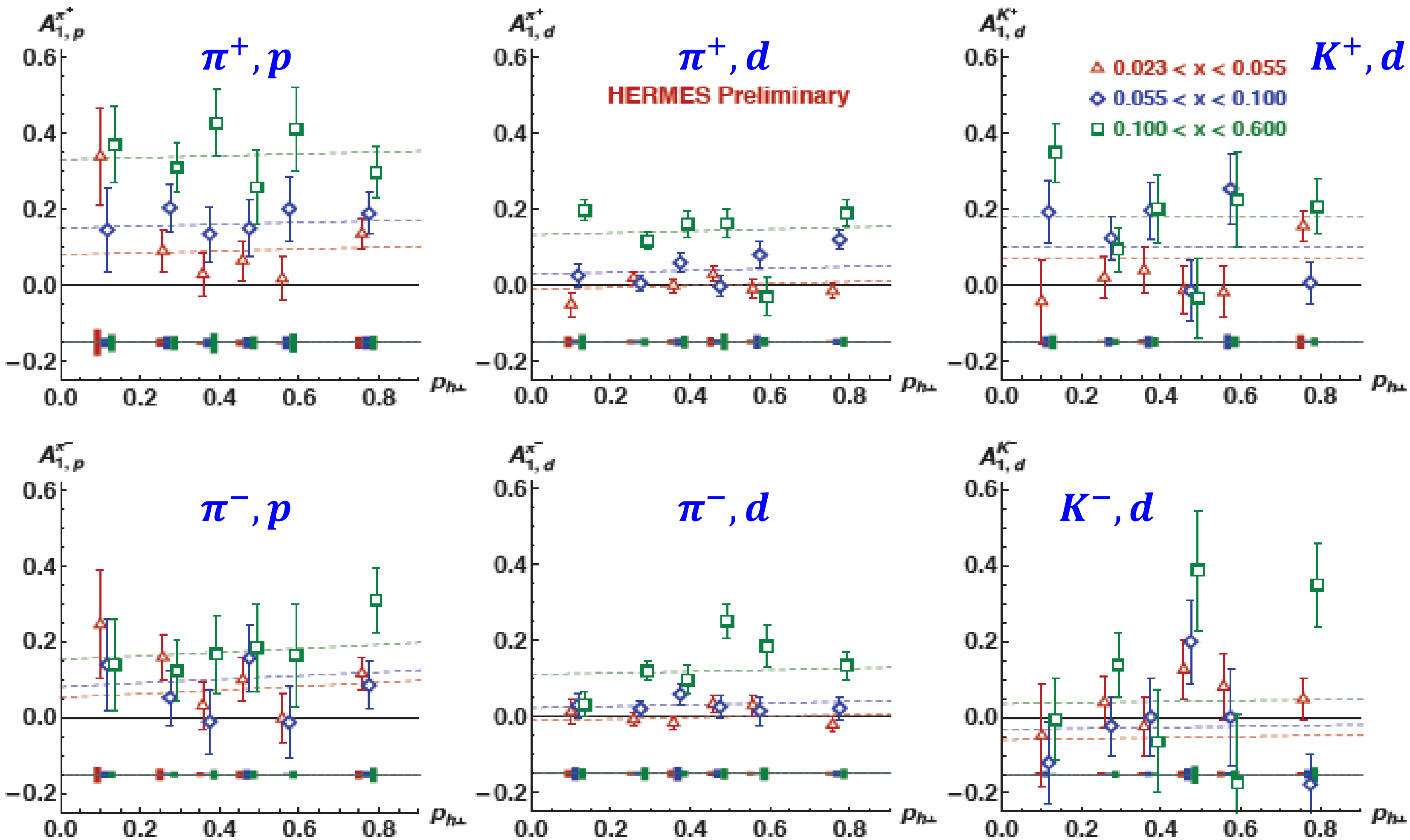
		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Helicity $F_{LL} = g_1 \otimes D_1$

- describes the distribution of longitudinally polarized quarks in a longitudinally polarized nucleon
- Accessible in A_{LL} DSAs
- Collinear version pretty well known
- TMD version poorly known

Helicity TMDs: $P_{h\perp}$-unintegrated A_{LL} DSAs

$$A_1 \propto \frac{F_{LL}}{F_{UU,T}} = \frac{g_1 \otimes D_1}{f_1 \otimes D_1} \approx \frac{1}{P_B P_t} \frac{N^+ - N^-}{N^+ + N^-}$$



Large asymmetries but only a weak dependence on $P_{h\perp}$ is observed