HERMES news on TMD observables

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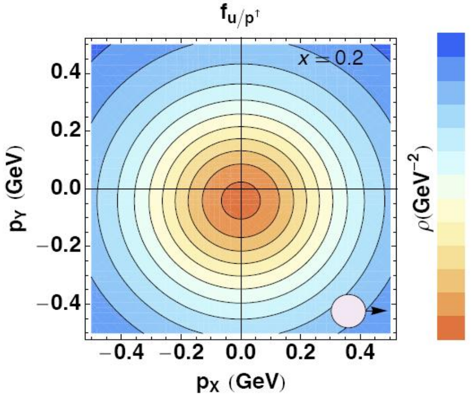
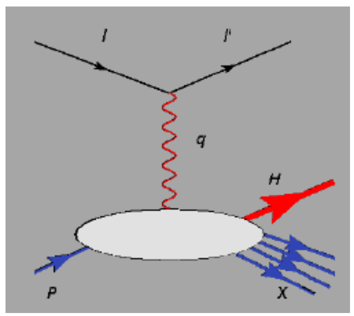
Nucleon tomography: two complementary approaches

TMDs $f(x, p_T)$

3D picture in momentum space



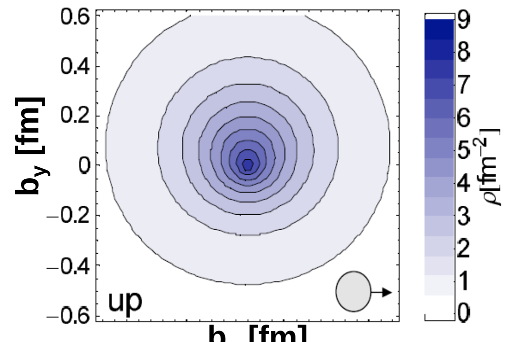


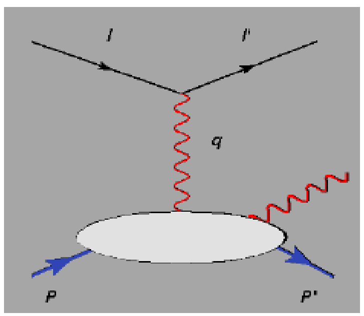
Semi-inclusive DIS

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

$H(x, \xi, t)$ GPDs

3D picture in coordinate space





Exclusive reactions

QCDSF/UKQCD, PRL 98 (07)

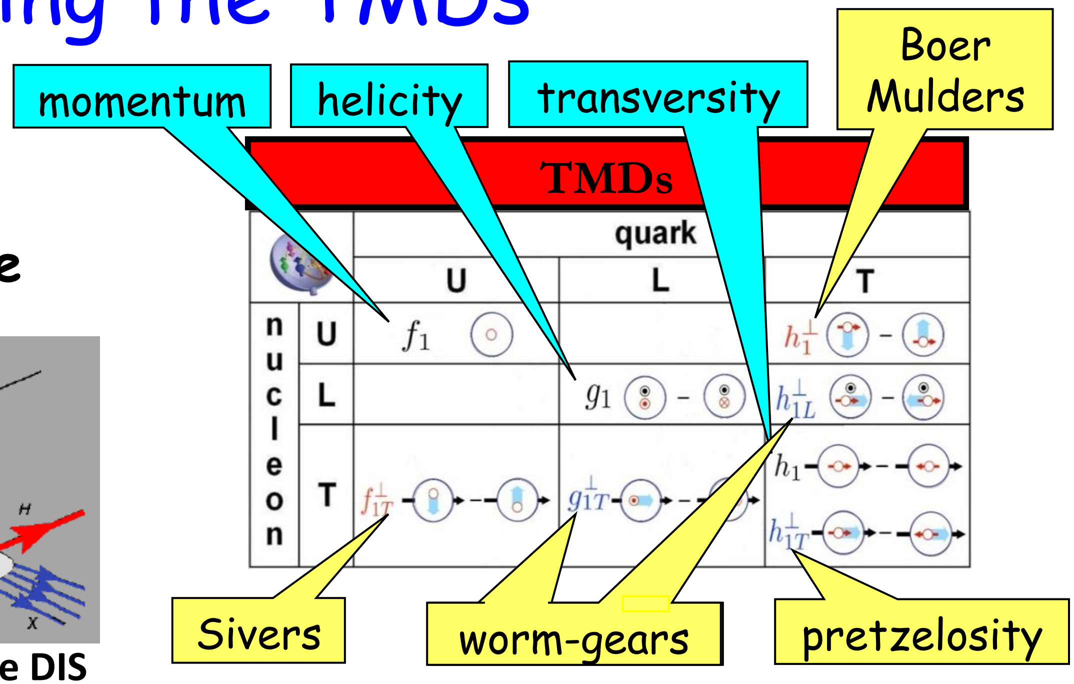
$$\int d^3r \qquad W(x, p_T, r) \qquad \int d^2p_T$$

Mother Wigner function:

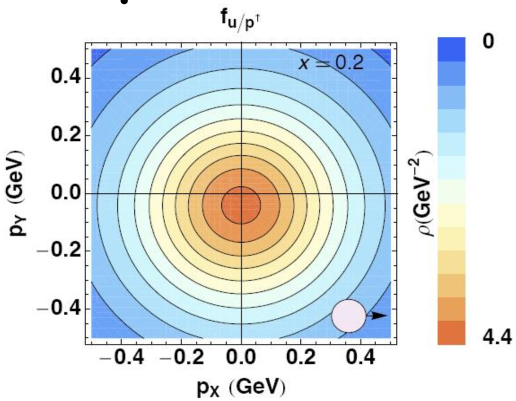
describes full phase-space distributions of partons, but not accessible experimentally

Accessing the TMDs

TMDs $f(x, p_T)$



3D picture in momentum space



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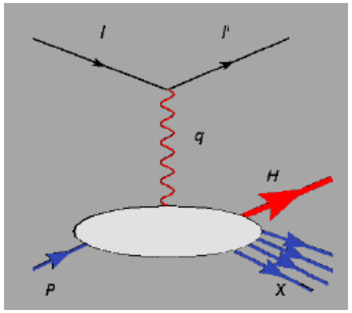
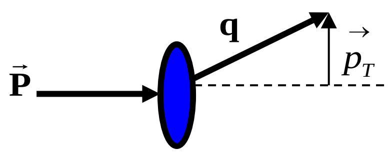


Semi-inclusive DIS

- Depend on x and p_T

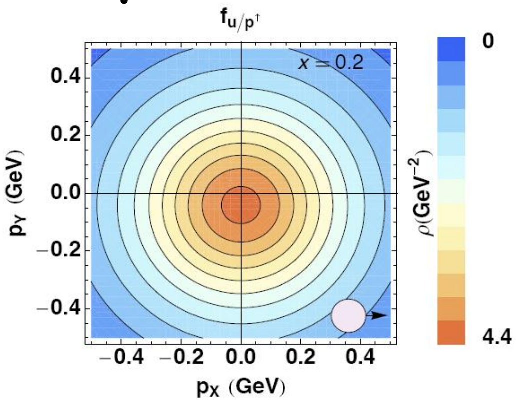


- Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)

Accessing the TMDs

TMDs $f(x, p_T)$

3D picture in momentum space



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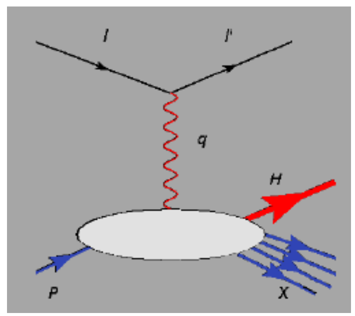

Semi-inclusive DIS

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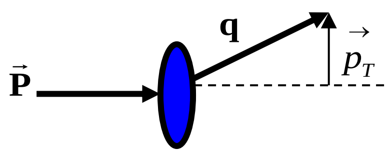


- Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)

TMDs

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, $h_{1T}^\perp$

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

TMD factorization for $P_{h\perp} \ll Q$

Fragmentation Functions

h \ quark	U	L	T
U	D_1		$H_1^\perp$

Part I

Semi-inclusive DIS

The SIDIS cross-section

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

TMDs

		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, $h_{1T}^\perp$

$$F_{XY,Z} \propto DF \otimes FF$$

target polarization (Y), beam polarization (X), virtual photon polarization (Z)

Fragmentation Functions

		quark U	quark L	quark T
h	U	D_1		$H_1^\perp$

The SIDIS cross-section

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

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

unpolarized

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

beam polarization

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

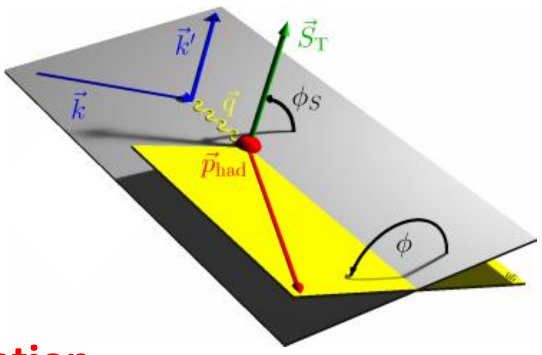
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

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

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

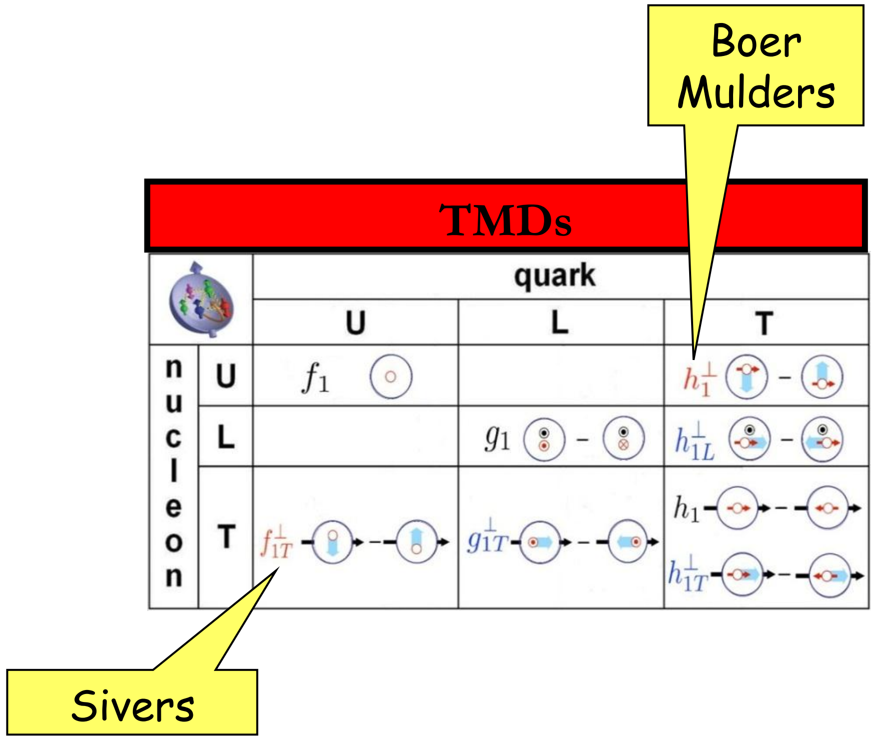
target polarization

beam and target polarization



Selected results (1)

The Naive-T-odd TMDs



Boer-Mulders function $h_1{}^{\perp}$

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

Naive-T-odd & Chiral-odd
Describes correlation between quark transverse momentum and transverse spin in unpolarized nucleon

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

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

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

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

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

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

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

$\propto h_1^\perp \otimes H_1^\perp$

B-M effect
[PRD 57 (1998)]

Boer-Mulders function $h_1{}^{\perp}$

	U	L	T
U			$h_1^{\perp}$
L			
T			

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$$

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\end{aligned}
$$

Naive-T-odd & Chiral-odd
Describes correlation between quark transverse momentum and transverse spin in unpolarized nucleon

$$
\propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2}\left[f_1 \otimes D_1 + \cdots\right]
$$

B-M effect
[PRD 57 (1998)]

Cahn effect
[PLB 78 (1978)]

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U			$h_1^{\perp}$
L			
T			

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$$\propto + \frac{1}{Q}[h_1^{\perp} \otimes H_1^{\perp} + f_1 \otimes D_1 \ldots]$$

B-M effect
[PRD 57 (1998)]

Cahn effect
[PLB 78 (1978)]

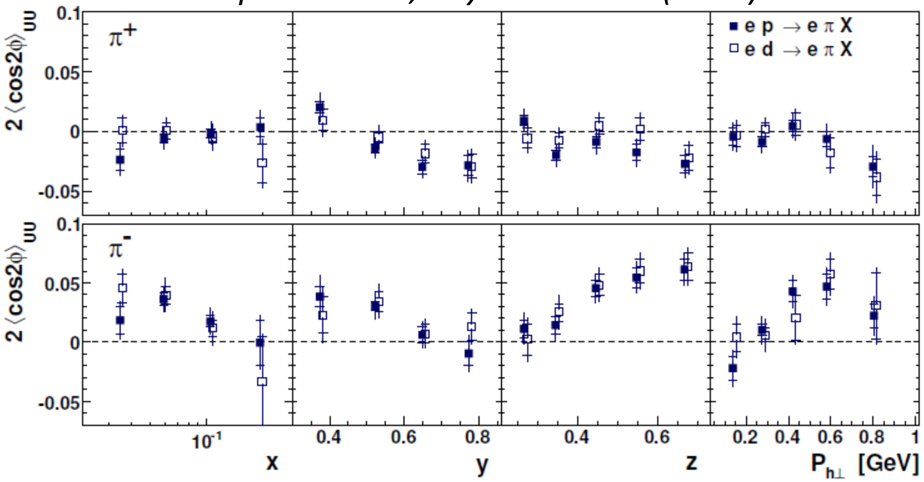
Interaction dependent terms

The cos2ϕ amplitudes

$$\propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2}[f_1 \otimes D_1 + \cdots]$$

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

A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



negative

positive

- **Amplitudes are significant → clear evidence of BM effect**
- **similar results for H & D indicate** $h_1^{\perp,u} \approx h_1^{\perp,d}$
- Opposite sign for π^+/π^- consistent with opposite signs of fav/unfav Collins

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U			$h_1^\perp$
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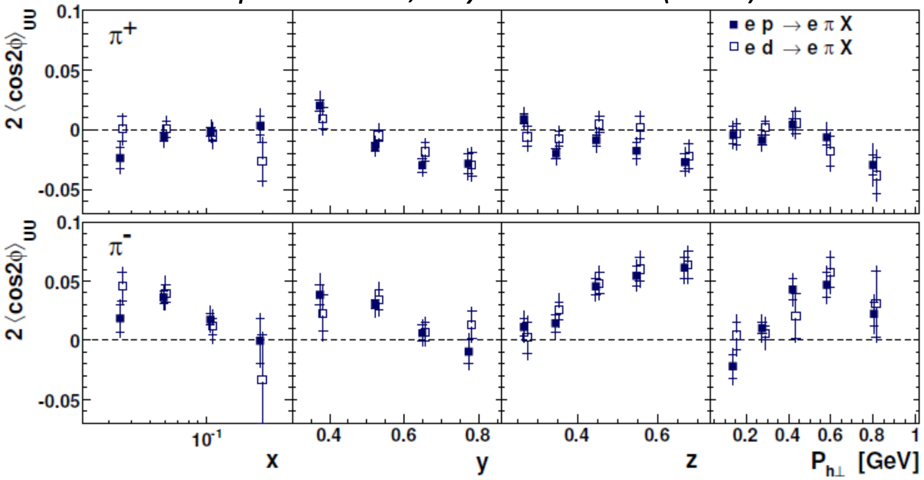

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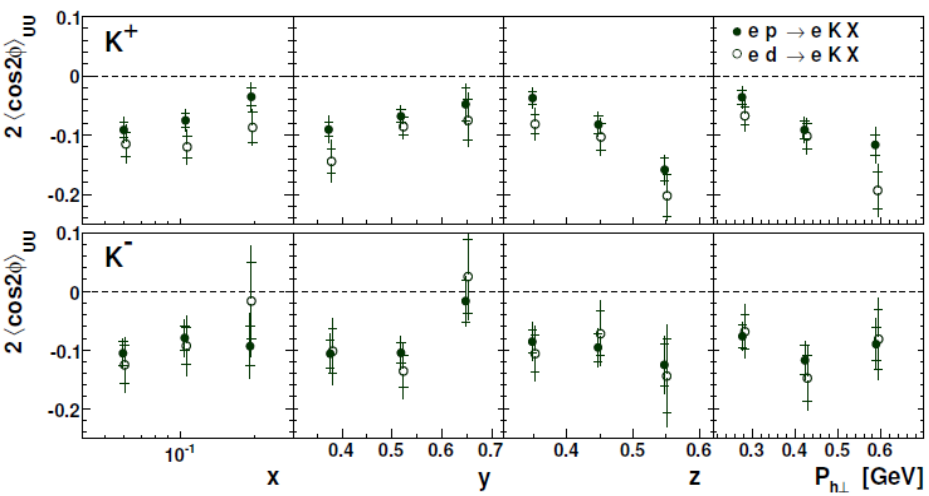


Large and negative

Large and negative

- **K^+/K^- amplitudes are larger than for pions, have different kinematic dependencies than pions and have same sign!!**
- different role of Collins FF for pions and kaons?
- Significant contribution from scattering off strange quarks?

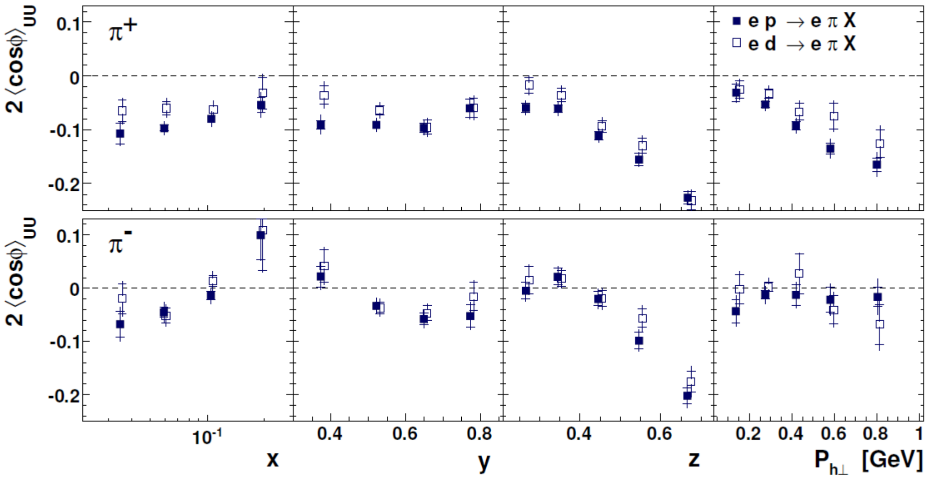
Analysis multi-dimensional in x, y, z,and Pt

Create your own projections of results through: http://www-hermes.desy.de/cosnphi/

The cosϕ amplitudes

$$\propto +\frac{1}{Q}[h_1^{\perp} \otimes H_1^{\perp} + f_1 \otimes D_1 \dots]$$

A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



negative

negative

- **Significant and of same sign (Chan effect expected to be weakly flavor dependent)**
- **Clear rise with z for π^+ & π^- and $P_{h\perp}$ for π^+ (Chan)**
- Different $P_{h\perp}$ dependence of π^+ & π^- indicates contributions of flavor dependent effects (e.g. BM) for π^-

Analysis multi-dimensional in x, y, z,and Pt

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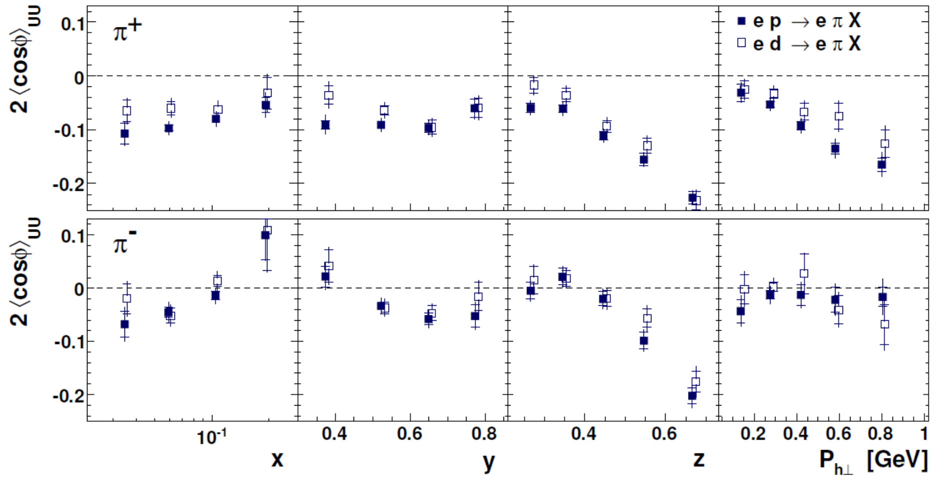

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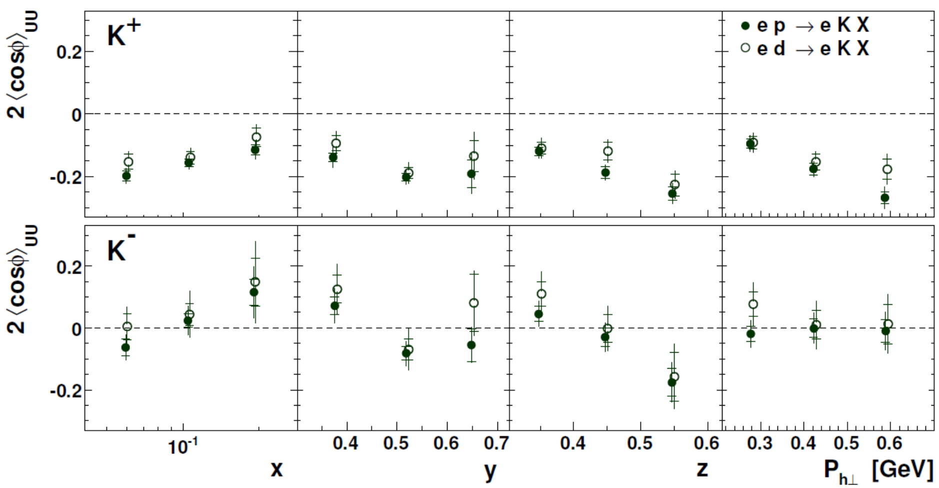


Large and negative

Consist. with 0

- **K^+ amplitudes larger than π^+**
- **$K^- \approx 0$ different than K^+ (in contrast to $\cos 2\phi$)**
- Significant contrib from interaction dependent terms?

Analysis multi-dimensional in x, y, z,and Pt

Create your own projections of results through: http://www-hermes.desy.de/cosnphi/

Sivers function $f_{1T}^{\perp}$

	U	L	T
U			
L			
T	$f_{1T}^{\perp}$		

Naive T-odd
Describes correlation between quark transverse momentum and nucleon transverse polarization

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

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

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

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

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

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

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

$\propto f_{1T}^{\perp} \otimes D_1$

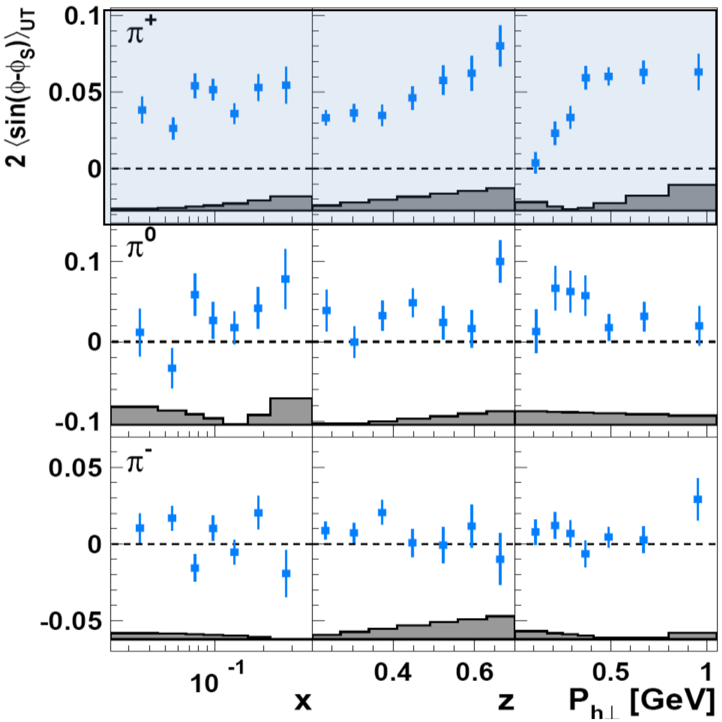
Sivers effect
[PRD 41 (1990)]

Sivers amplitudes

$$\propto f_{1T}^{\perp} \otimes D_1$$

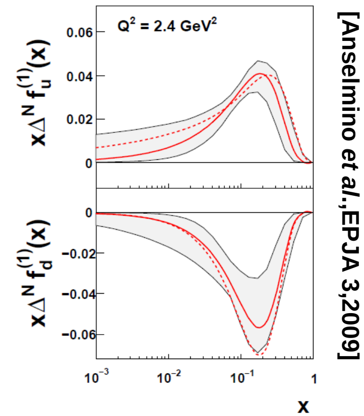
	U	L	T
U			
L			
T	$f_{1T}^{\perp}$		

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



- **significantly positive**
- **slightly positive** (isospin-symmetry)
- **consistent with zero**

consistent with Sivers func. of opposite sign for u and d quarks

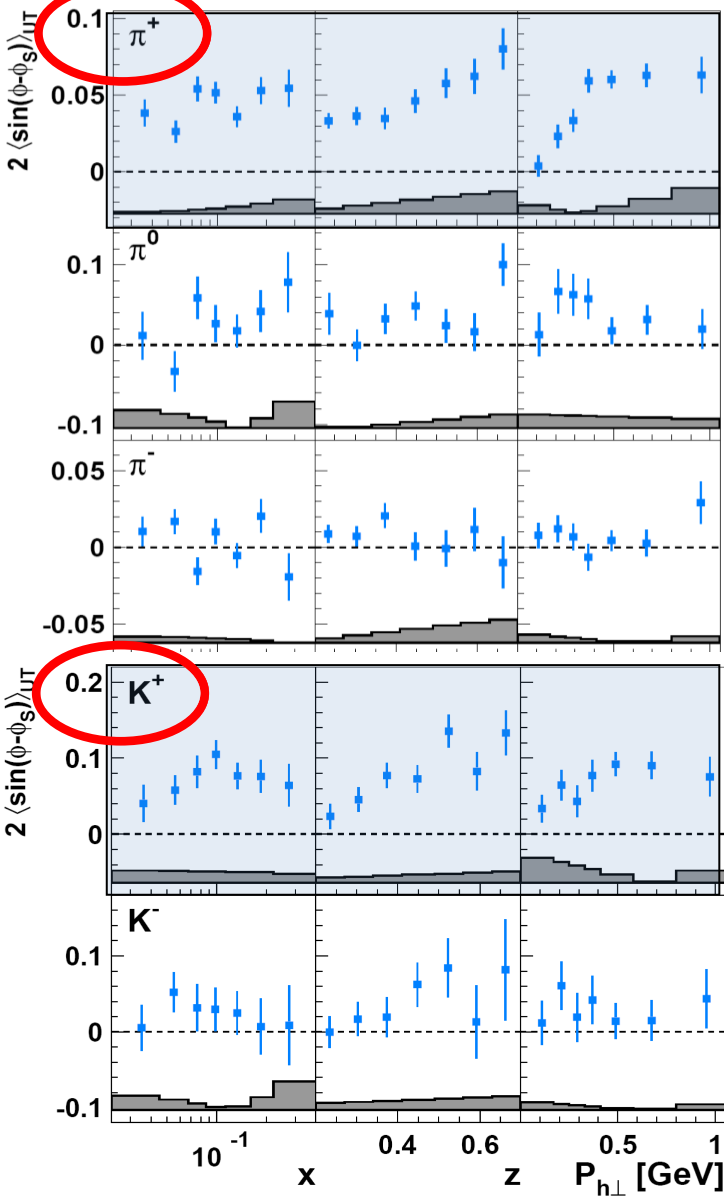


Sivers amplitudes

$\propto f_{1T}^{\perp} \otimes D_1$

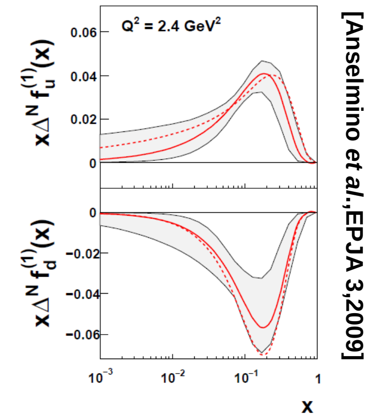
	U	L	T
U			
L			
T	$f_{1T}^{\perp}$		

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



- significantly positive
- slightly positive (isospin-symmetry)
- consistent with zero

consistent with Sivers func. of opposite sign for u and d quarks



- Larger than π^{+}!!

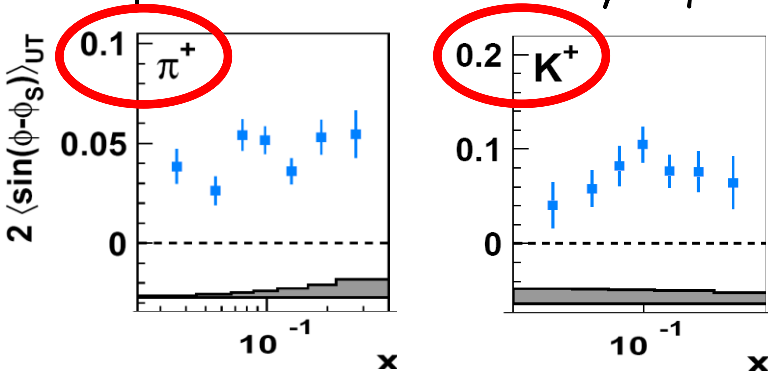
Again unexpected pion-kaon differences!

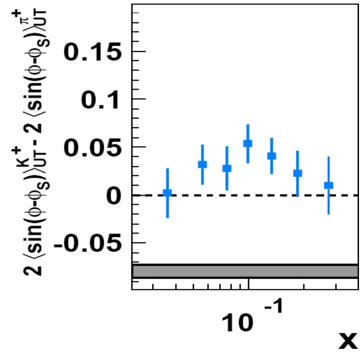
- Slightly positive

The kaon puzzle in Sivers

	U	L	T
U			
L			
T	$f_{1T}^{\perp}$		

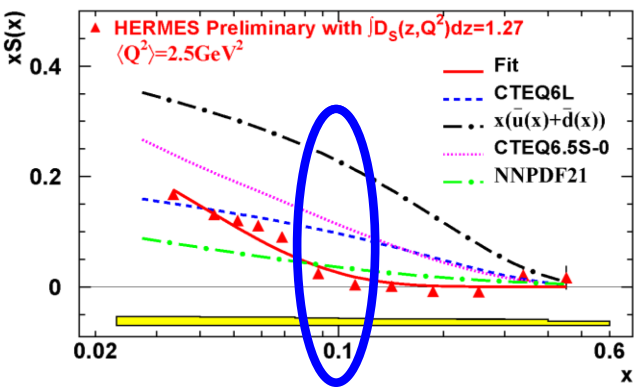
π^+/K^+ production dominated by u-quarks, but:





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

different role of the antiquarks $\bar{u}, \bar{s}$?



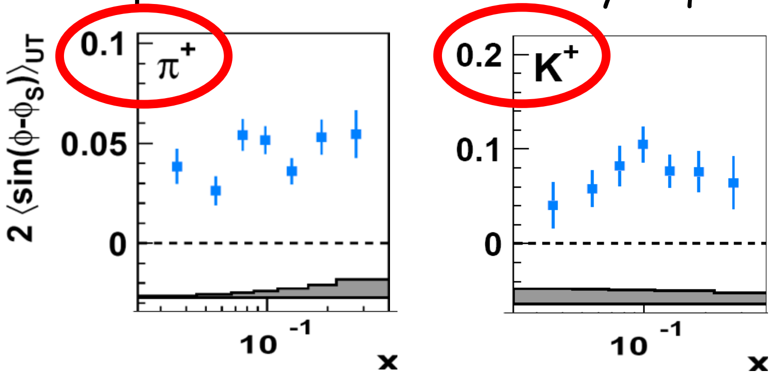
Flavor dependence of k_T in fragment.

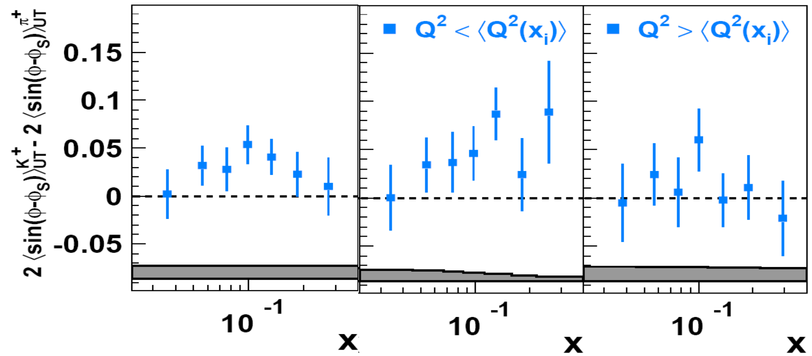
$\rightarrow$ impact through convolution integral

The kaon puzzle in Sivers

	U	L	T
U			
L			
T	$f_{1T}^{\perp}$		

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

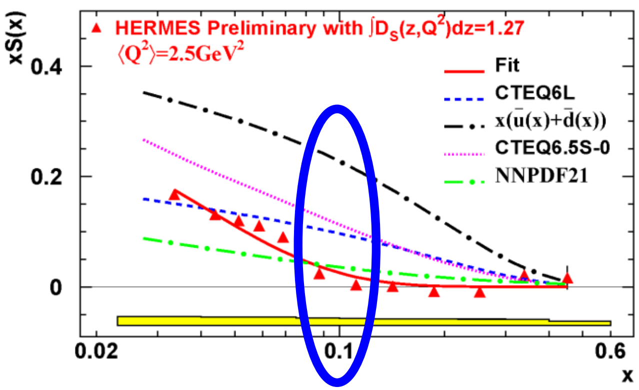


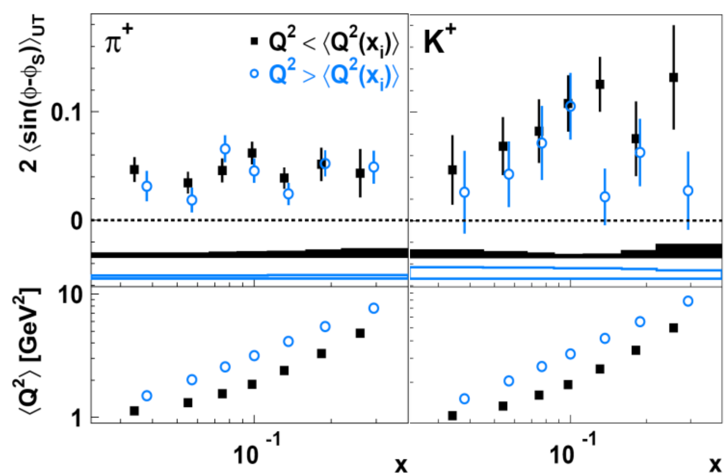


Each x-bin divided into 2 Q^2-bins

Significant deviations observed only at low Q^2

$\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle \ \rightarrow$
different role of the antiquarks $\bar{u}, \bar{s}$?





Flavor dependence of k_T in fragment.

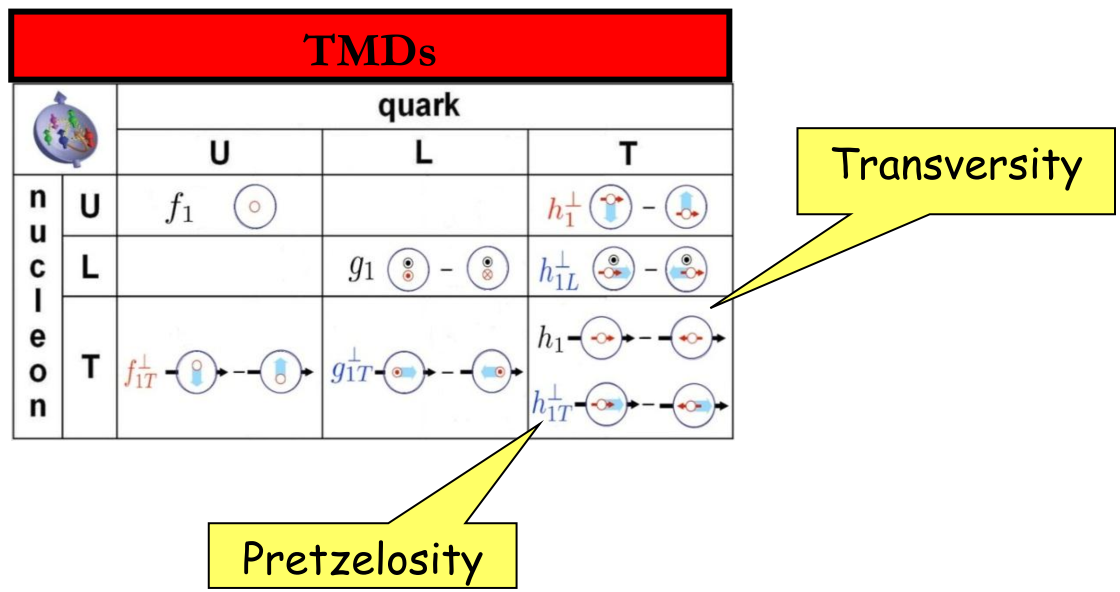
$\rightarrow$ impact through convolution integral

Hint of systematic diff. only for K^+

Higher-twist contrib. for Kaons

Selected results (2)

The “transverse corner”



Transversity & Pretzelosity

	U	L	T
U			
L			
T			h_1,

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

$$
\begin{aligned}
\Big\{ \quad & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \quad \lambda_l \quad & \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ \; S_L \quad & \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ \; S_L\;\lambda_l \quad & \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ \; S_T \quad & \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \; S_T\;\lambda_l \quad & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$

Chiral-odd
Describes probability to find transversely polarized quarks in a transversely polarized nucleon

$\propto h_1 \otimes H_1^{\perp}$

Collins effect
[Nucl. Phys. B 396 (1993)]

Transversity & Pretzelosity

	U	L	T
U			
L			
T			h_1, $h_{1T}^{\perp}$

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

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

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

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

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

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

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

Chiral-odd
Describes probability to find transversely polarized quarks in a transversely polarized nucleon

$\propto h_1 \otimes H_1^{\perp}$

Collins effect
[Nucl. Phys. B 396 (1993)]

Chiral-odd
Describes correlation between quark transverse momentum and transverse spin in a transversely pol. nucleon

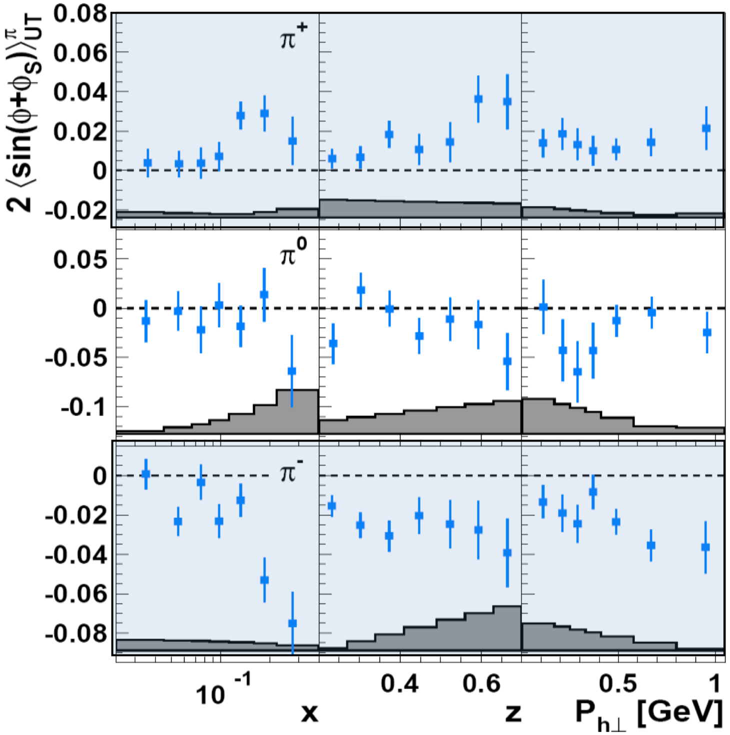
$\propto h_1^{\perp} \otimes H_1^{\perp}$

Collins amplitudes

$\propto h_1 \otimes H_1^{\perp}$

	U	L	T
U			
L			
T			h_1,

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



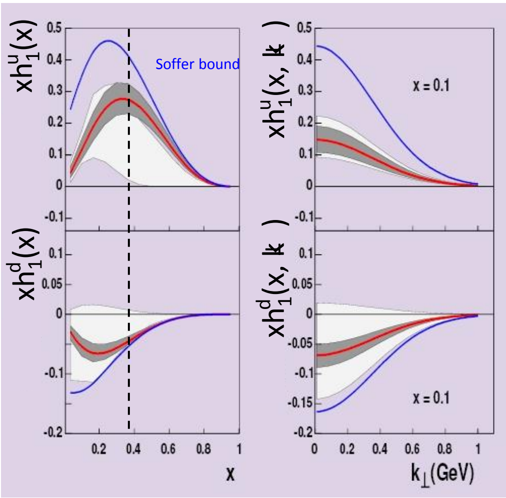
- **positive**
- **consistent with zero** (isospin-symmetry)
- **large and negative!**

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

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

Consistent with Belle/BaBar measurements in e^+e^-

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



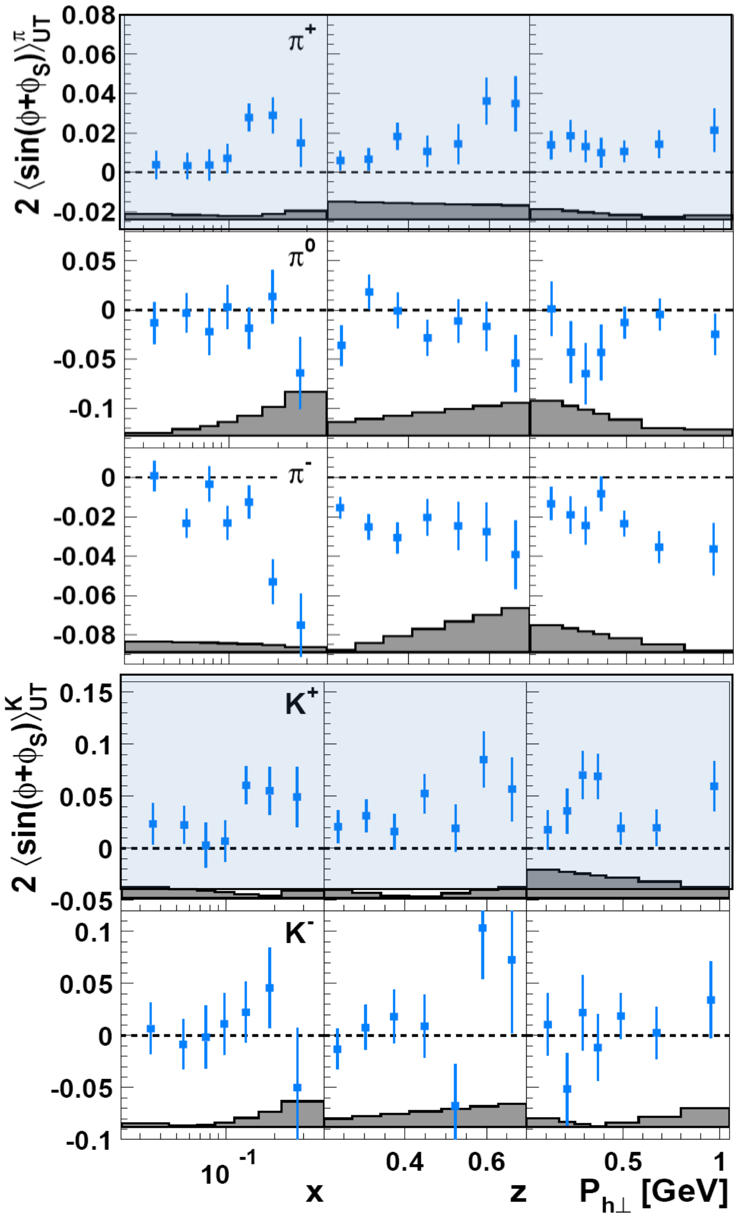
Anselmino et al. Phys. Rev. D 75 (2007)

Collins amplitudes

$\propto h_1 \otimes H_1^{\perp}$

	U	L	T
U			
L			
T			h_1,

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



- positive
- consistent with zero (isospin-symmetry)
- large and negative!

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

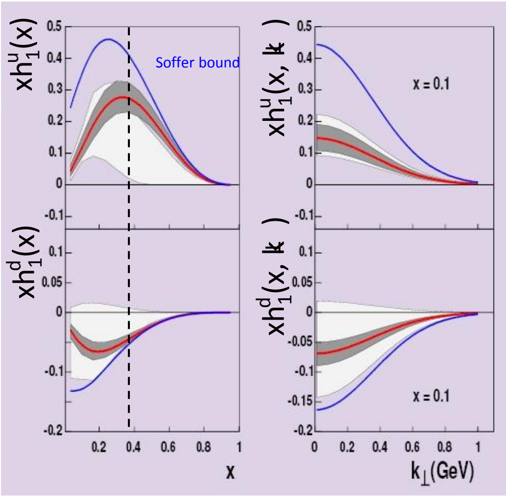
$$H_1^{\perp,unfav}(z) \approx -H_1^{\perp,fav}(z)$$

Consistent with Belle/BaBar measurements in e^+e^-

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

- significantly positive

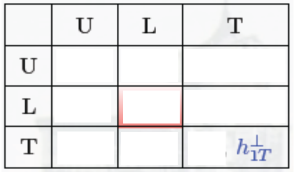
  Similar to π^+ but larger
- consistent with zero

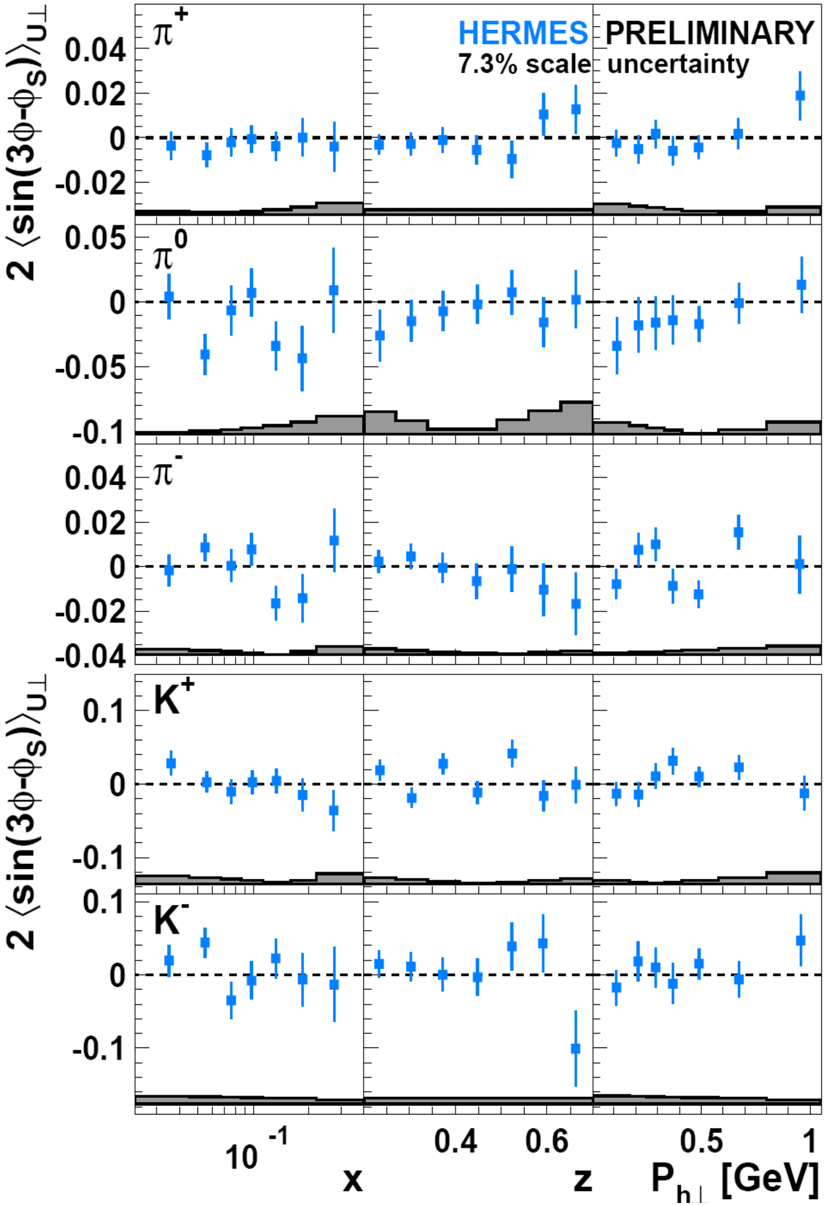


Anselmino et al. Phys. Rev. D 75 (2007)

The sin(3ϕ-ϕ_s) amplitude

$\propto h_1^\perp \otimes H_1^\perp$



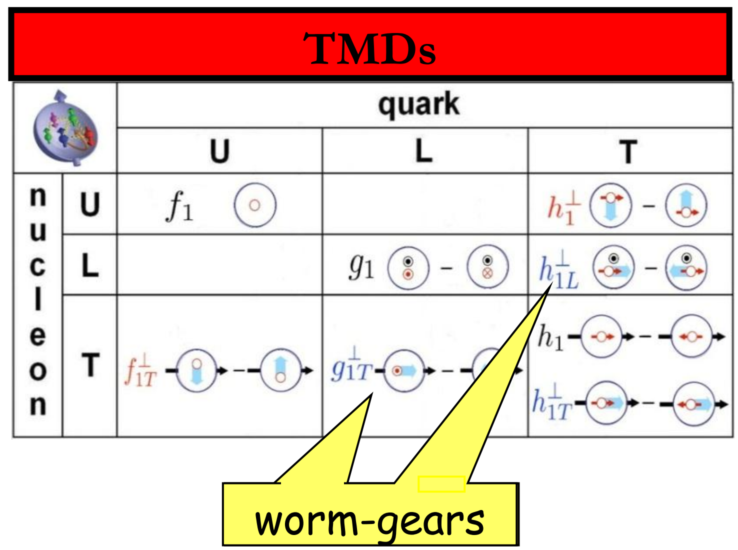


All amplitudes consistent with zero

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

Selected results (3)

The worm-gears



Worm-gear $h^{\perp}_{1L}$

	U	L	T
U			
L			$h_{1L}^{\perp}$
T			

Probability to find transversely polarized quarks in a longitudinally polarized nucleon

$\propto h_{1L}^{\perp} \otimes H_1^{\perp}$

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

Worm-gear $h^{\perp}{}_{1L}$ & g_{1T}

	U	L	T
U			
L			$h_{1L}^{\perp}$
T		g_{1T}	

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

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

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

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

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

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

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

Probability to find transversely polarized quarks in a longitudinally polarized nucleon

$\propto h_{1L}^{\perp} \otimes H_1^{\perp}$

Probability to find longitudinally polarized quarks in a transversely polarized nucleon!

- requires interference between wave funct. components that differ by 1 unit of **OAM** $\rightarrow$ **related to orbital motion of partons**
- Can be accessed in **LT DSAs**

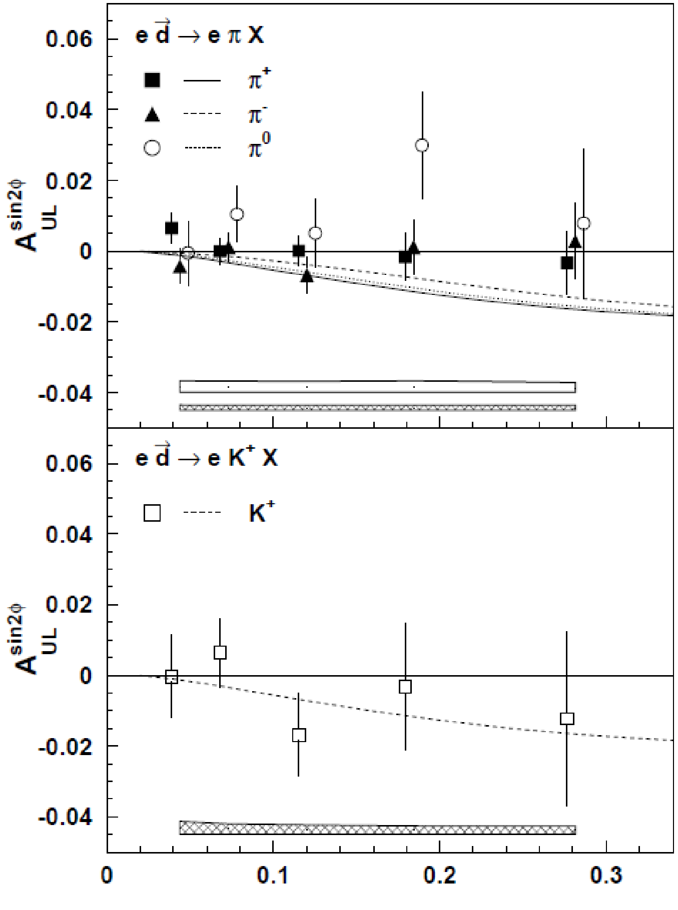
$\propto g_{1T} \otimes D_1$

The sin(2ϕ) amplitude

$\propto h_{1L}^{\perp} \otimes H_1^{\perp}$

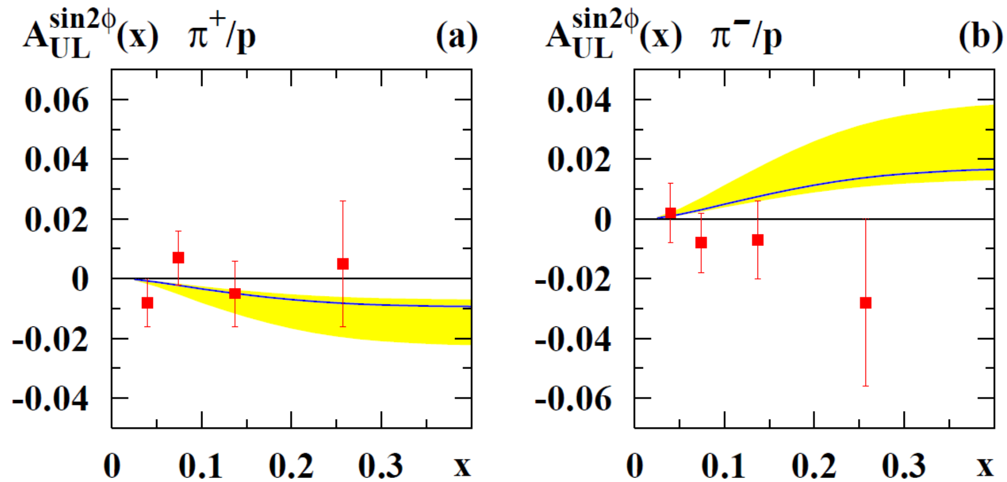
	U	L	T
U			
L			$h_{1L}^{\perp}$
T			

Deuterium target



A. Airapetian et al, Phys. Lett. B562 (2003)

Hydrogen target



A. Airapetian et al, Phys. Rev. Lett. 84 (2000)

Amplitudes consistent with zero for all mesons and for both H and D targets.

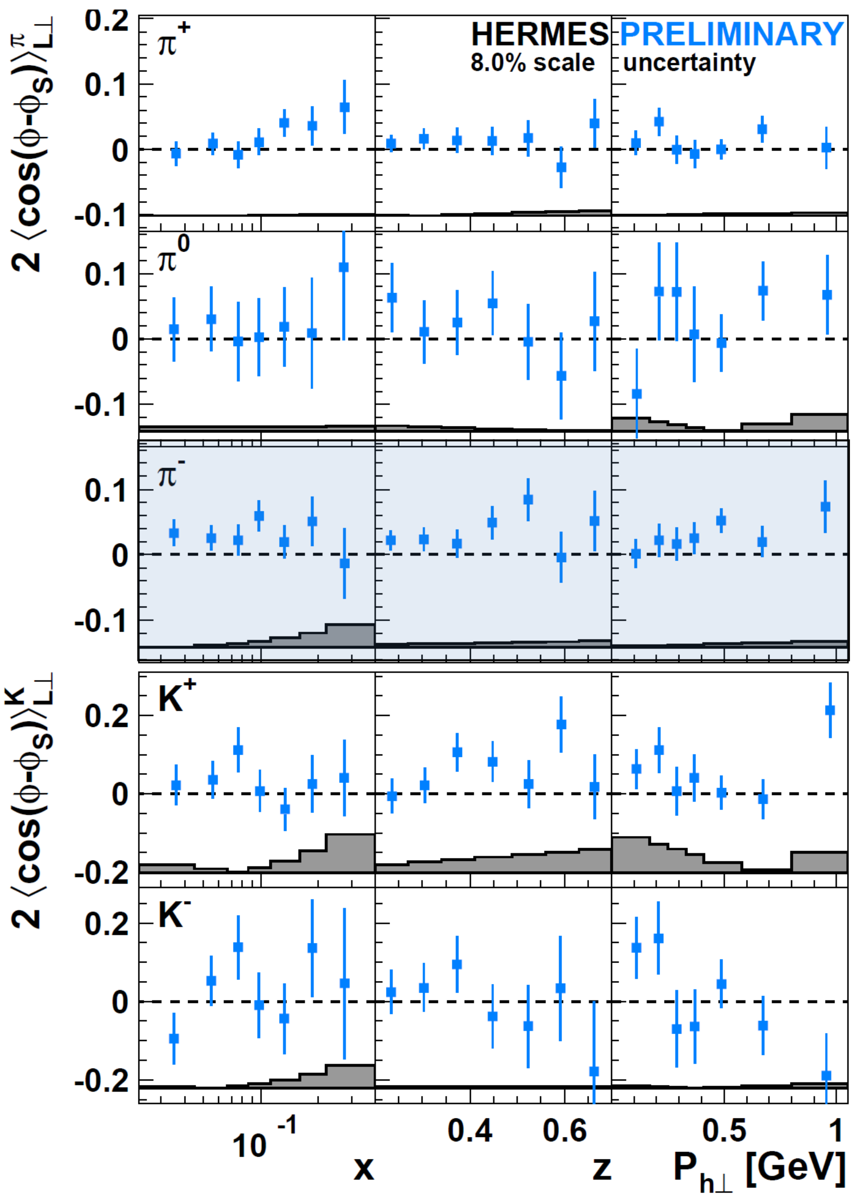
Similar observations by COMPASS on deuterium

CLAS reported significant amplitudes for pions on a proton target.

The cos(ϕ-ϕ$_S$) amplitudes

$\propto g_{1T} \otimes D_1$

	U	L	T
U			
L			
T		g_{1T}	



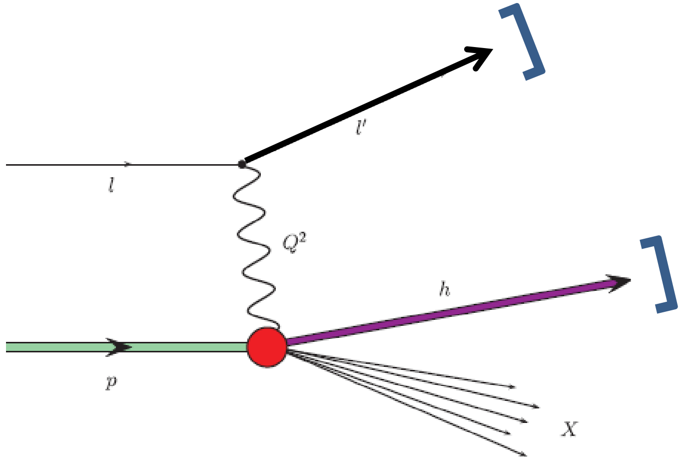
- ☛ slightly positive ?
- ☛ consistent with zero
- ☛ positive!!
- ☛ slightly positive ?
- ☛ consistent with zero

similar observations from Hall-A and COMPASS

Part II

Inclusive electroproduction of hadrons

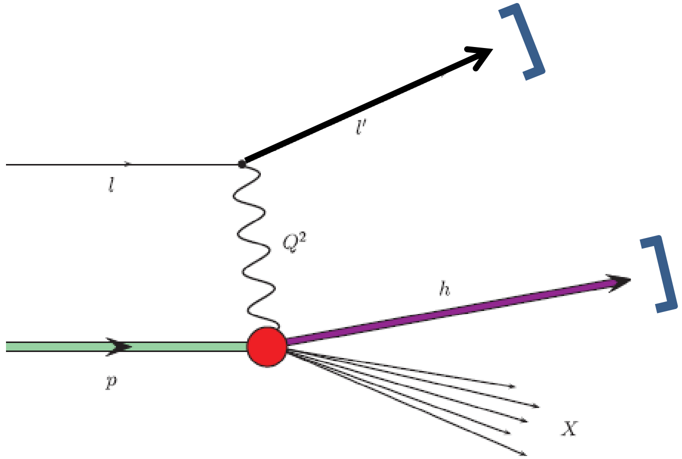
From SIDIS to inclusive hadron production

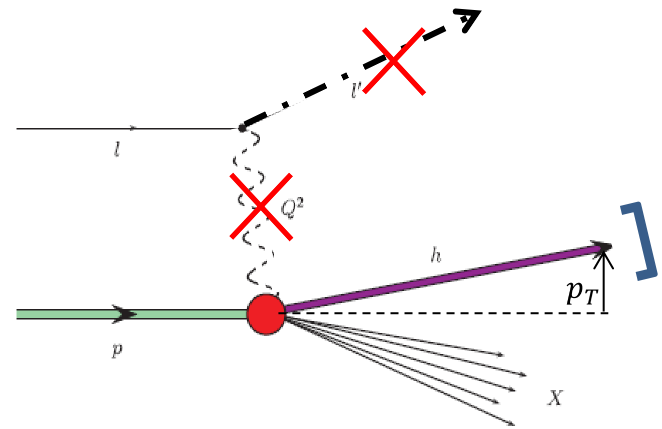


SIDIS: $\boldsymbol{lp^{\uparrow} \rightarrow l'hX}$

- Hadron detected in coincidence with lepton
- DIS regime ($Q^2 > 1\ GeV^2$)
- Hard scales: $Q^2, P_{h\perp}$ (w.r.t. γ^*)
- Factorization valid for ${P_{h\perp}}^2 \ll Q^2$

From SIDIS to inclusive hadron production





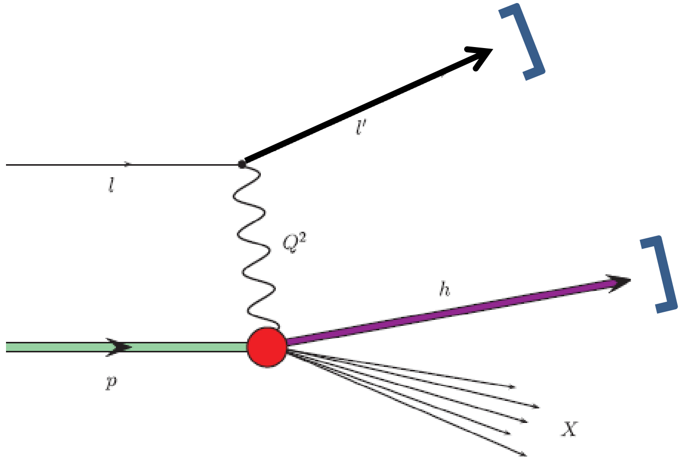
SIDIS: $lp^{\uparrow} \rightarrow l'hX$

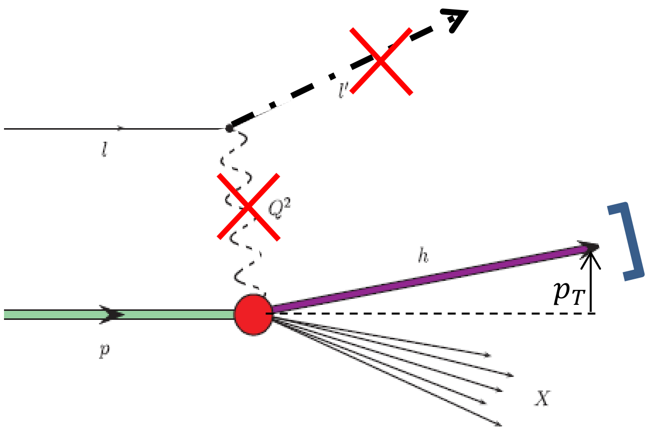
- Hadron detected in coincidence with lepton
- DIS regime ($Q^2 > 1\ GeV^2$)
- Hard scales: Q^2, $P_{h\perp}$ (w.r.t. γ^*)
- Factorization valid for ${P_{h\perp}}^2 \ll Q^2$

Inclusive hadrons: $lp^{\uparrow} \rightarrow hX$

- **Lepton is not detected** $\rightarrow$ no info on Q^2
- data dominated by $Q^2 \approx 0$ (**quasi-real photoproduction regime**)
- Hard scales: P_T (w.r.t. incident lepton)
- Factorization valid for large P_T?
- Main variables: $x_F = 2\frac{P_L}{\sqrt{s}}$, P_T
- **Selected events** contain at least 1 charged hadron track (π or K) regardless of whether there was also a scattered lepton in acceptance or not.

From SIDIS to inclusive hadron production





SIDIS: $lp^{\uparrow} \rightarrow l'hX$

- Hadron detected in coincidence with lepton
- DIS regime ($Q^2 > 1\ GeV^2$)
- Hard scales: Q^2, $P_{h\perp}$ (w.r.t. γ^*)
- Factorization valid for $P_{h\perp}{}^2 \ll Q^2$

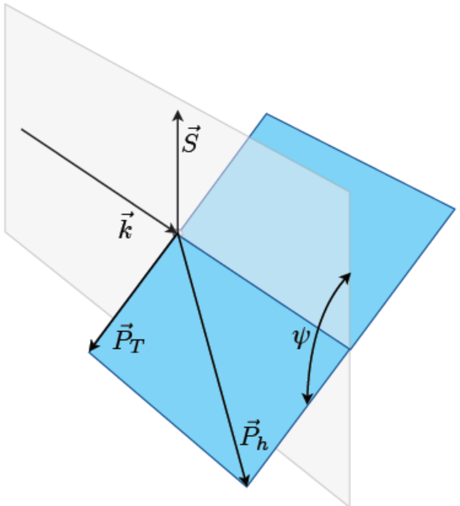
Hadron yields for UT data

	π^+	π^-	K^+	K^-
SIDIS	7.3 M	5.4 M	131 K	54 K
Incl. h	60 M	50 M	5.1 M	2.8 M

Inclusive hadrons: $lp^{\uparrow} \rightarrow hX$

- **Lepton is not detected** $\rightarrow$ no info on Q^2
- data dominated by $Q^2 \approx 0$ (**quasi-real photoproduction regime**)
- Hard scales: P_T (w.r.t. incident lepton)
- Factorization valid for large P_T?
- Main variables: $x_F = 2\frac{P_L}{\sqrt{s}}$, P_T
- **Selected events** contain at least 1 charged hadron track (π or K) regardless of whether there was also a scattered lepton in acceptance or not.
- **SIDIS events constitute a small subsample**

Cross section and azimuthal asymmetries

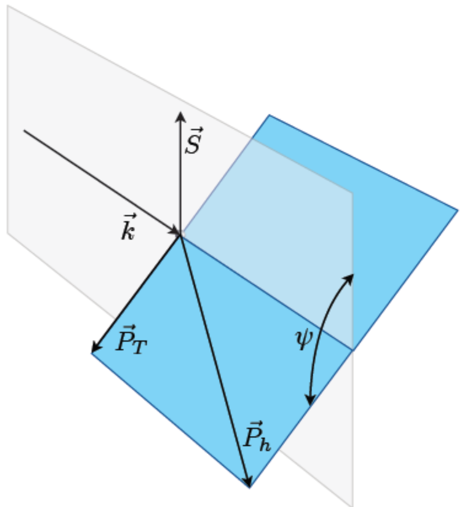


$$d\sigma = d\sigma_{UU}\left[1 + S_{\perp} A_{UT}{}^{sin\psi} \sin\psi\right]$$

$$\vec{S} \cdot \left(\vec{P}_h \times \vec{k}\right) \propto \sin\psi$$

ψ: azimuthal angle between the upwards target spin direction and hadron production plane around the beam direction

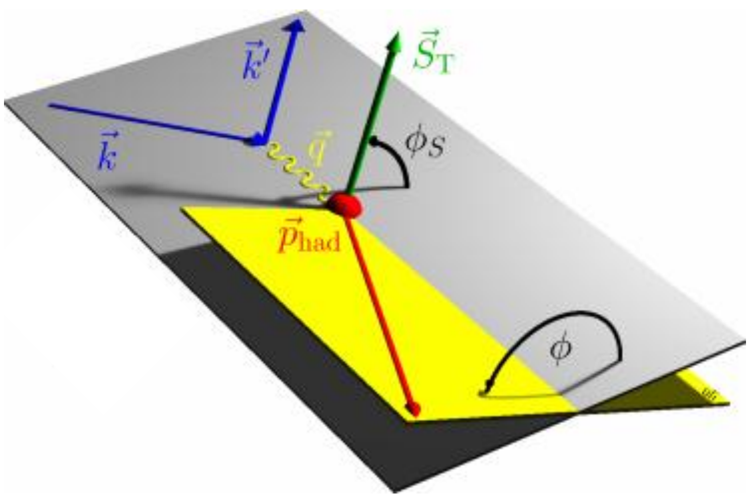
Cross section and azimuthal asymmetries



$$d\sigma = d\sigma_{UU}\left[1 + S_\perp A_{UT}^{\sin\psi}\sin\psi\right]$$

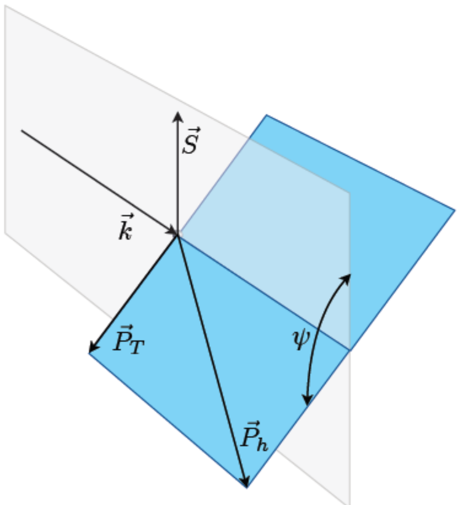
$$\vec{S}\cdot(\vec{P}_h \times \vec{k}) \propto \sin\psi$$

$\boldsymbol{\psi}$: azimuthal angle between the upwards target spin direction and hadron production plane around the beam direction



$$\boldsymbol{\psi \approx \phi - \phi_S}$$

Cross section and azimuthal asymmetries



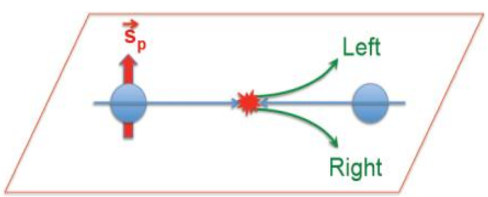
$$d\sigma = d\sigma_{UU}\left[1 + S_\perp A_{UT}^{\sin\psi} \sin\psi\right]$$

$$\vec{S} \cdot (\vec{P}_h \times \vec{k}) \propto \sin\psi$$

$\boldsymbol{\psi}$: azimuthal angle between the upwards target spin direction and hadron production plane around the beam direction

For an ideal detector with full 2π coverage in ψ:

$$A_{UT}^{\sin\psi} = -\frac{\pi}{2} \cdot \frac{\int_0^\pi d\psi\, d\sigma_{UT}\, \sin\psi}{\int_0^\pi d\psi\, d\sigma_{UT}} = -\frac{\pi}{2} A_N$$



$$A_N \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$

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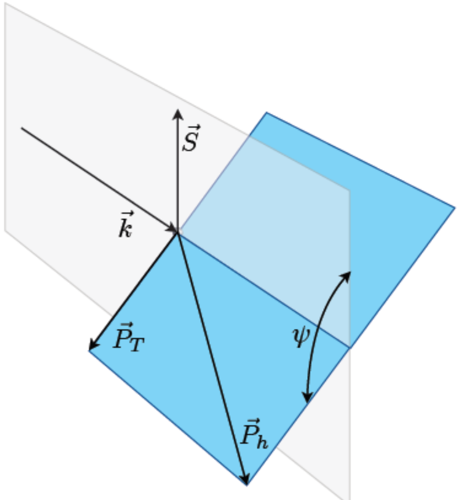

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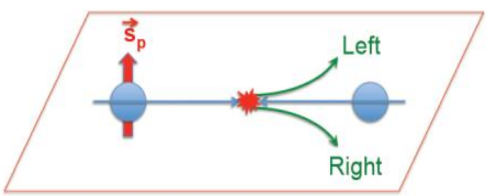

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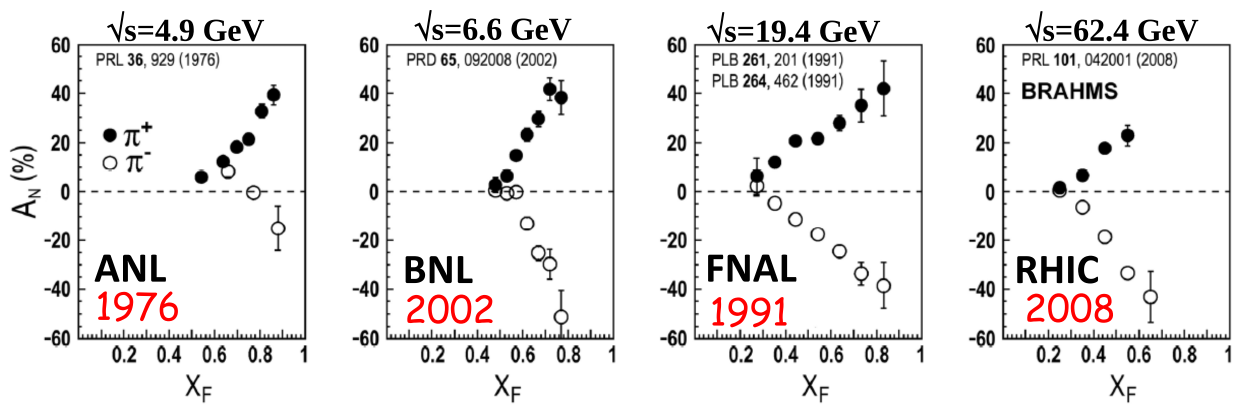
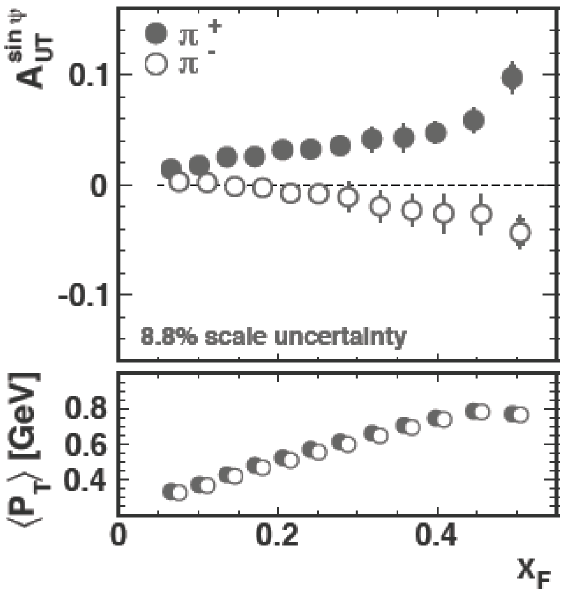


Polarized pp scattering experiments observe asymmetries up to 40%!

- **mirror symmetric for π^+ and π^- vs. x_F**
- **reproduced by various exp. over 35 years, persistent with energy ($\sqrt{s}$ from 5 to 200 GeV !)**
- **Cannot be interpreted using the standard leading-twist framework based on collinear factorization**

Inclusive hadrons results **In press on PLB!!!**

arXiv:1310.5070



π^+ amplitude rises linearly with x_F up to 10%

π^- is negative, similar trend, smaller (up to 4%)

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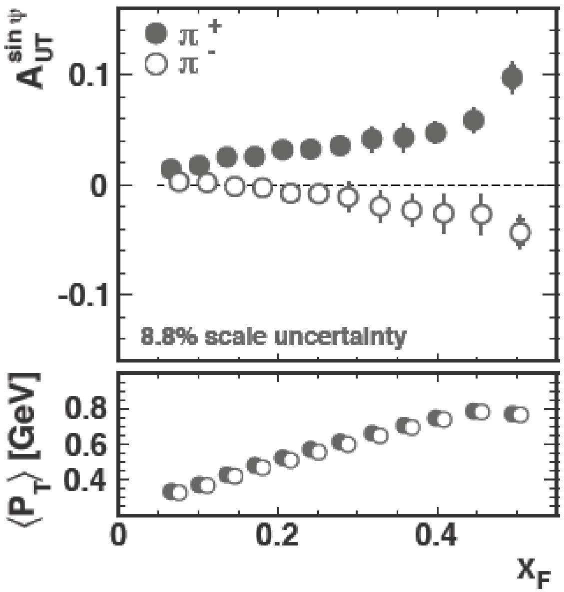

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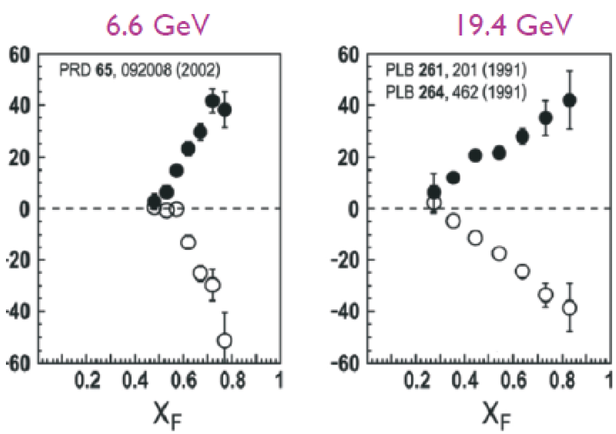
General trend very similar to A_N in $pp^\uparrow$ hard scattering



- A_N in $p^\uparrow p$ scattering is much larger and mirror symmetric for π^+ and π^-
- u-quark dominance in $ep^\uparrow$ scattering can explain the relatively smaller size for π^-

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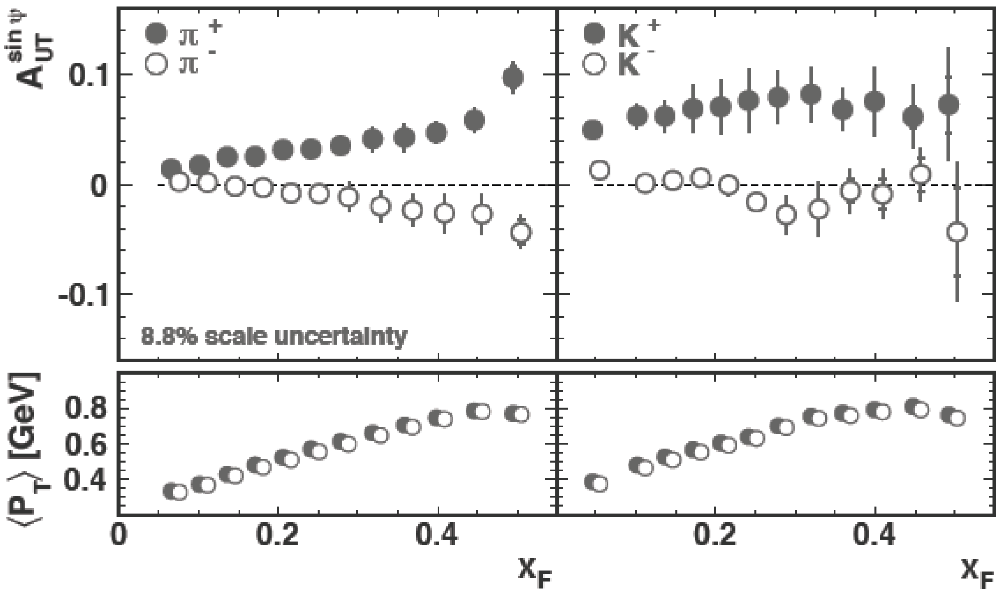


π^+ amplitude rises linearly with x_F up to 10%

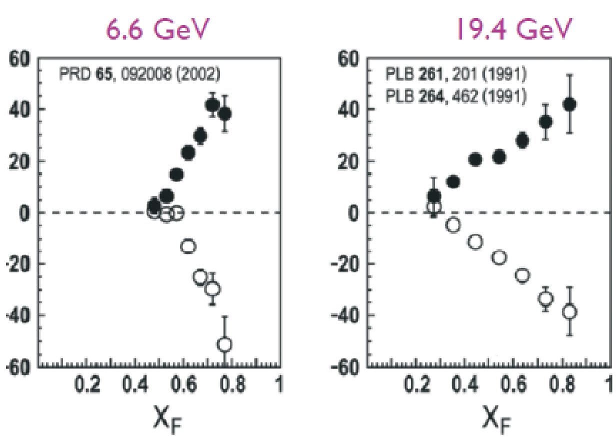
π^- is negative, similar trend, smaller (up to 4%)

K^+ is about constant around 7%

$K^- \approx 0$

Again kaon behave differently than pions!

General trend very similar to A_N in $pp^{\uparrow}$ hard scattering



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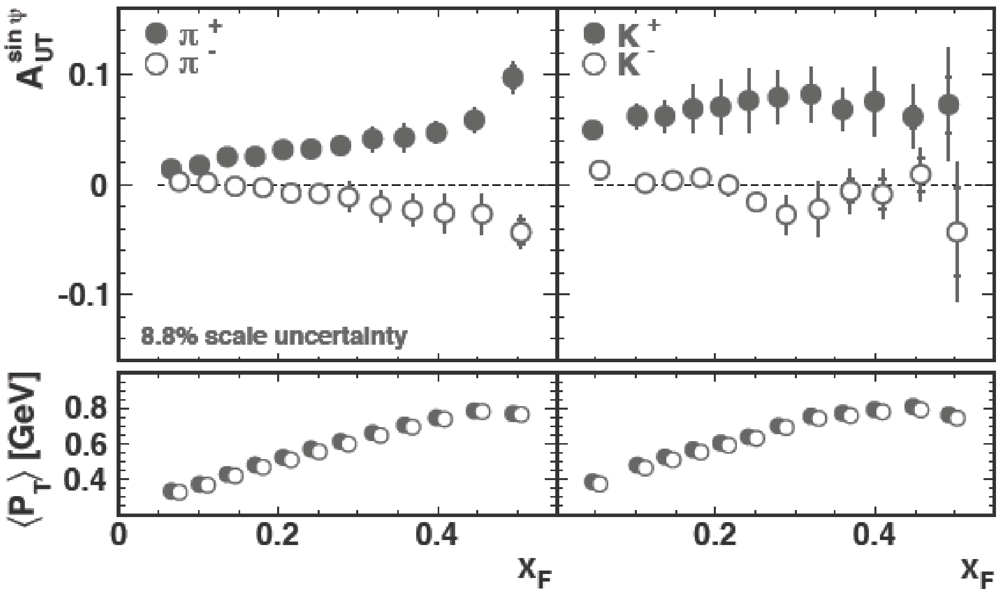

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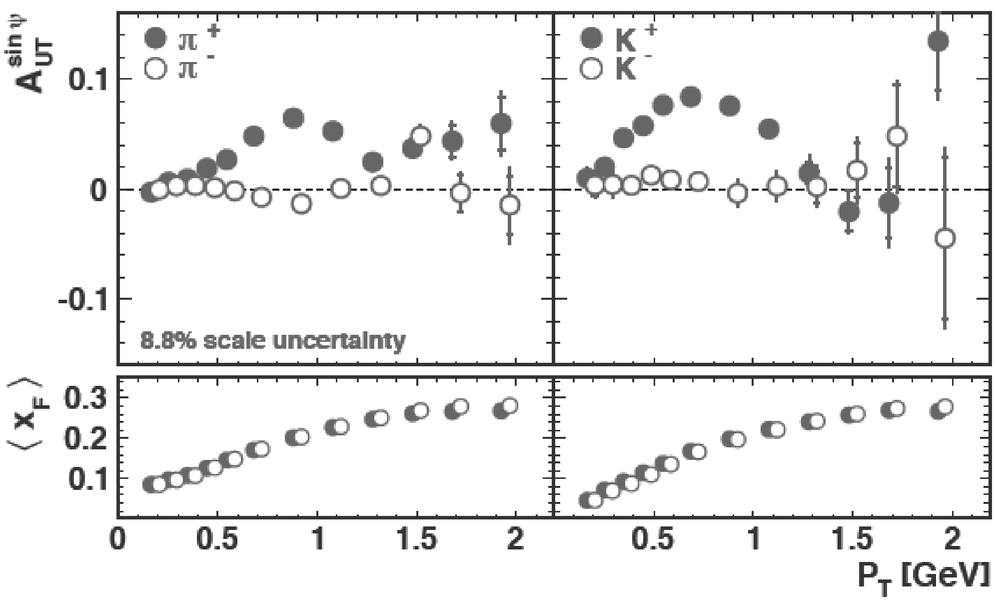

π^+ and K^+ amplitudes rise linearly up to $P_T \approx 0.8\ GeV$ then decrease with increasing P_T

π^+ also show a clear rise above $P_T \approx 1.3\ GeV$

Amplitudes of negative mesons are much smaller apart for a π^- point at $P_T \approx 1.5\ GeV$

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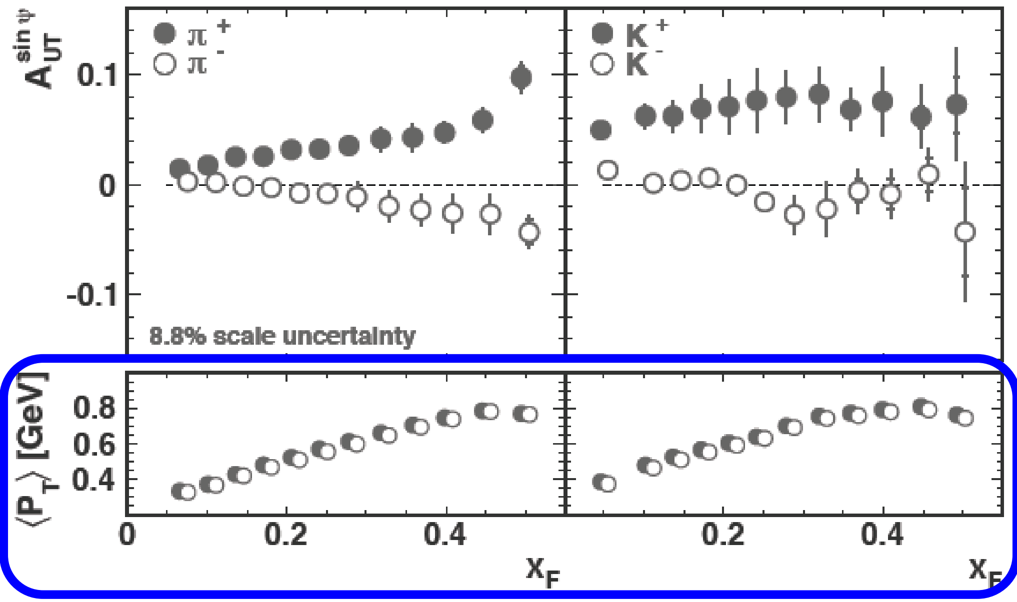

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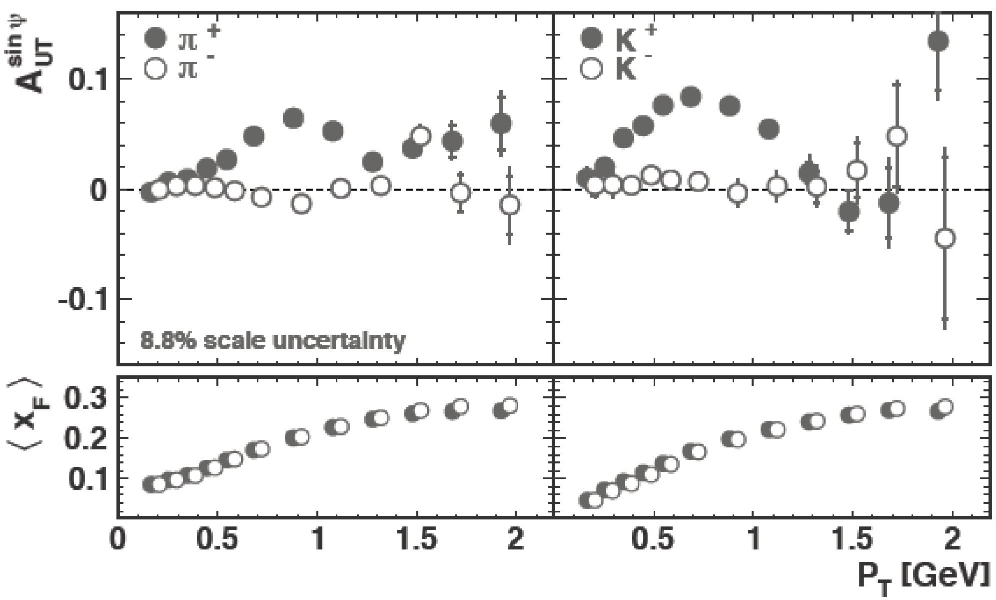
Again kaon behave differently than pions!

x_F and P_T strongly correlated.
Important to look at **2D extractions**



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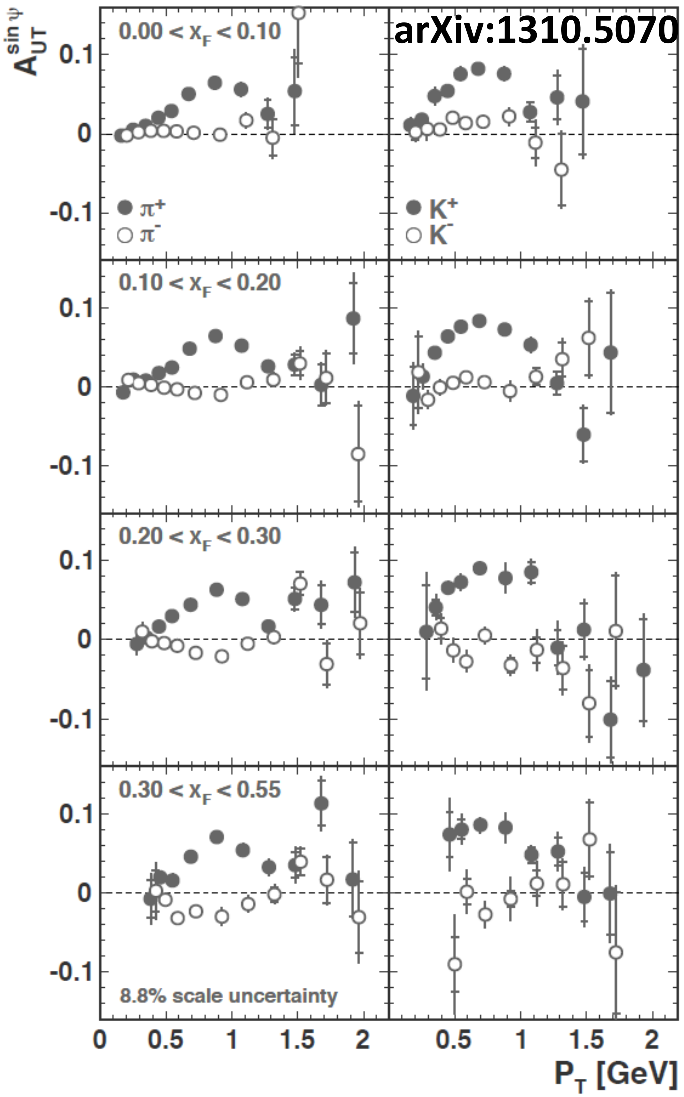

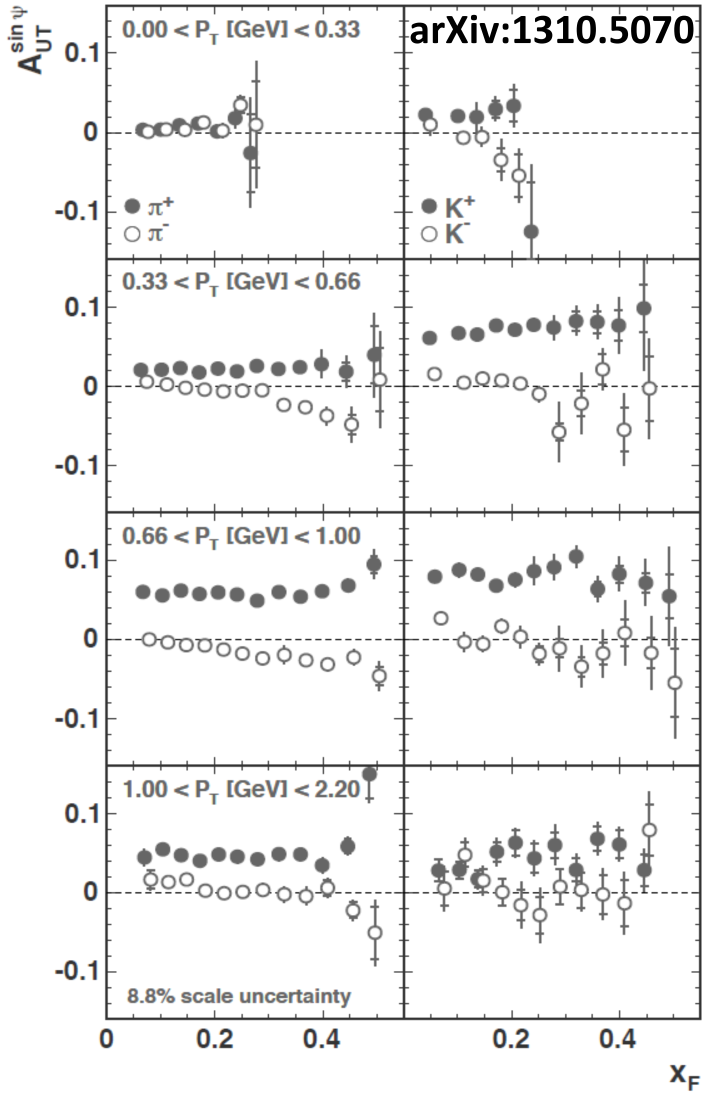

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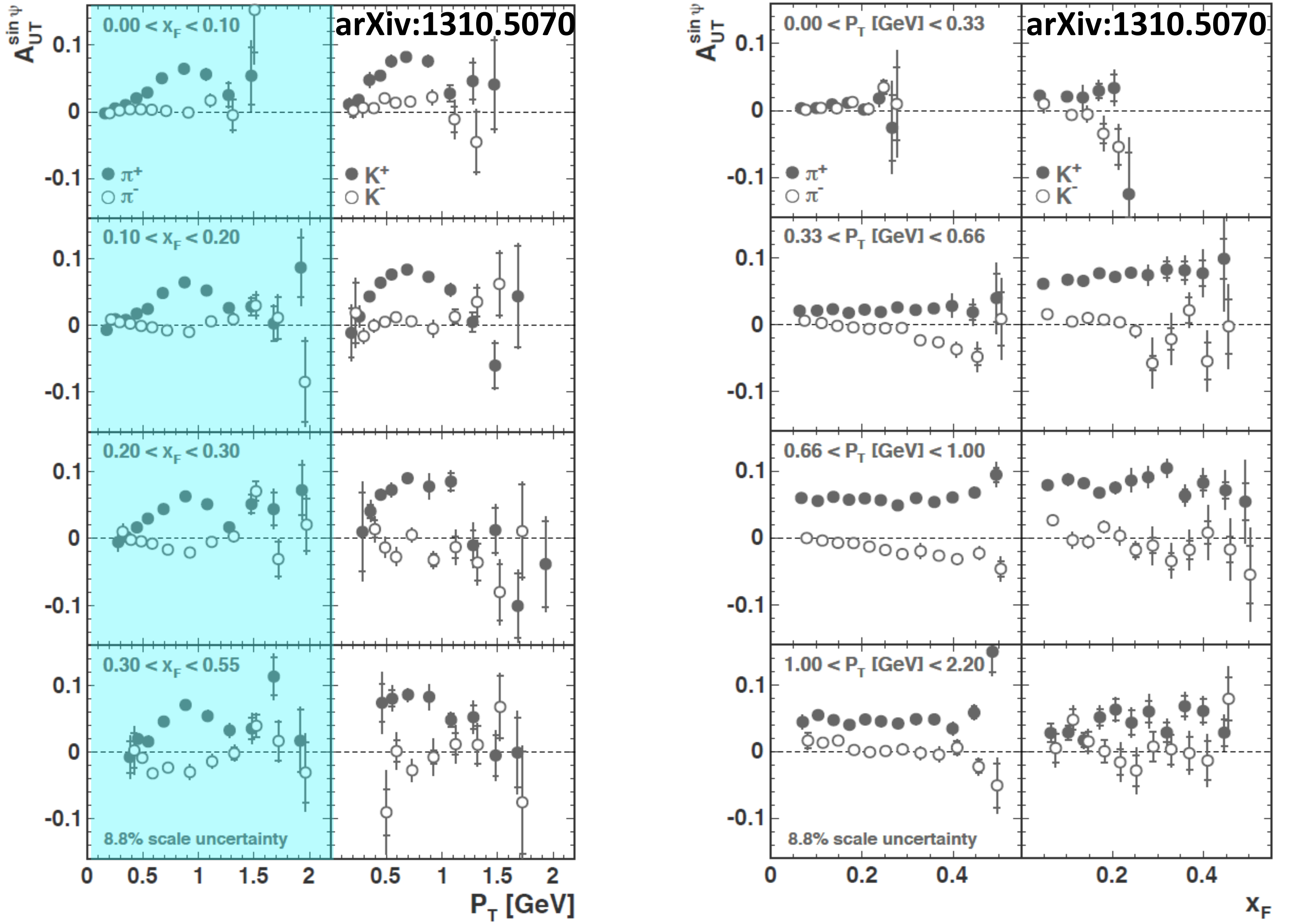

- π^+ amplitudes vs. P_T are basically the same in all x_F bins $\rightarrow$ apparent increase in magnitude vs. x_F in 1D projections is a reflection of underlying dependence on P_T
- π^- amplitudes vs. P_T are vanishing at low x_F and become negative at high x_F

Interpretation

- The inclusive hadron electroproduction data set is a **mixture of various contributions** with different kinematic dependences ⇒ difficult to draw conclusions on the underlying physics from the observed kinematic dependences

- More insight may be gained by studying separately the asymmetries for different subsamples

Inclusive hadron production
(all events)

↓

Quasi-real photoproduction
($Q^2 \approx 0$)

events without scattered lepton in acceptance (**"anti-tagged"**)

DIS $0.2 < z < 0.7$
(SIDIS)

DIS $z > 0.7$
(Exclusive)

identified lepton

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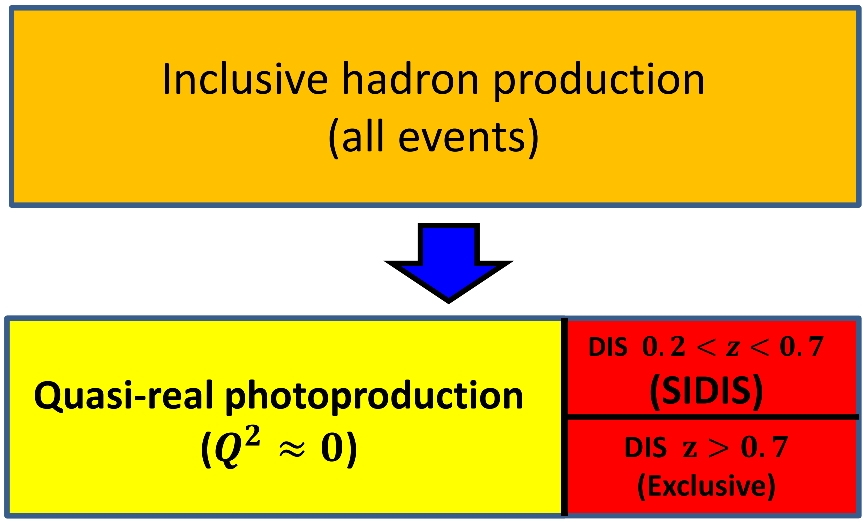

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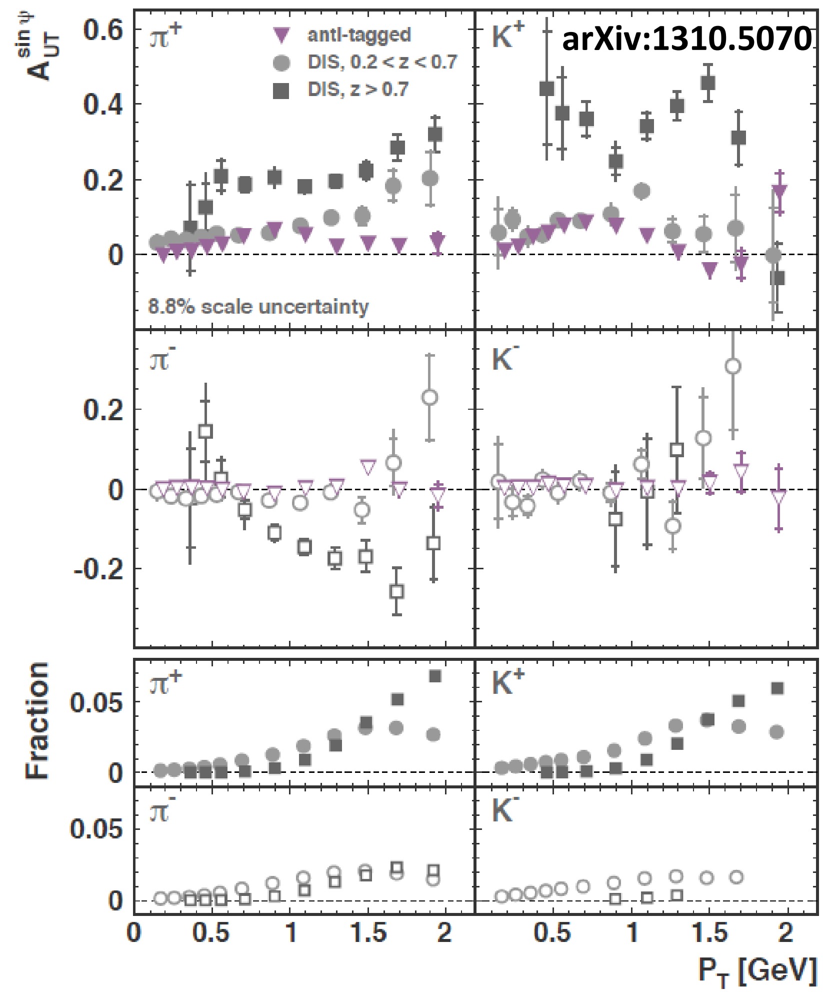

Anti-tagged:

- About 98% of total statistics → asymmetries vs. P_T essentially identical to inclusive amplitudes at low-to-intermediate P_T.
- For $P_T > 1.3\ GeV$ they differ due to the contributions from the other subsamples to the full inclusive sample

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- π^+/π^- amplitudes larger than inclusive amplitudes in full P_T range and rise linearly with P_T (up to 20% for π^+)
- In this regime $Q^2 > {P_T}^2$ and TMDs can contribute without P_T-suppression
- Since ψ **and** $\phi - \phi_S$ **are very closely related** the observed P_T dependence might arise from the **Sivers effect**

Quasi-real photoproduction ($Q^2 \approx 0$)	**DIS $0.2 < z < 0.7$ (SIDIS)**
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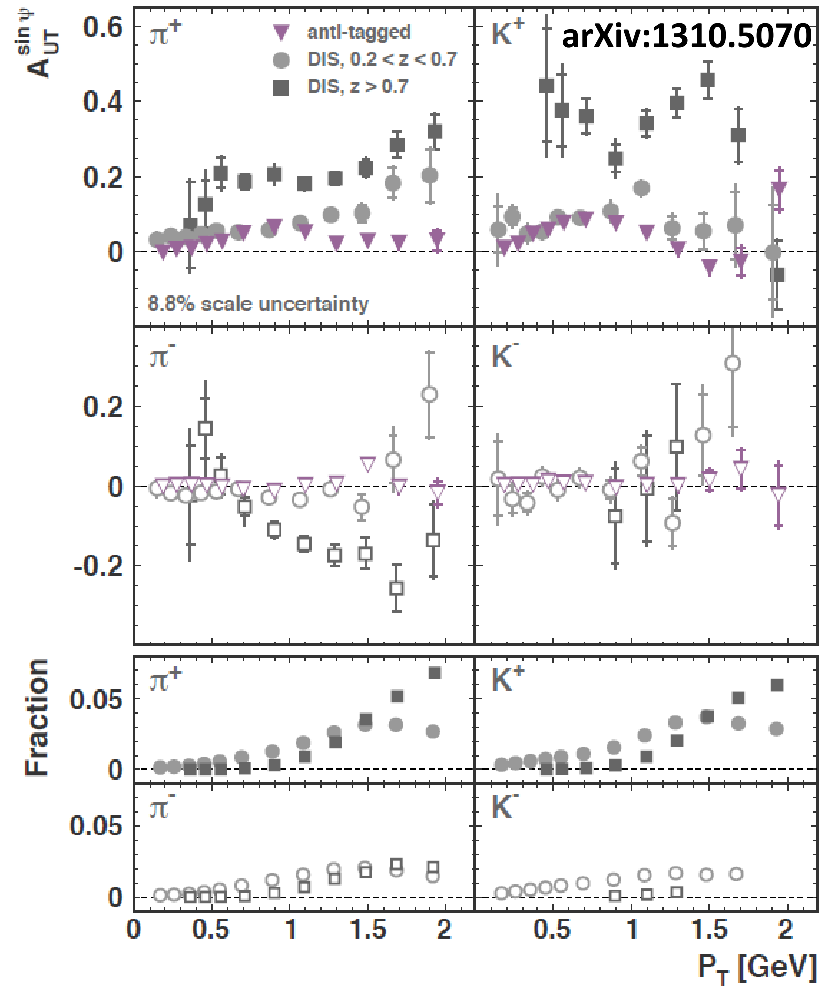

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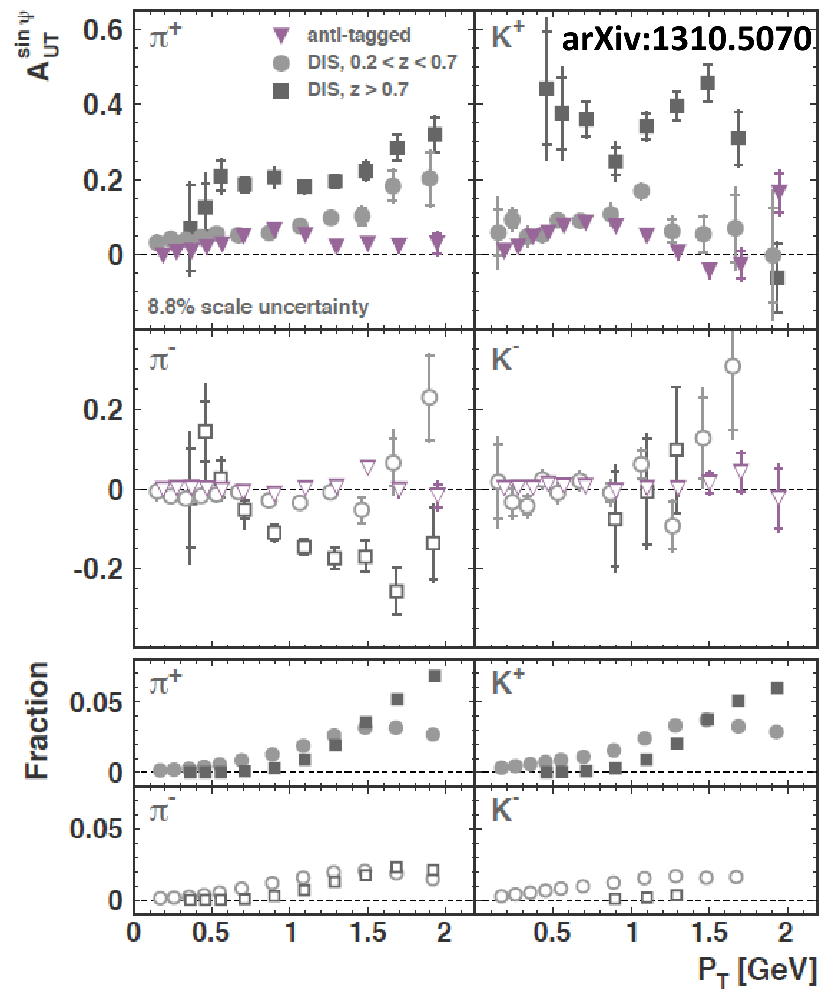
DIS $z > 0.7$ (Exclusive):

- Very large asymmetries observed for pions and especially K^+ (more than 40%!)
- Pions receive large contributions from decays of exclusive ρ
- π^- large amplitude may come from **d-quark Sivers function in conjunction with favored fragmentation of the struck (down) quark**



Quasi-real photoproduction ($Q^2 \approx 0$)	DIS $0.2 < z < 0.7$ (SIDIS)
	DIS $z > 0.7$ (Exclusive)
events without scattered lepton in acceptance (**"anti-tagged"**)	**identified lepton**

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Conclusions

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Flavor sensitivity ensured by the excellent hadron ID revealed interesting facets of data

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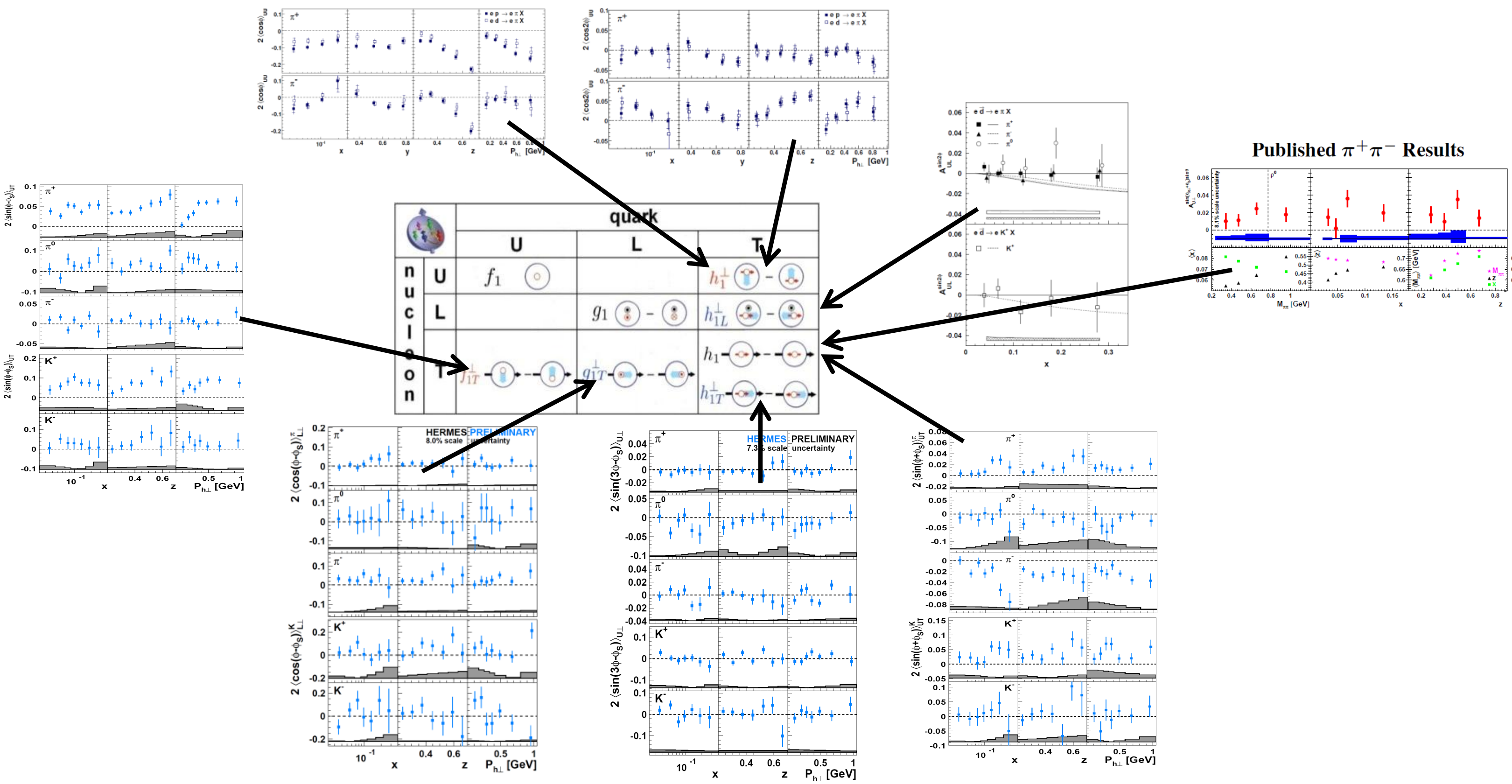

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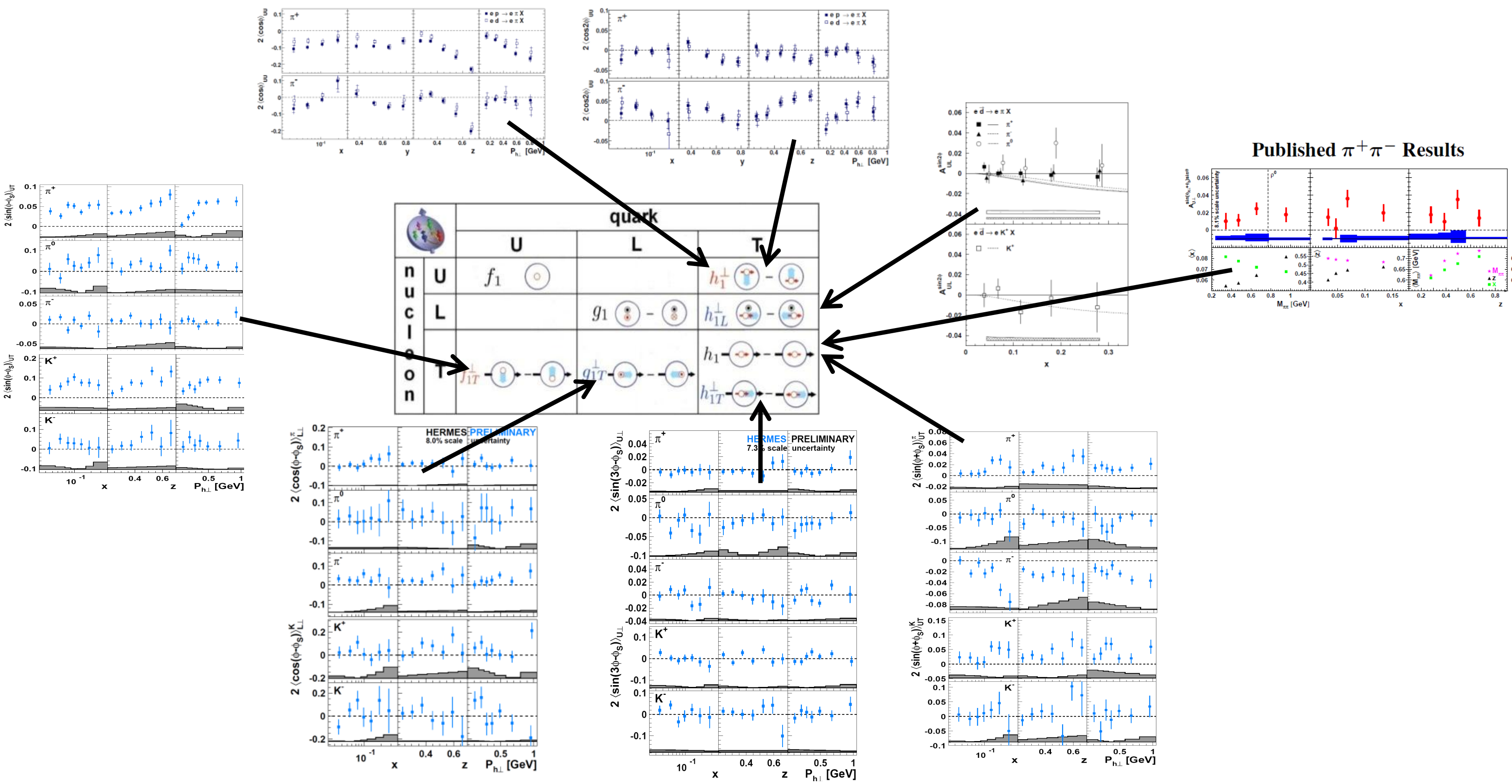

HERMES results in inclusive hadron electroproduction reveal interesting features in common with A_N in $pp^{\uparrow}$ scattering and with Sivers effect in SIDIS.

A rich phenomenology is revealed when the various subsamples are analyzed separately

Back-up

Selected results (4)

Higher-twist

The higher-twist $F_{LU}^{\sin\phi}$ term

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

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

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

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

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

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

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

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

Sensitive to f_1 , Boer-Mulders + higher-twist DF and FF

$$\propto +\frac{1}{Q}\left[e\otimes H_1^\perp + \boldsymbol{f_1}\otimes\tilde{G}^\perp + g^\perp\otimes D_1 + \boldsymbol{h_1}^\perp\otimes\tilde{E}\right]$$

The $F_{LU}^{\sin\phi}$ term

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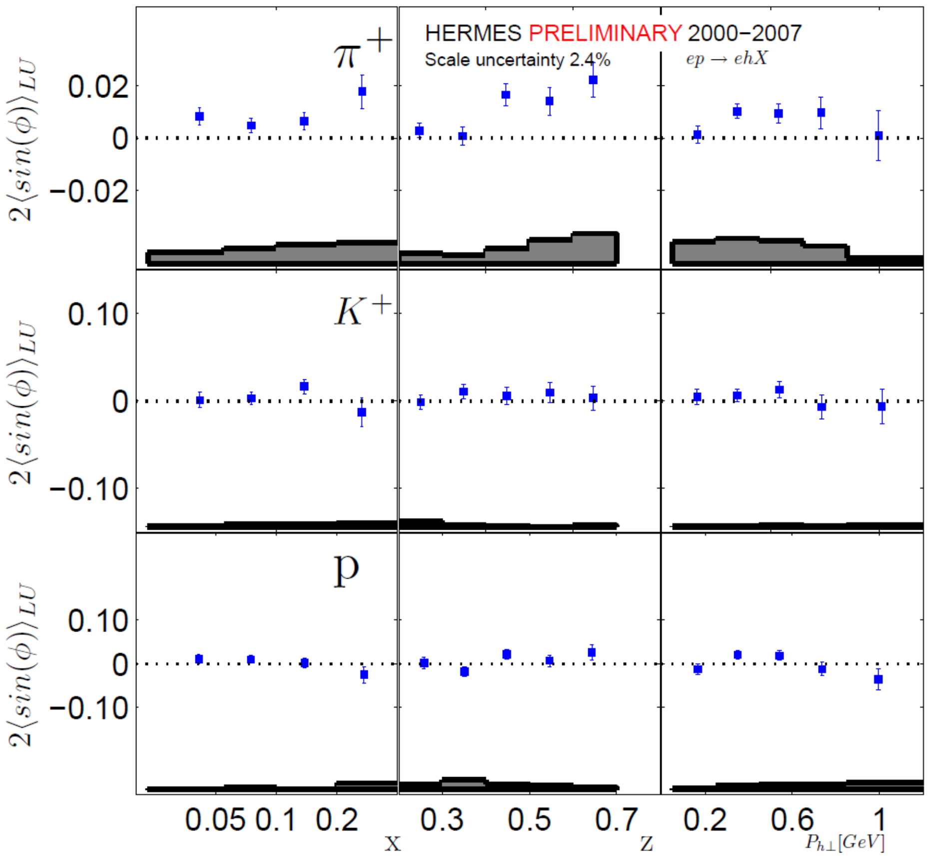
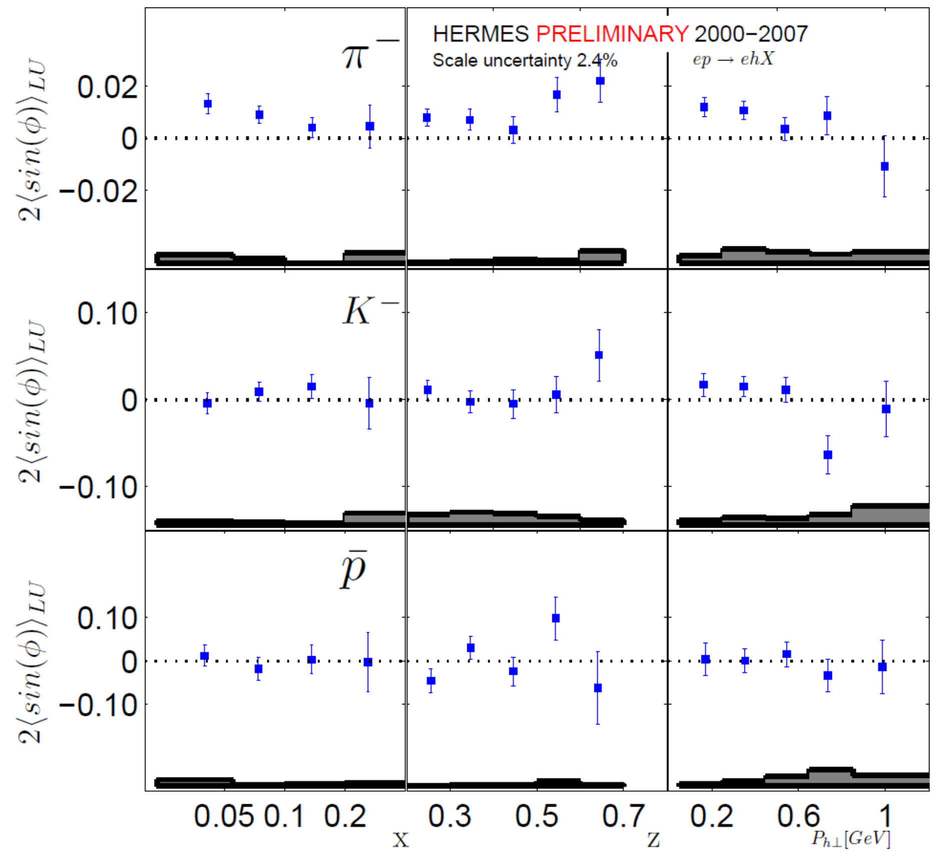
	U	L	T
U	f_1		$h_1^{\perp}$
L			
T			

H target, 2000-2007 data 0.2<z<0.7





Amplitudes are positive for pions and consistent with zero for kaons and protons

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	U	L	T
U	f_1		$h_1^{\perp}$
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T			

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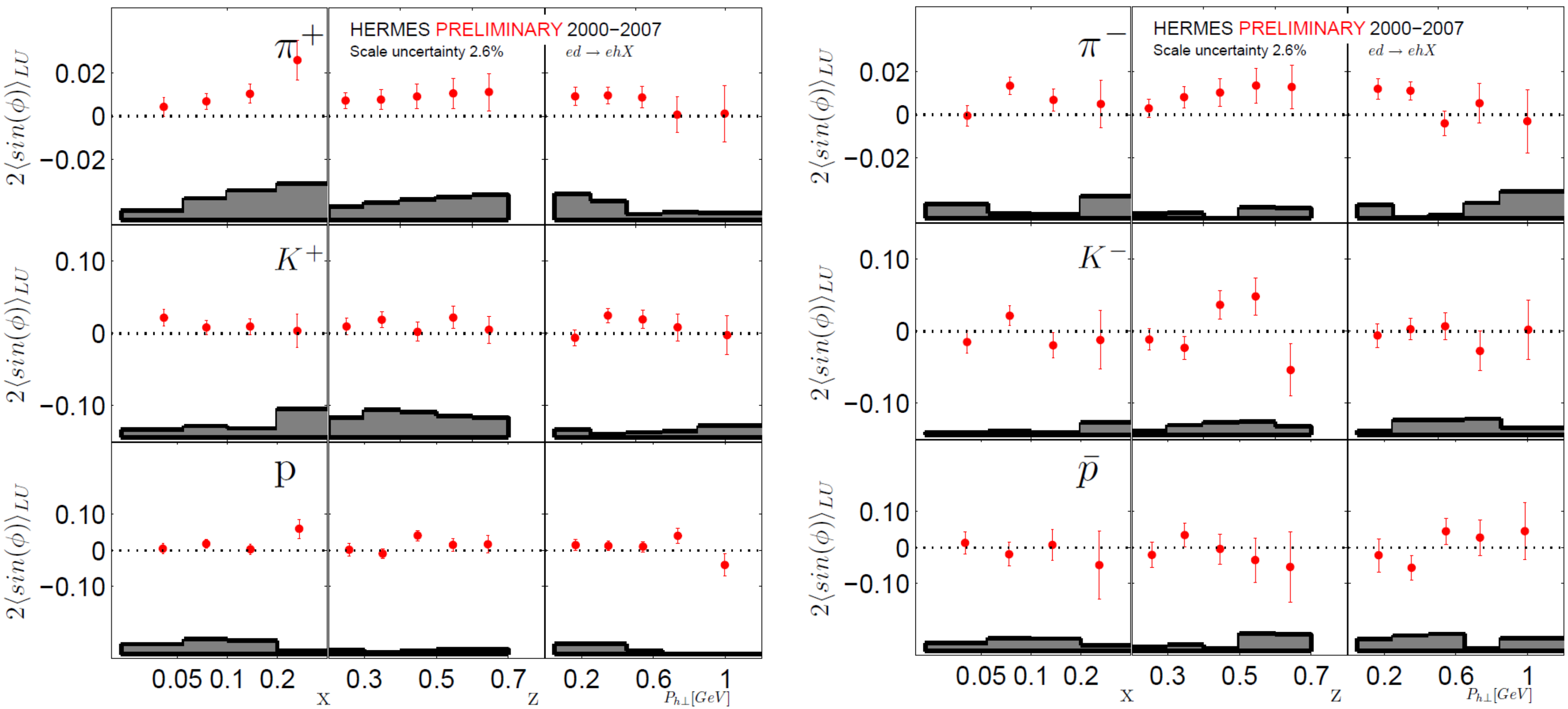

Amplitudes are positive for pions and consistent with zero for kaons and protons
Deuterium target: same features, less statistics

The higher-twist $F_{UT}^{\sin\phi_S}$ term

	U	L	T
U			
L			
T	$f_{1T}^{\perp}$	g_{1T}	$h_1,$

Sensitive to transversity, Sivers, g_{1T} + higher-twist DF and FF

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

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$$\propto +\frac{1}{Q}\Big[f_T \otimes D_1 - \boldsymbol{h_1} \otimes \tilde{H} - h_T^{\perp} \otimes H_1^{\perp} + \boldsymbol{f_{1T}^{\perp}} \otimes D^{\perp} - h_T \otimes H_1^{\perp} - \boldsymbol{g_{1T}} \otimes \tilde{G}^{\perp}\Big]$$

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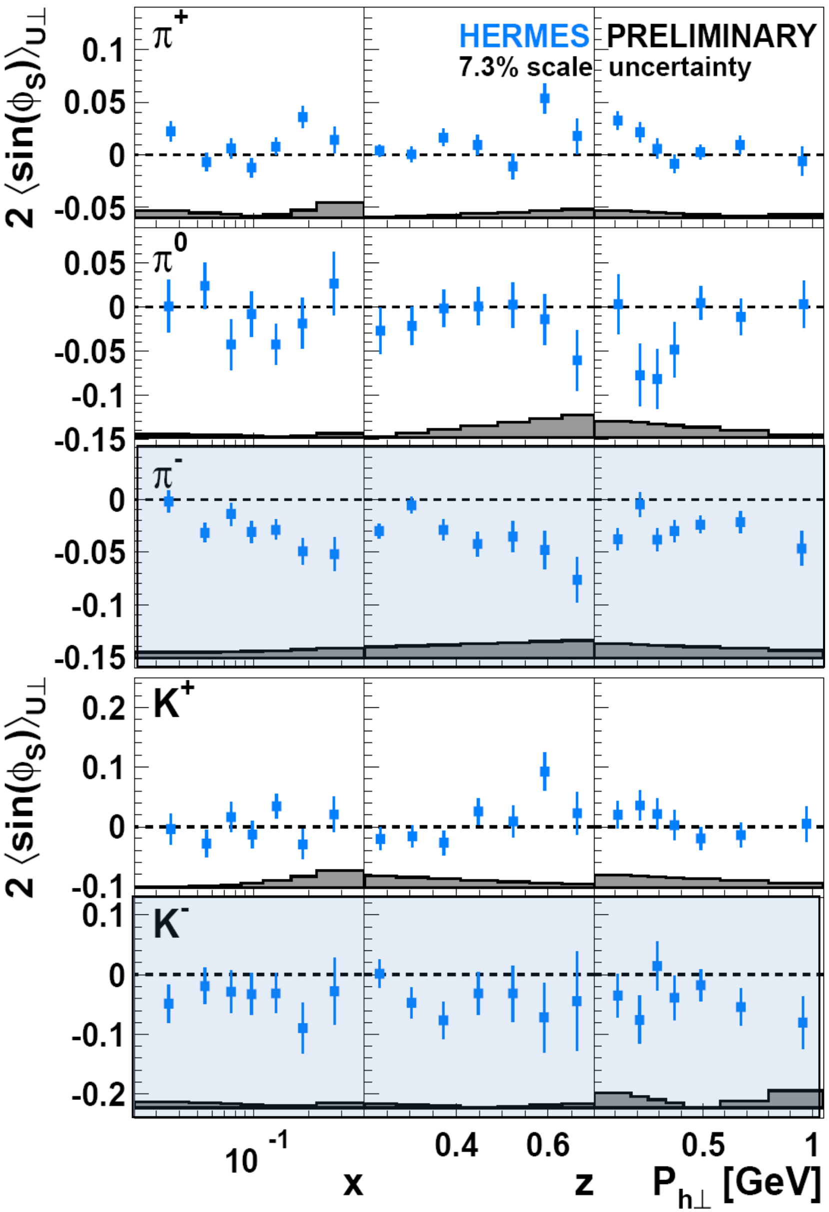
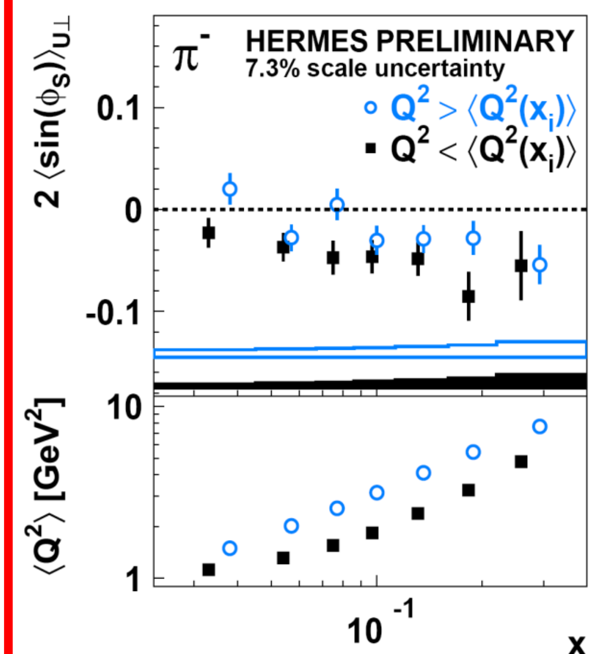
	U	L	T
U			
L			
T	$f_{1T}^{\perp}$	g_{1T}	$h_1,$



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

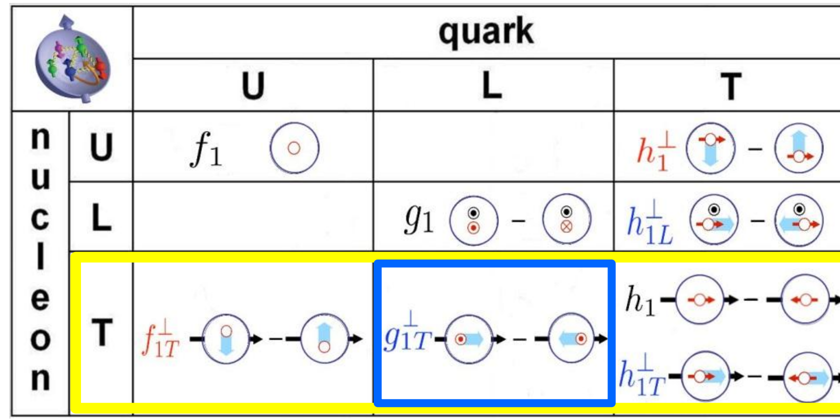
Large and negative

negative

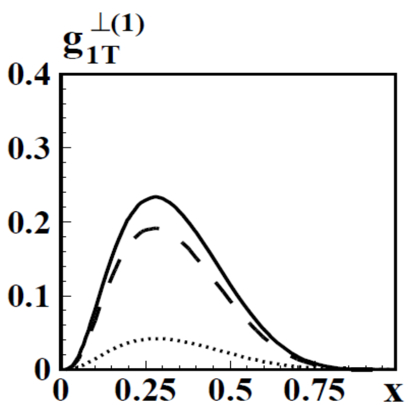


- low-Q^2 amplitude larger
- hint of Q^2 dependence for π^-

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

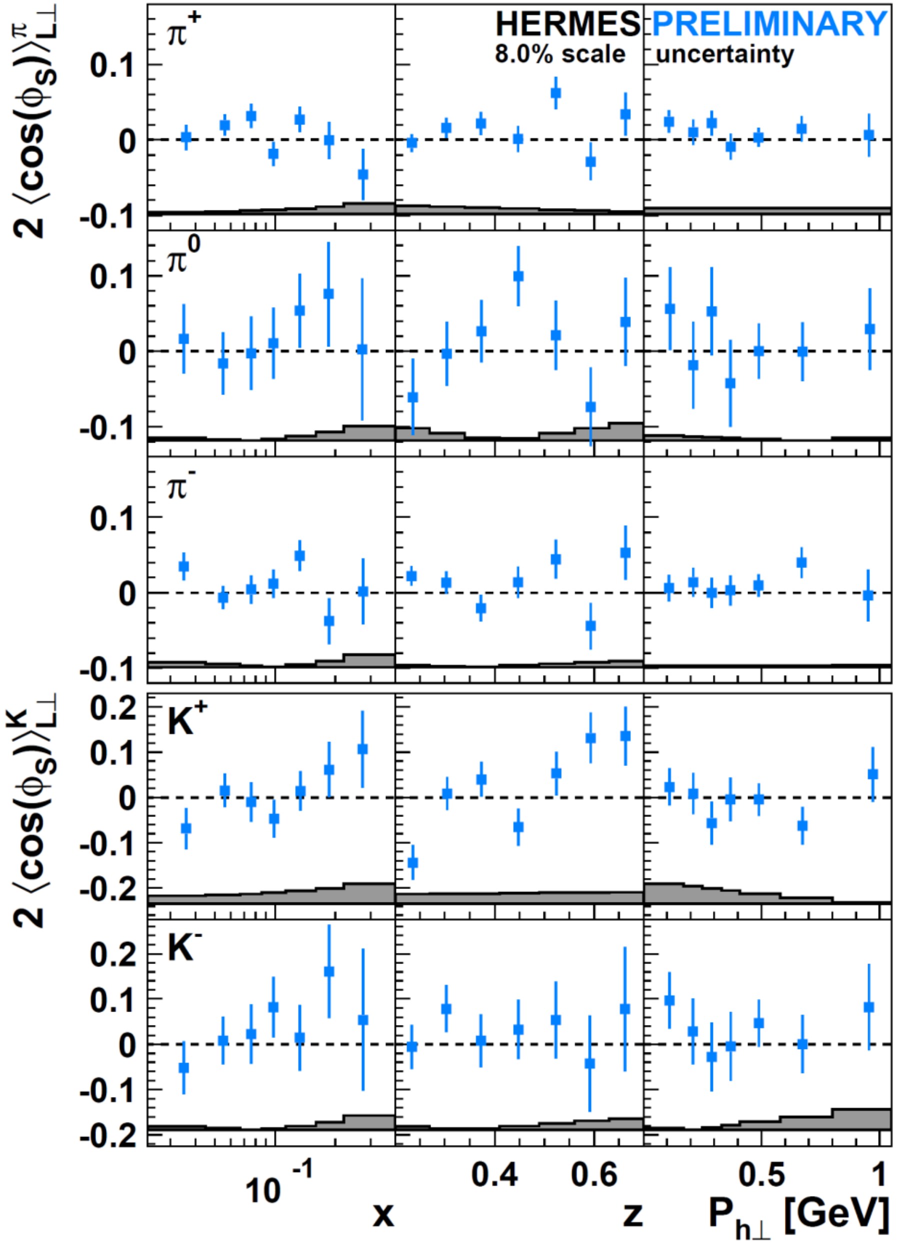
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\, g_{1T} D_1\right]$$

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

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

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

The cos(ϕ_S) Fourier component



≈ 0

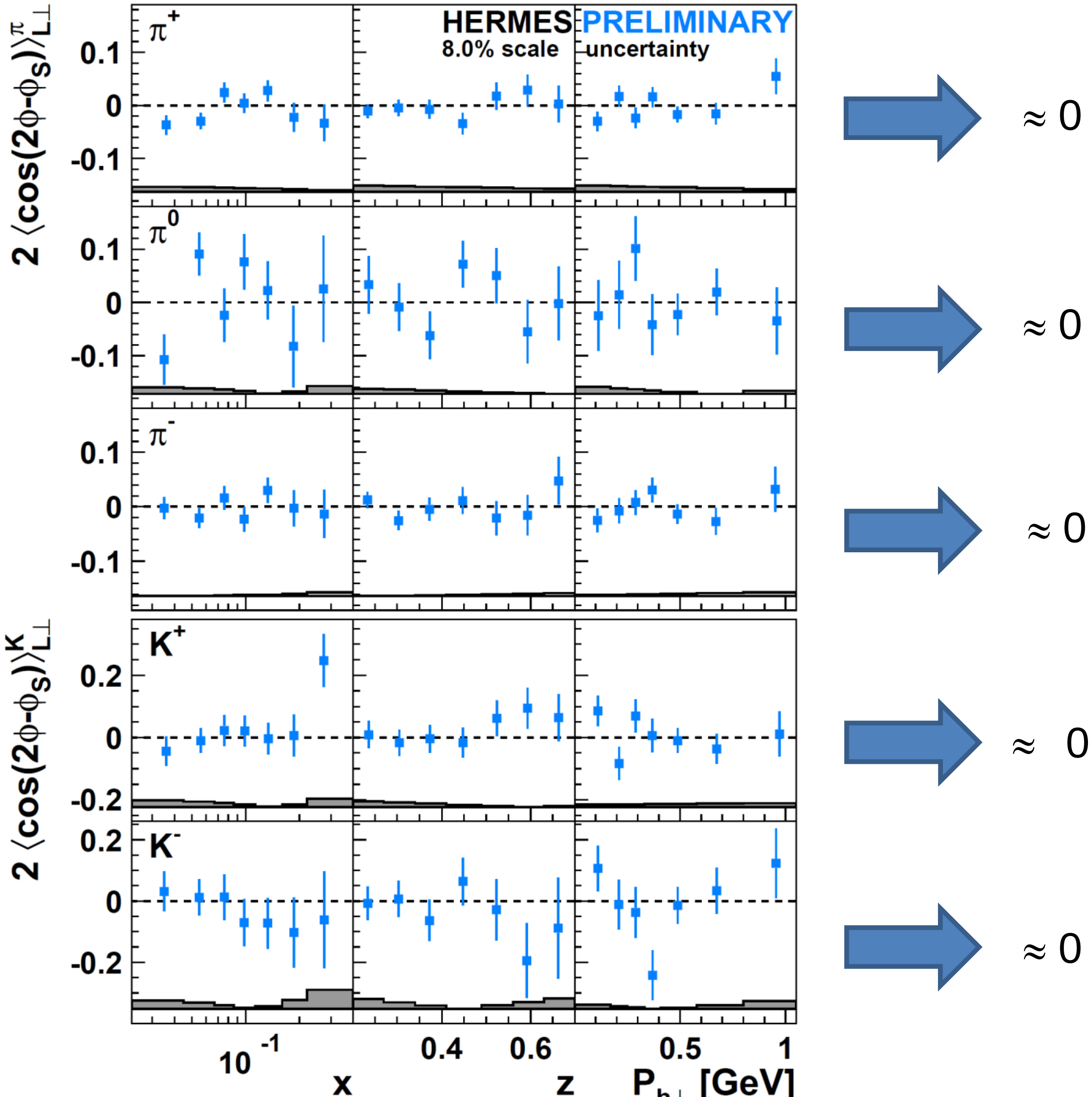
≈ 0

≈ 0

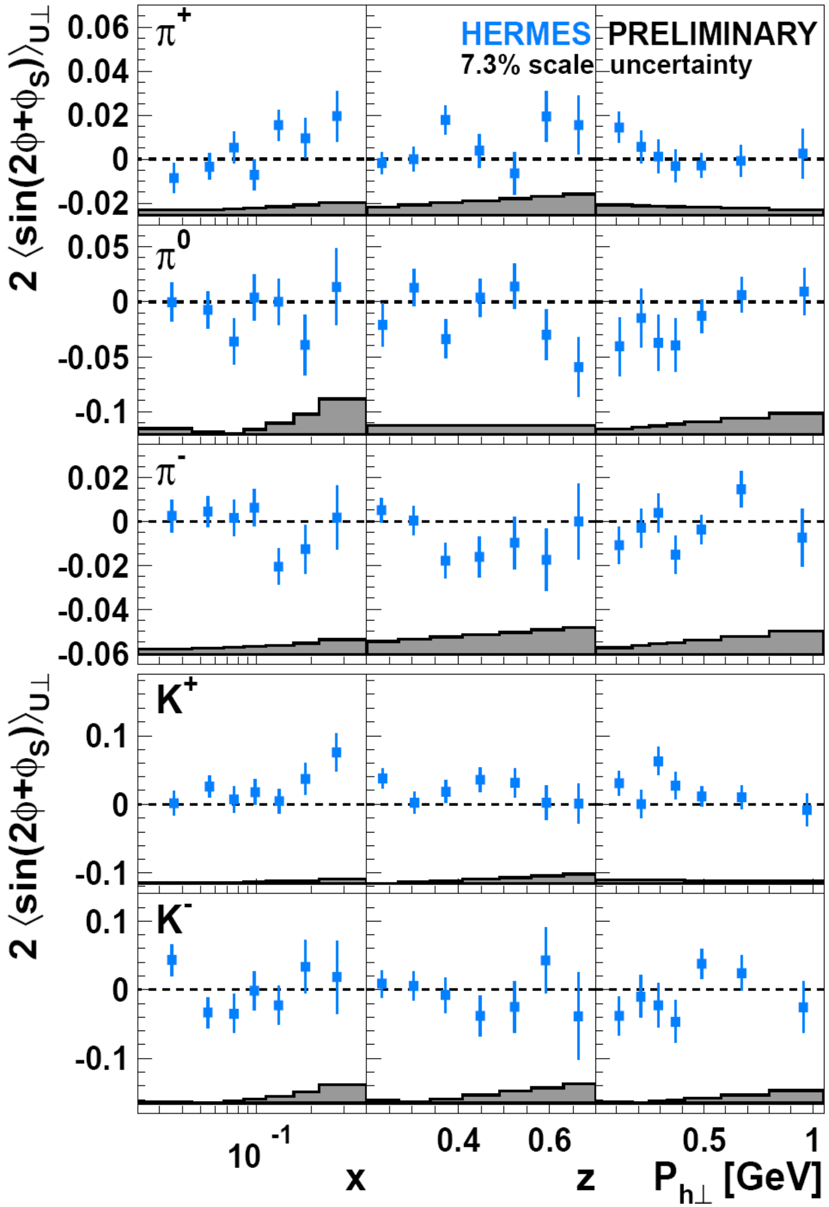
$\approx$ 0
sign change?

≈ 0

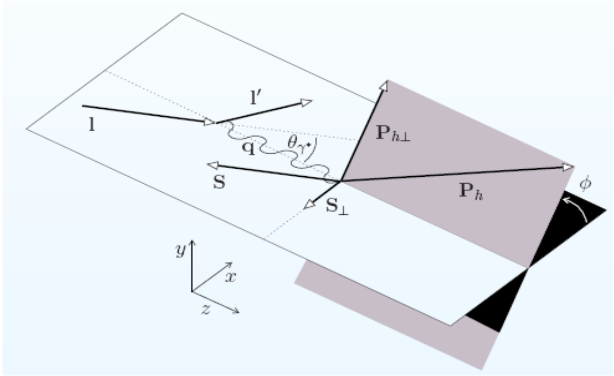
The cos(2ϕ-ϕ$_S$) Fourier component



The sin(2φ+φ$_S$) Fourier component



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

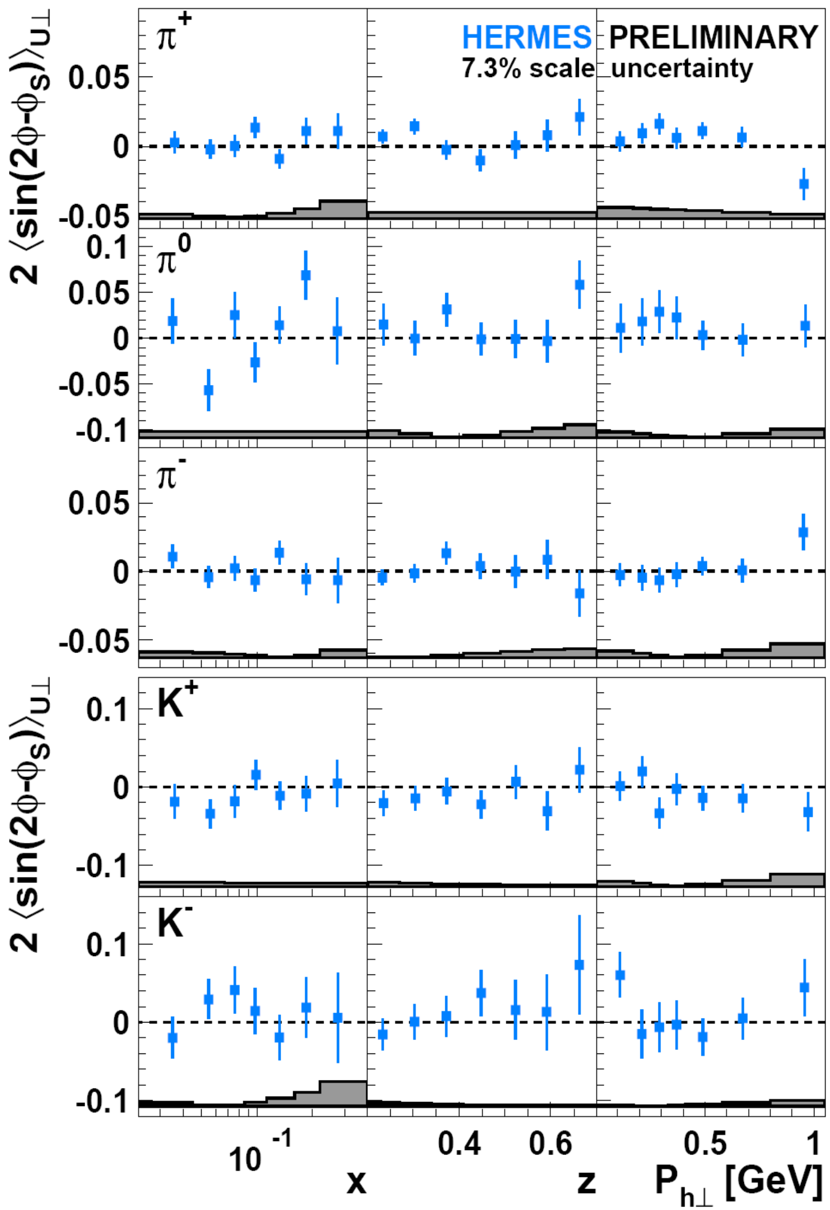


- related to <sin(2φ)>$_{UL}$ Fourier comp:

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

- *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+)**

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**

2-hadron SIDIS results

Following formalism developed by **Steve Gliske**

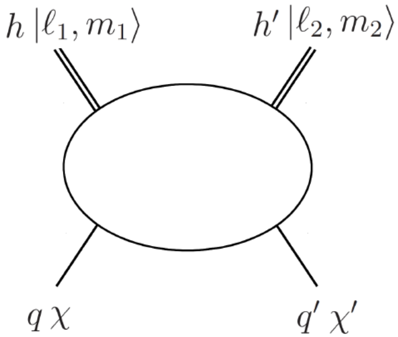
Find details in

Transverse Target Moments of Dihadron Production in Semi-inclusive Deep Inelastic Scattering at HERMES
S. Gliske, PhD thesis, University of Michigan, 2011

http://www-personal.umich.edu/~lorenzon/research/HERMES/PHDs/Gliske-PhD.pdf

A short digression on di-hadron fragmentation functions

Standard definition of di-hadron FF assume no polarization of final state hadrons (pseudo-scalar mesons) or define mixtures of certain partial waves as new FFs



In the **new formalism there are only two di-hadron FFs**. Names and symbols are entirely associated with the quark spin, whereas the partial waves of the produced hadrons ($|l_1 m_1\rangle, |l_2 m_2\rangle$) are associated with partial waves of FFs.

$$\chi = \chi' \Longrightarrow D_1 = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta) e^{im(\phi_R - \phi_k)} D_1^{|\ell,m\rangle}(z, M_h, |\boldsymbol{k}_T|)$$

$$\chi \neq \chi' \Longrightarrow H_1^{\perp} = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta) e^{im(\phi_R - \phi_k)} H_1^{\perp|\ell,m\rangle}(z, M_h, |\boldsymbol{k}_T|)$$

The cross-section is identical to the ones in literature, the only difference is the interpretation of the FFs:

$$D_1^{|0,0\rangle} = D_{1,OO} = \left(\frac{1}{4} D_{1,OO}^{s} + \frac{3}{4} D_{1,OO}^{p}\right)$$

$$D_1^{|1,0\rangle} = D_{1,OL},$$

$$D_1^{|1,\pm1\rangle} = D_{1,OT} \mp \frac{|\boldsymbol{k}_T|\,|\boldsymbol{R}|}{M_h^2} G_{1,OT}^{\perp},$$

$$D_1^{|2,0\rangle} = \frac{1}{2} D_{1,LL},$$

$$D_1^{|2,\pm1\rangle} = \frac{1}{2}\left(D_{1,LT} \mp \frac{|\boldsymbol{k}_T|\,|\boldsymbol{R}|}{M_h^2} G_{1,LT}^{\perp}\right),$$

$$D_1^{|2,\pm2\rangle} = D_{1,TT} \mp \frac{1}{2}\frac{|\boldsymbol{k}_T|\,|\boldsymbol{R}|}{M_h^2} G_{1,TT}^{\perp},$$

$$H_1^{\perp|0,0\rangle} = H_{1,OO}^{\perp} = \frac{1}{4} H_{1,OO}^{\perp s} + \frac{3}{4} H_{1,OO}^{\perp p},$$

$$H_1^{\perp|1,1\rangle} = H_{1,OT}^{\perp} + \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} \bar{H}_{1,OT}^{\sphericalangle} = \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} H_{1,OT}^{\sphericalangle}$$

$$H_1^{\perp|1,0\rangle} = H_{1,OL}^{\perp}$$

$$H_1^{\perp|1,-1\rangle} = H_{1,OT}^{\perp}$$

$$H_1^{\perp|2,2\rangle} = H_{1,TT}^{\perp} + \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} \bar{H}_{1,TT}^{\sphericalangle} = \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} H_{1,TT}^{\sphericalangle},$$

$$H_1^{\perp|2,1\rangle} = \frac{1}{2} H_{1,LT}^{\perp} + \frac{1}{2}\frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} \bar{H}_{1,LT}^{\sphericalangle} = \frac{1}{2}\frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} H_{1,LT}^{\sphericalangle},$$

$$H_1^{\perp|2,0\rangle} = \frac{1}{2} H_{1,LL}^{\perp},$$

$$H_1^{\perp|2,-1\rangle} = \frac{1}{2} H_{1,LT}^{\perp},$$

$$H_1^{\perp|2,-2\rangle} = H_{1,TT}^{\perp}.$$

The di-hadron SIDIS cross-section

$$
\begin{aligned}
d\sigma_{UT} &= \frac{\alpha^2 M_h P_{h\perp}}{2\pi x y Q^2}\left(1+\frac{\gamma^2}{2x}\right)|\boldsymbol{S}_\perp| \\
&\times \sum_{\ell=0}^{2}\sum_{m=-\ell}^{\ell}\Bigg\{ A(x,y)\Big[P_{\ell,m}\sin((m+1)\phi_h - m\phi_R - \phi_S)) \\
&\qquad \times \left(F_{UT,T}^{P_{\ell,m}\sin((m+1)\phi_h-m\phi_R-\phi_S)} + \epsilon F_{UT,L}^{P_{\ell,m}\sin((m+1)\phi_h-m\phi_R-\phi_S)}\right)\Big] \\
&\quad + B(x,y)\Big[P_{\ell,m}\sin((1-m)\phi_h + m\phi_R + \phi_S)F_{UT}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_R+\phi_S)} \\
&\qquad + P_{\ell,m}\sin((3-m)\phi_h + m\phi_R - \phi_S)F_{UT}^{P_{\ell,m}\sin((3-m)\phi_h+m\phi_R-\phi_S)}\Big] \\
&\quad + V(x,y)\Big[P_{\ell,m}\sin(-m\phi_h + m\phi_R + \phi_S)F_{UT}^{P_{\ell,m}\sin(-m\phi_h+m\phi_R+\phi_S)} \\
&\qquad + P_{\ell,m}\sin((2-m)\phi_h + m\phi_R - \phi_S)F_{UT}^{P_{\ell,m}\sin((2-m)\phi_h+m\phi_R-\phi_S)}\Big]\Bigg\}.
\end{aligned}
$$

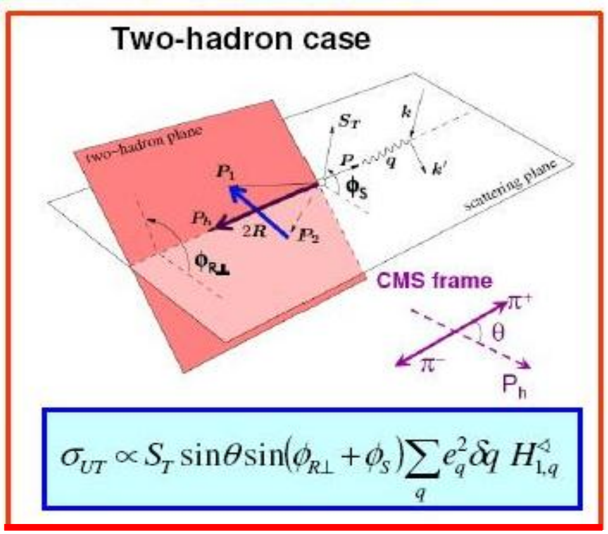
l and m correspond to $|lm\rangle$ angular momentum state of the hadron

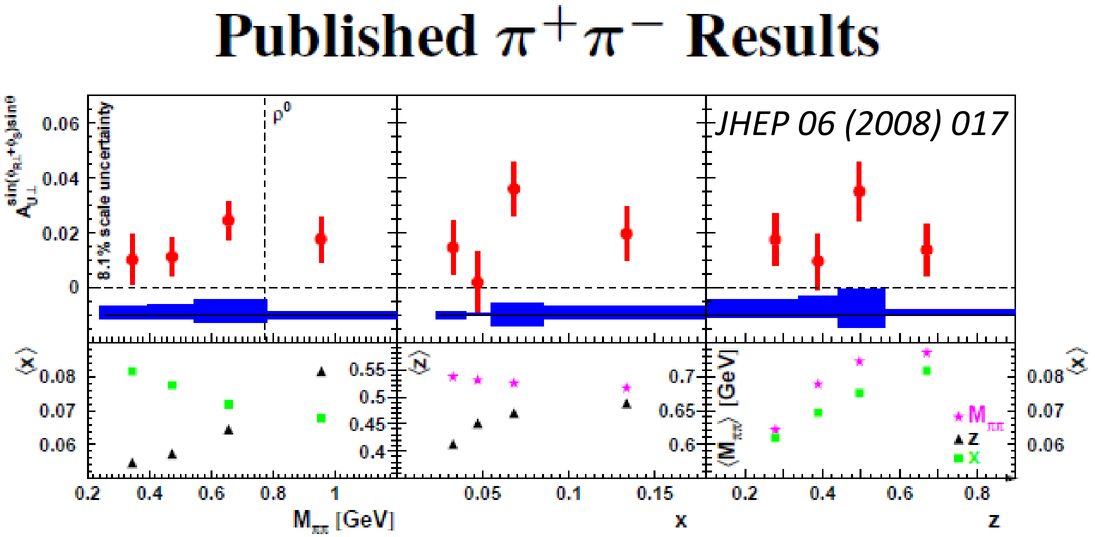
Considering all terms ($d\sigma_{UU}, d\sigma_{LU}, d\sigma_{UL}, d\sigma_{LL}, d\sigma_{UT}, d\sigma_{LT}$) there are **144 non-zero structure functions** at twist-3 level. The most known is

$$
F_{UT}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_R+\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{k}_T|}{M_h}\cos\left((m-1)\phi_h - \phi_p - m\phi_k\right)\, h_1 H_1^{\perp|\ell,m\rangle}\right]
$$

which for $l=1$ and $m=1$ reduces to the well known collinear $F_{UT}{}^{\sin\vartheta\,\sin(\phi_R+\phi_S)}$ related to transversity

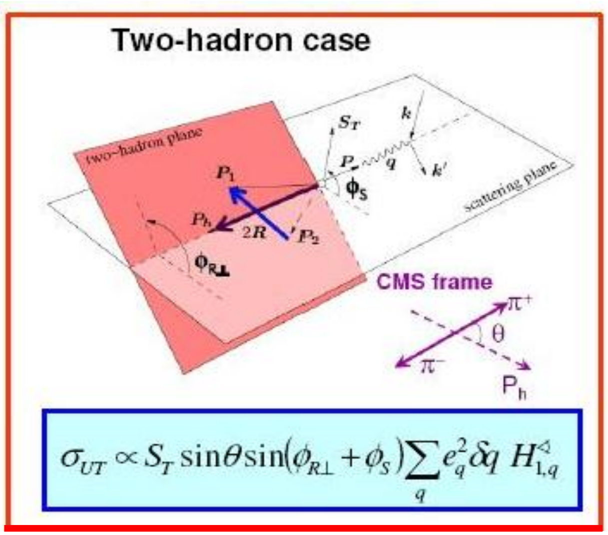
The di-hadron SIDIS cross-section



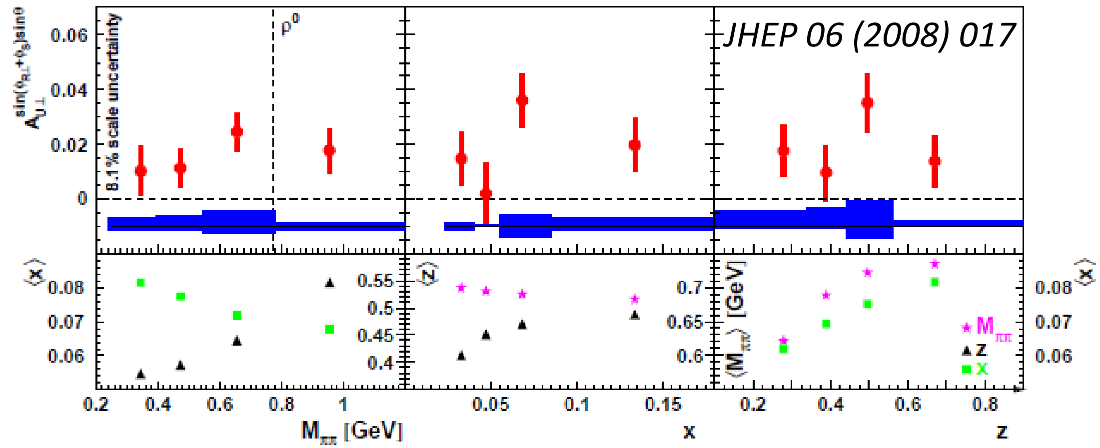


- independent way to access transversity
- Collinear $\rightarrow$ no convolution integral
- significantly positive amplitudes
- 1^{st} evidence of non zero dihadron FF
- limited statistical power (v.r.t. 1 hadron)

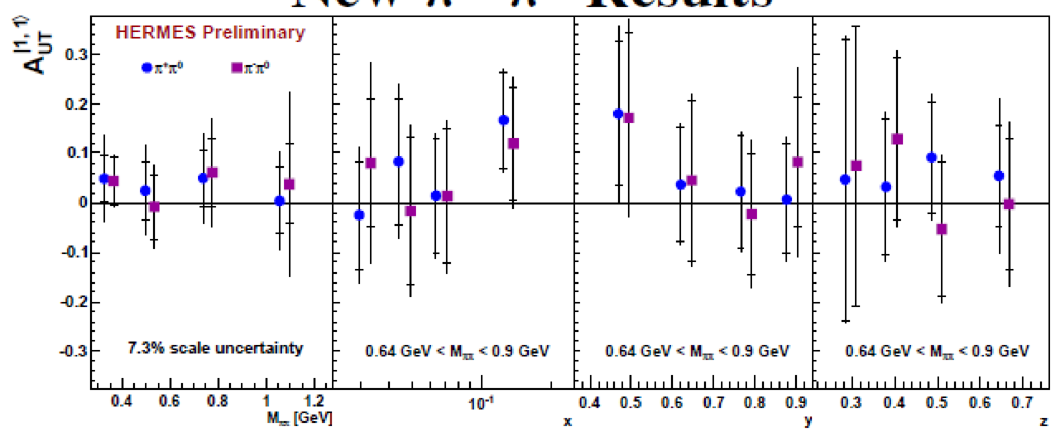
The di-hadron SIDIS cross-section



Published $\pi^+\pi^-$ Results



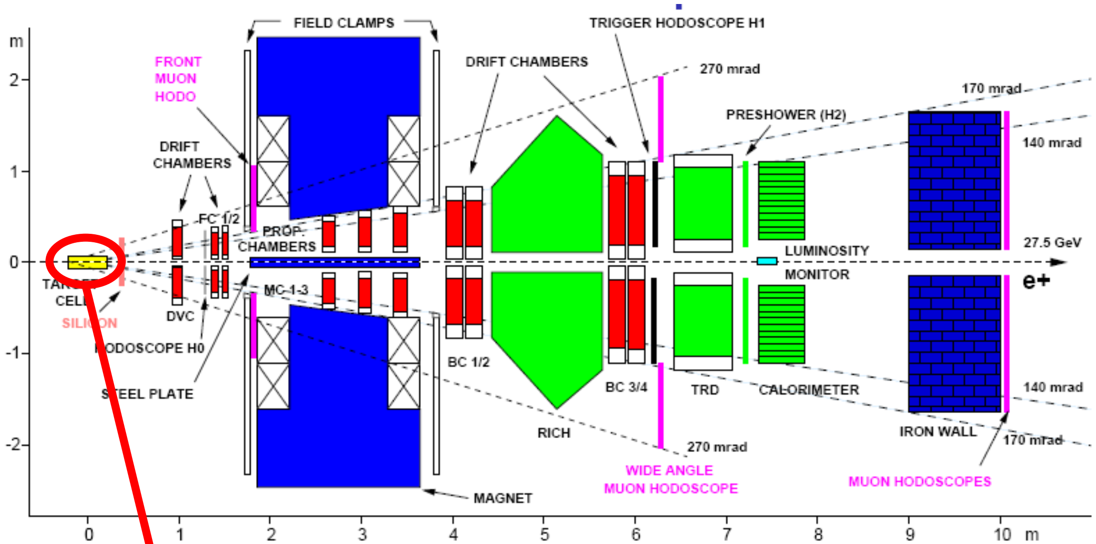
New $\pi^\pm\pi^0$ Results

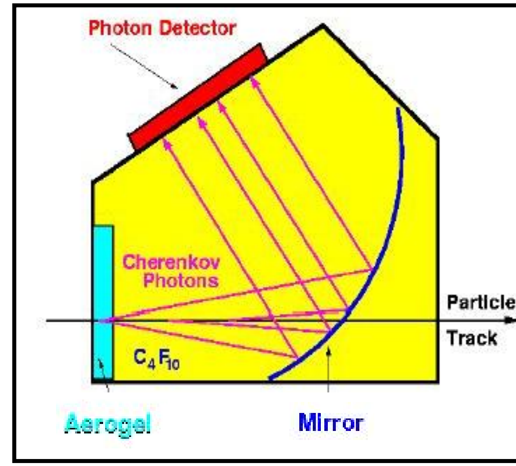


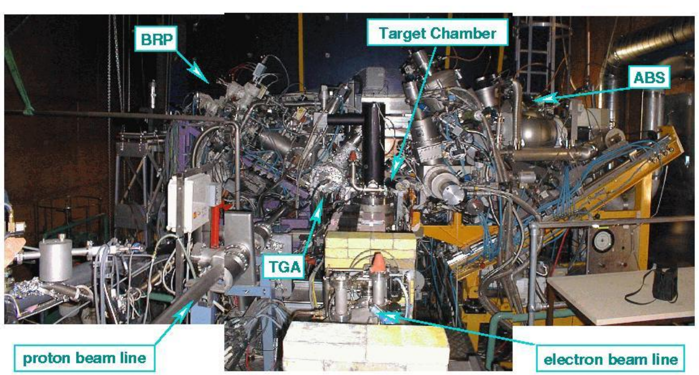
- independent way to access transversity
- Collinear → no convolution integral
- significantly positive amplitudes
- 1^{st} evidence of non zero dihadron FF
- limited statistical power (v.r.t. 1 hadron)
- signs are consistent for all $\pi\pi$ species
- statistics much more limited for $\pi^\pm\pi^0$
- despite uncertainties may still help to constrain global fits and may assist in $u - d$ flavor separation

- New tracking, new PID, use of ϕ_R rather than $\phi_{R\perp}$
- Different fitting procedure and function
- Acceptance correction

The HERMES experiment at HERA

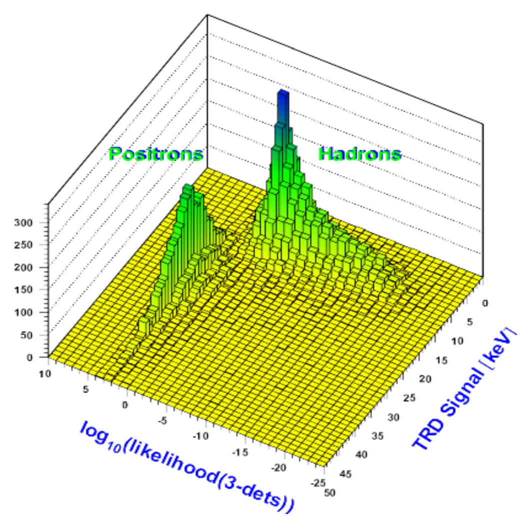




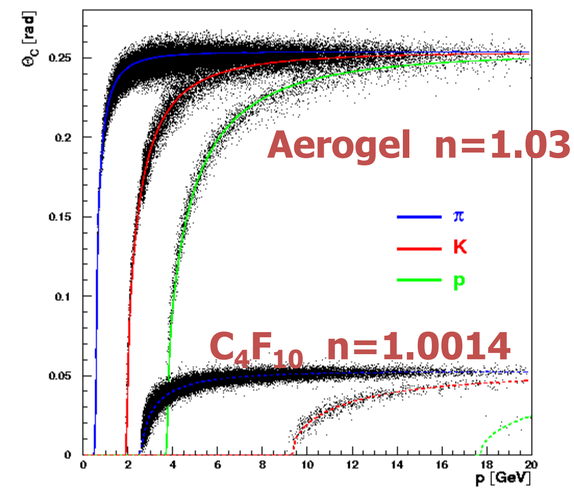


TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%



hadron separation



π ~ 98%, K ~ 88% , P ~ 85%