Recent results on TMDs from the HERMES Experiment

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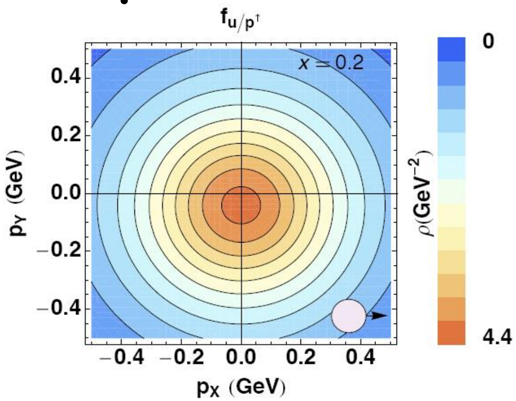
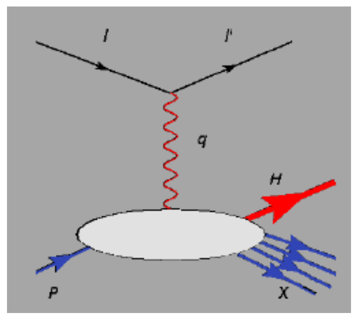
The nucleon tomography

TMDs $f(x, p_T)$

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

3D picture in momentum space

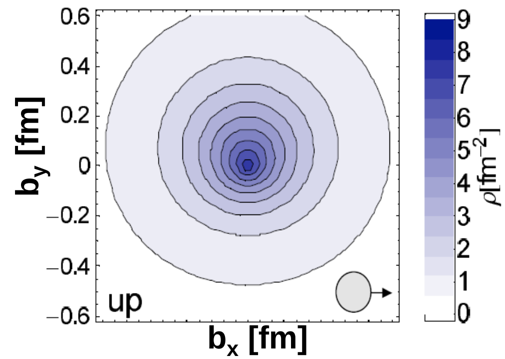


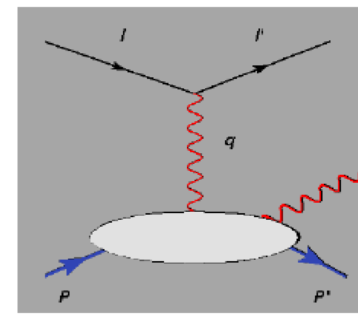


Semi-inclusive DIS

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

3D picture in coordinate space





Exclusive reactions

QCDSF/UKQCD, PRL 98 (07)

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

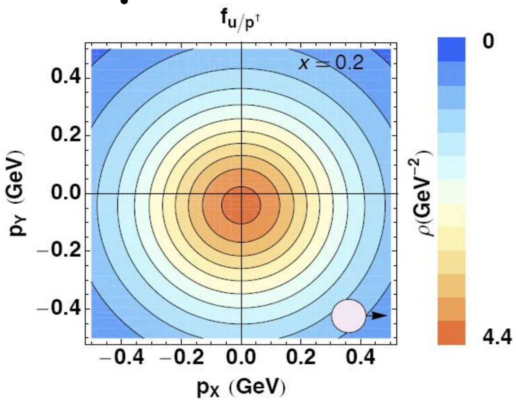
Mother Wigner function:

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

The nucleon tomography

TMDs $f(x, p_T)$

3D picture in momentum space



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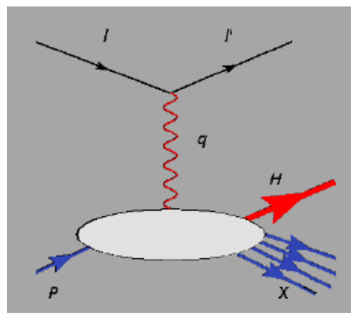

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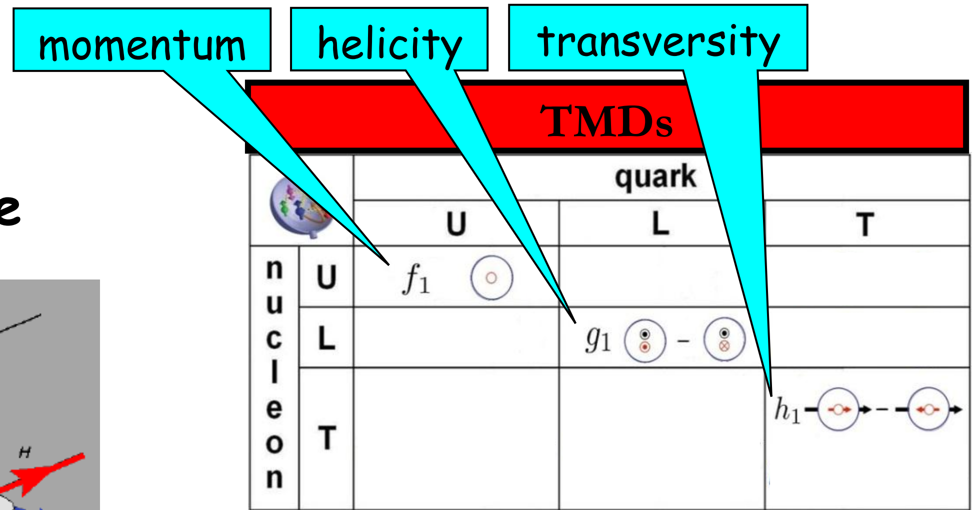
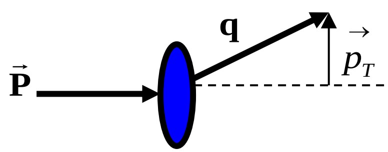


Diagonal elements survive integration over p_T

- **Momentum** and **Helicity** well known from inclusive DIS
  Now focus on p_T dependence
- **Transversity** accessed only recently in SIDIS, still poorly known (differs from helicity due to relativistic effects)

- Depend on x and p_T

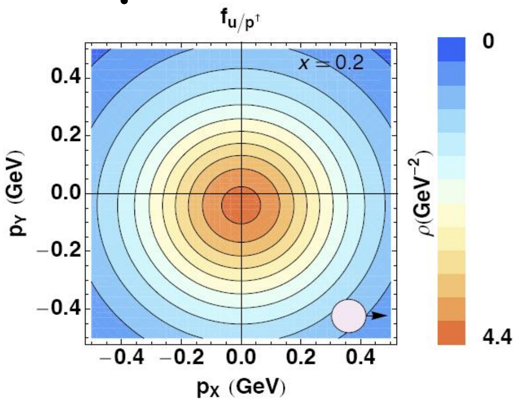


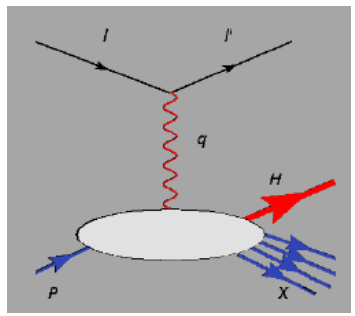
- Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)

The nucleon tomography

TMDs $f(x, p_T)$

3D picture in momentum space





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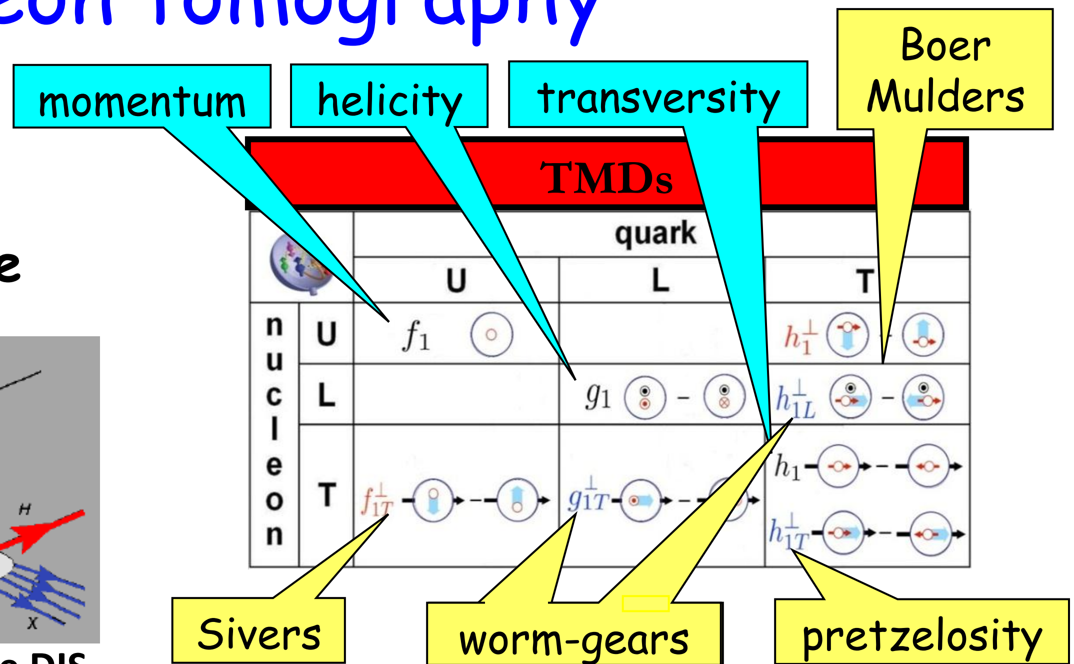
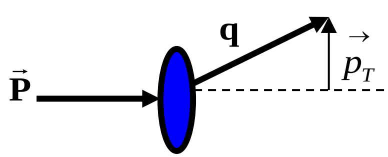


- Depend on x and p_T



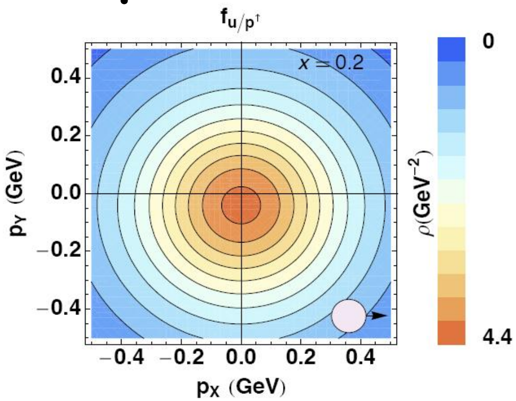
- Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)

- **Momentum** and **Helicity** well known from inclusive DIS Now focus on p_T dependence
- **Transversity** accessed only recently in SIDIS, still poorly known (differs from helicity due to relativistic effects)
- **Sivers** and **BM**: T-odd → require non-trivial (process-dependent!) gauge-link. Recently probed in SIDIS. Non zero and strongly flavour dependent
- **w-g g_{1T}**: hint of non-zero signal. Very preliminary access.
- **w-g h_{1L}**: zero at HERMES and COMPASS, significant amplitudes at CLAS!
- **pretzelosity** consistent with zero (HERMES, COMPASS)

Accessing the TMDs

TMDs $f(x, p_T)$

3D picture in momentum space



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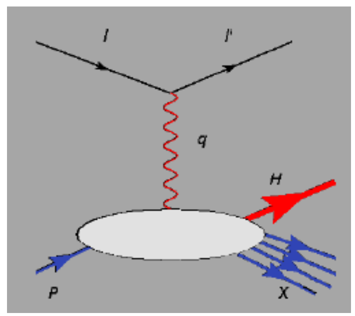

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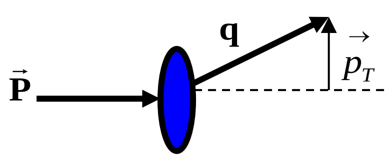
- Depend on x and p_T



- 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 $P_{h\perp} << Q$

Fragmentation Functions

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

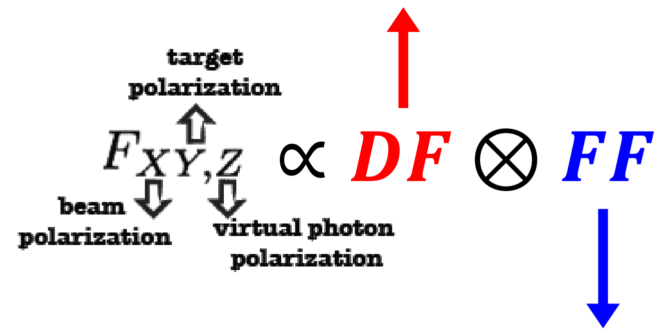
The SIDIS cross-section

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

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

TMDs

		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, $h_{1T}^\perp$



Fragmentation Functions

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

The SIDIS cross-section

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

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

unpolarized

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

beam polarization

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

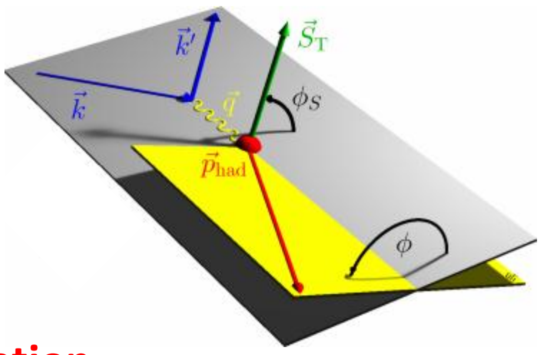
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\rm LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\rm LL}^{\cos(\phi)}\Big]$$

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

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

target polarization

beam and target polarization



The SIDIS cross-section

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

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

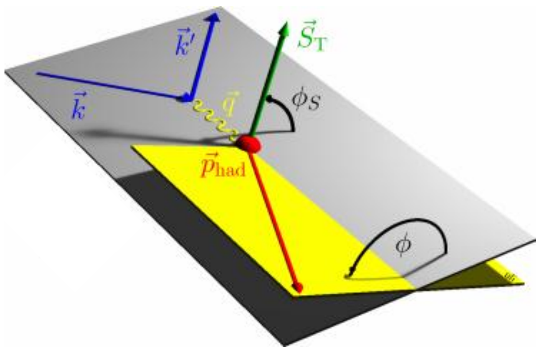
$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\rm LU}^{\sin(\phi)}\right]$$

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

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

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

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

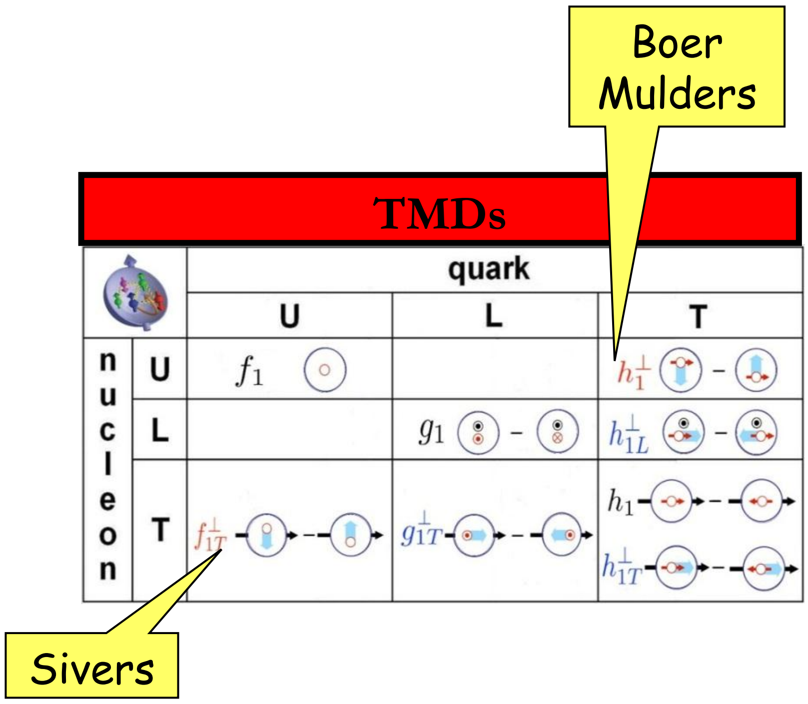


Leading twist

Sub-leading Twist

Selected results (1)

The Naive-T-odd TMDs



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

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

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

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

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

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

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

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

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

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

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

B-M effect
[PRD 57 (1998)]

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

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

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

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)]

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

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

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

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

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

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

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

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

B-M effect [PRD 57 (1998)]

Cahn effect [PLB 78 (1978)]

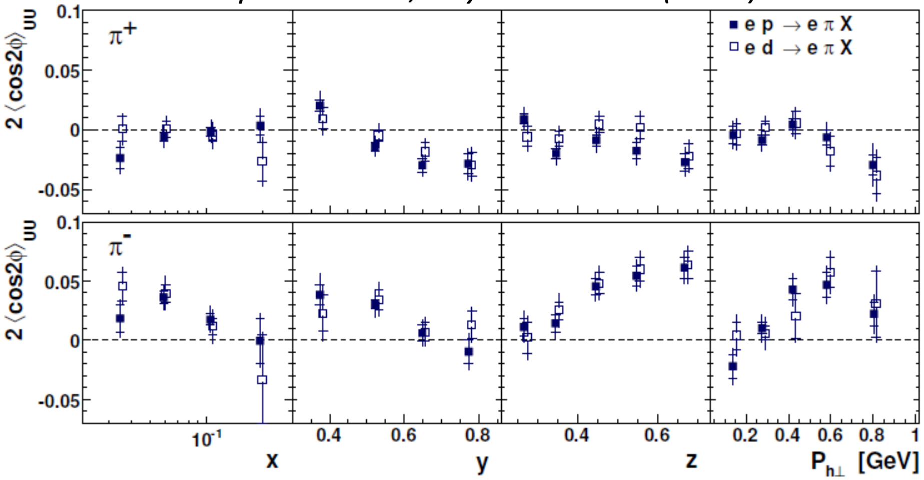
Interaction dependent terms

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 $h_1^{\perp,u} \approx h_1^{\perp,d}$

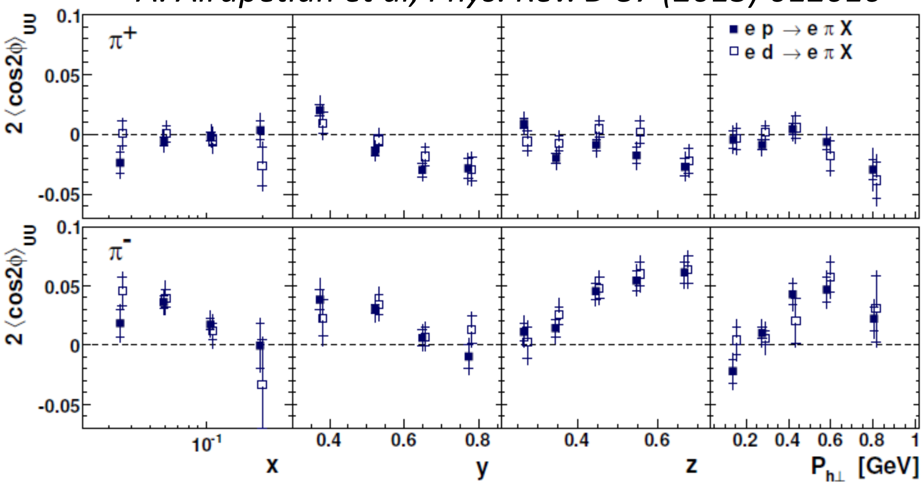
- Opposite sign for π^+/π^- consistent with opposite signs of fav/unfav Collins

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



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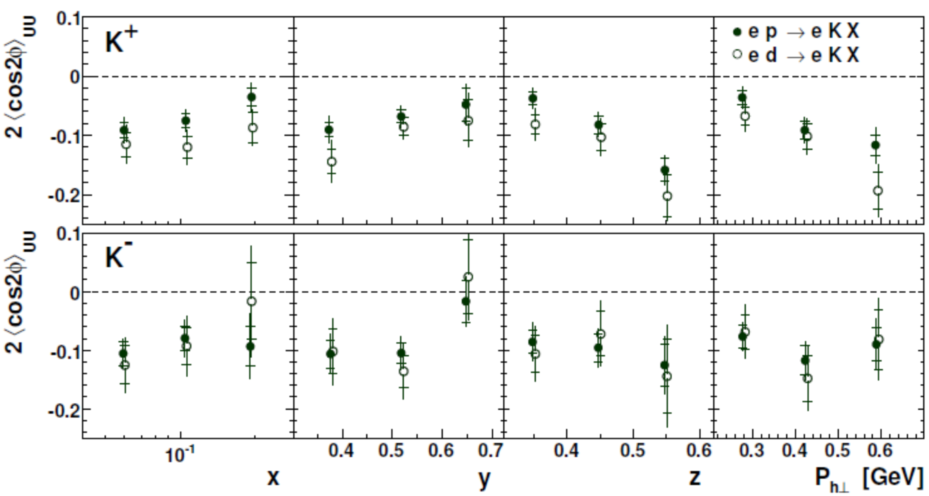


Large and negative

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?

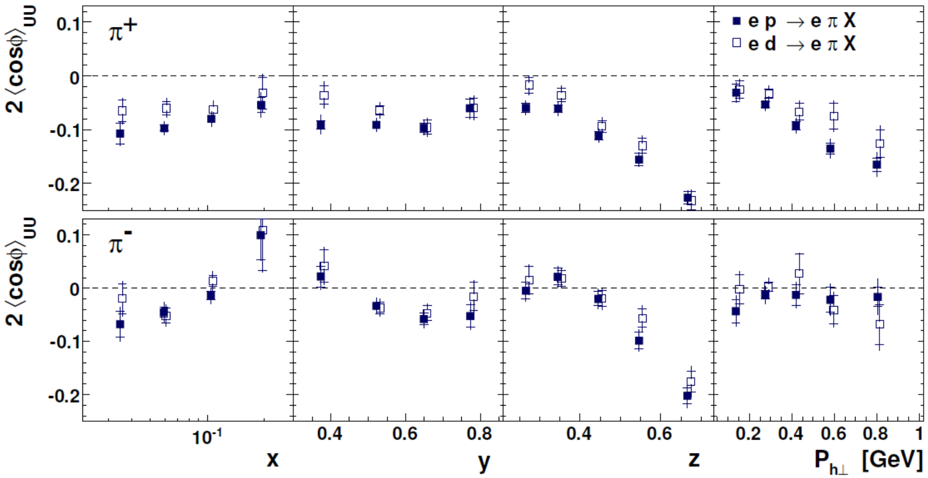
Analysis multi-dimensional in x, y, z,and Pt

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

The cosϕ amplitudes

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

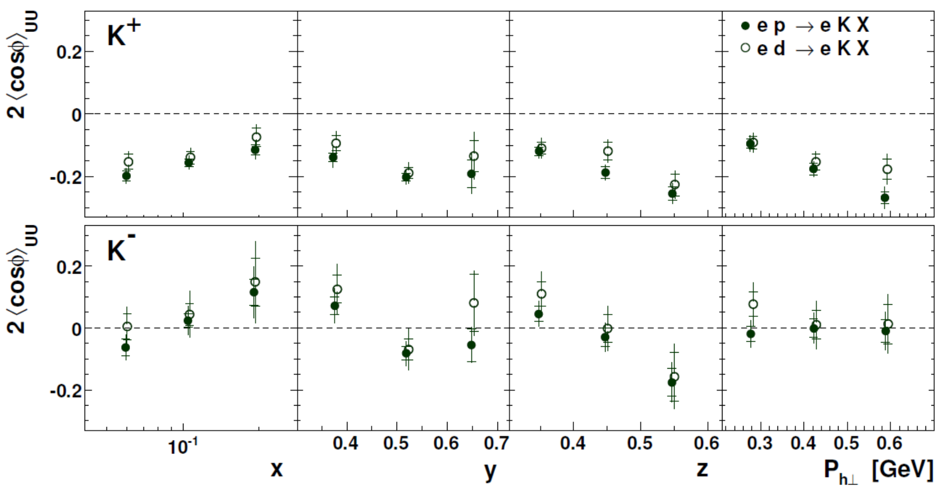
A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



negative

negative

- **Significant and of same sign (Chan effect expected to be weekly 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^-



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

Describes correlation between quark transverse momentum and nucleon transverse polarization

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

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

Sivers effect

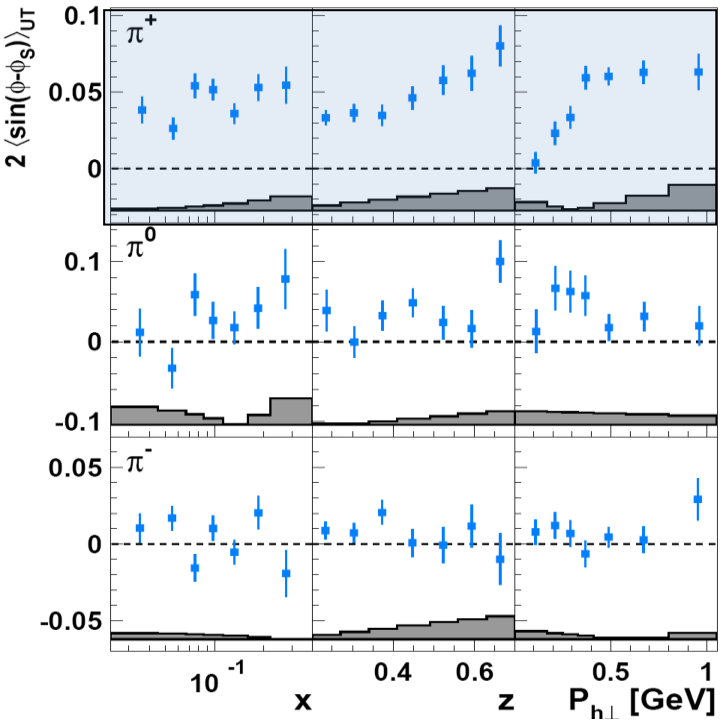
[PRD 41 (1990)]

Sivers amplitudes

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

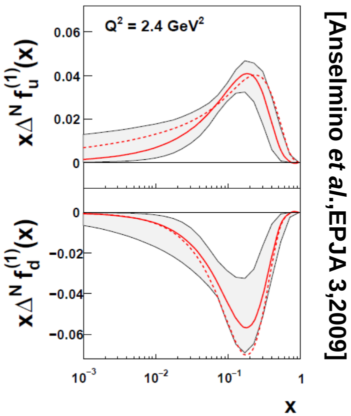
	U	L	T
U			
L			
T	$f_{1T}^{\perp}$		

[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

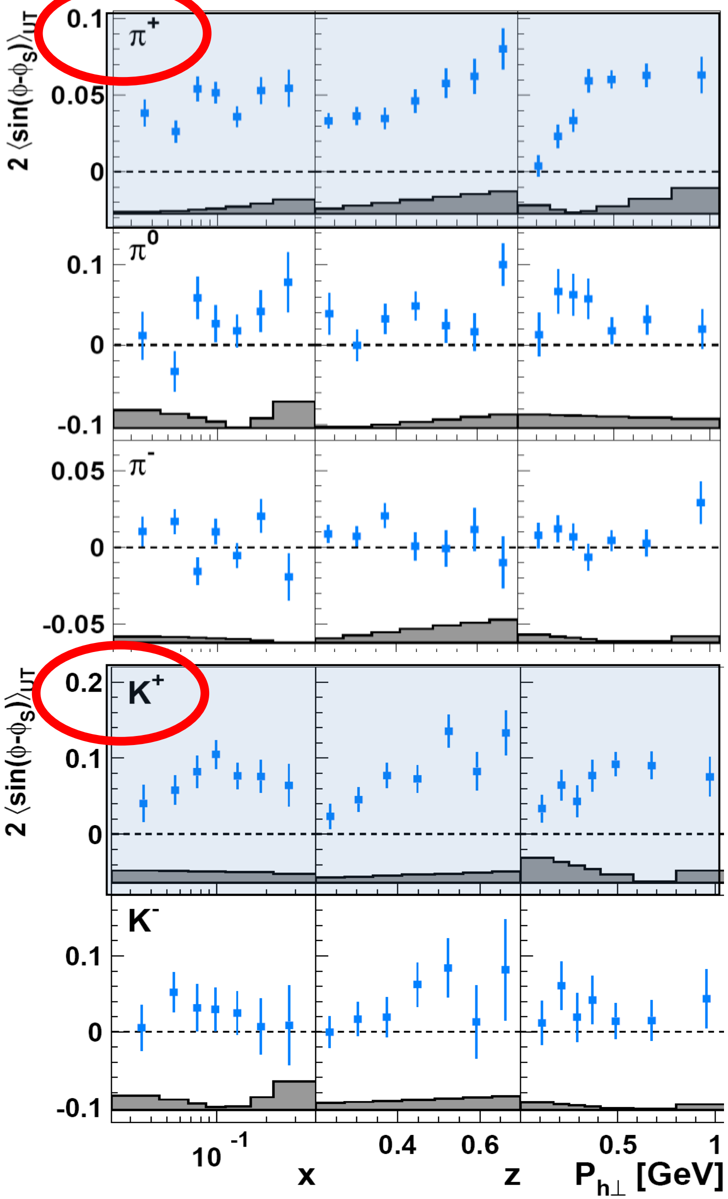


Sivers amplitudes

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

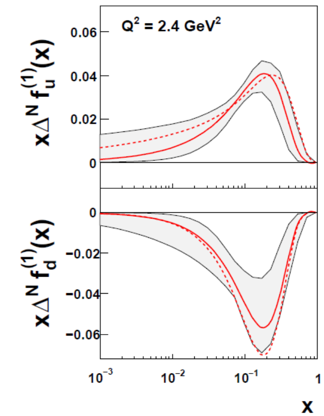
	U	L	T
U			
L			
T	$f_{1T}^{\perp}$		

[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



[Anselmino *et al.*,EPJA 3,2009]

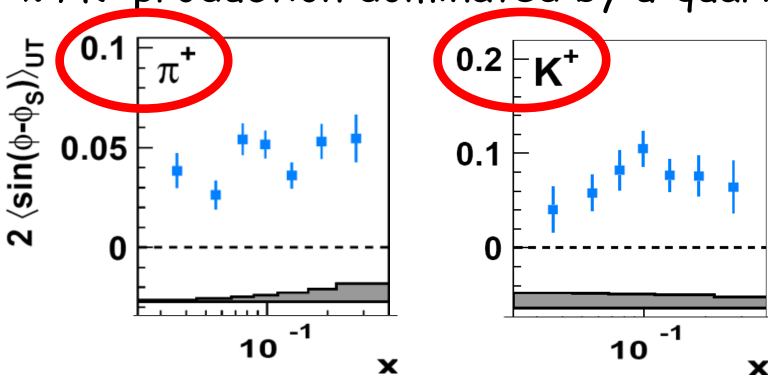
- Larger than π^+!!

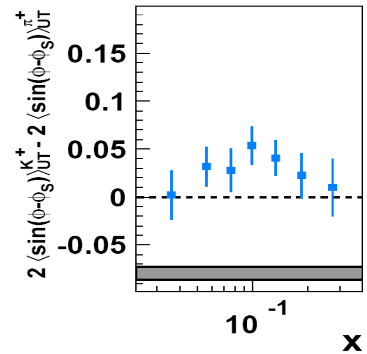
Again unexpected pion-kaon differences!

The kaon puzzle in Sivers

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

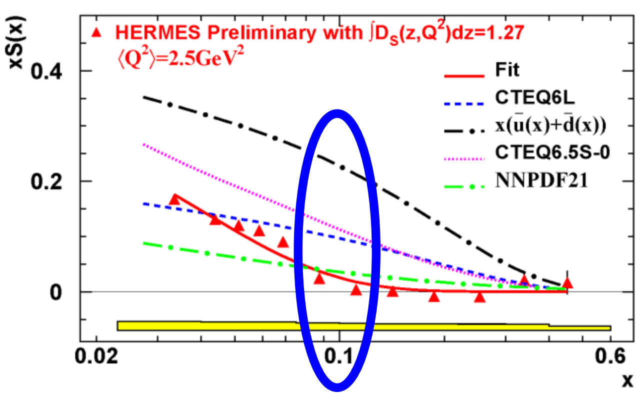
π^+/K^+ production dominated by u-quarks, but:





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

different role of various sea quarks ?



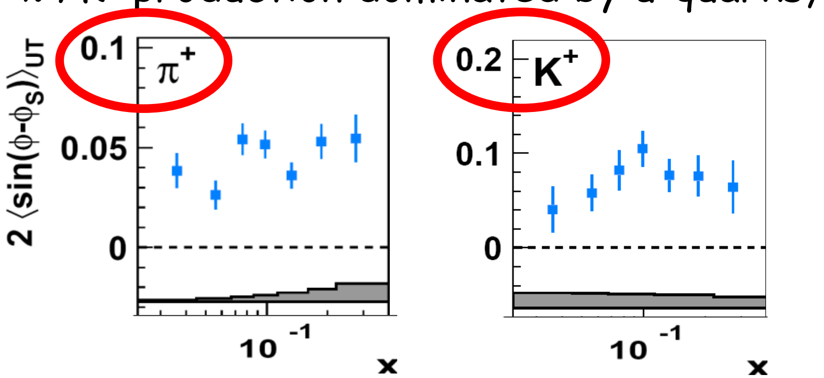
Flavor dependence of k_T in fragment.

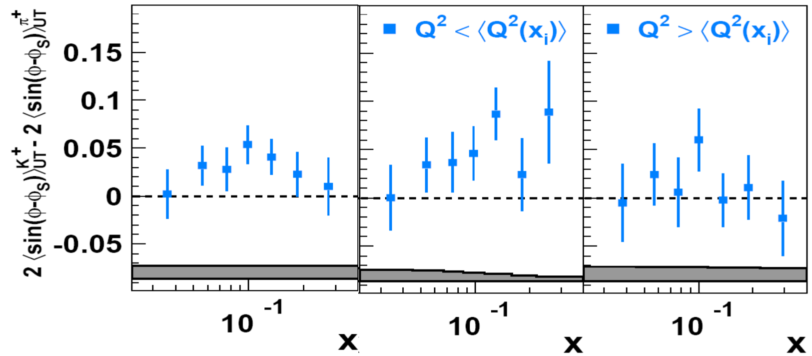
$\rightarrow$ impact through convolution integral

The kaon puzzle in Sivers

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

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

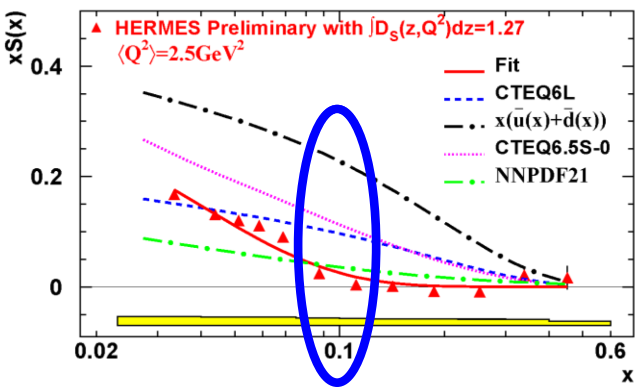


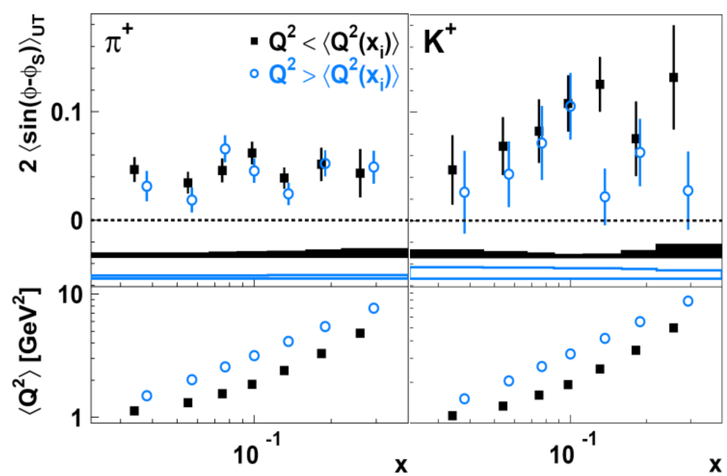


Each x-bin divided into 2 Q^2-bins

Significant deviations observed only at low Q^2

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





Flavor dependence of k_T in fragment.

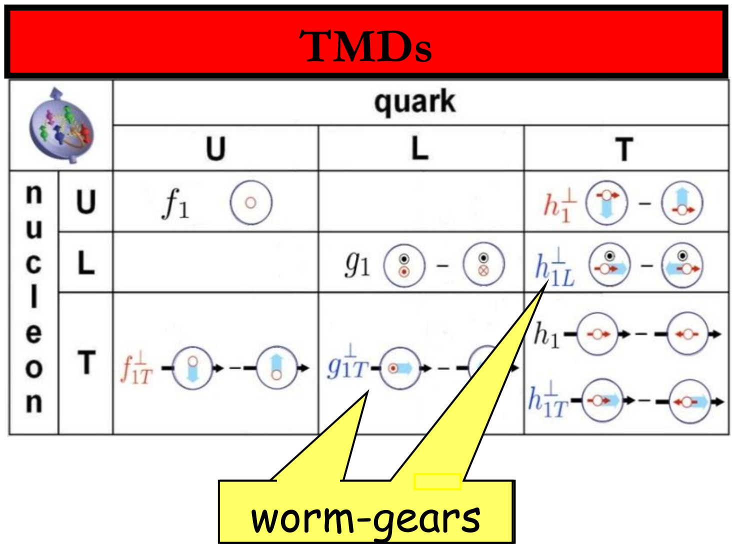
$\rightarrow$ impact through convolution integral

Hint of systematic diff. only for K^+

Higher-twist contrib. for Kaons

Selected results (2)

The worm-gears



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

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

Probability to find transversely polarized quarks in a longitudinally polarized nucleon

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

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

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

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

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

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

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

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

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

	U	L	T
U			
L			$h^{\perp}_{1L}$
T		g_{1T}	

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

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

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

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

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

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

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

Probability to find transversely polarized quarks in a longitudinally polarized nucleon

$\propto h^{\perp}_{1L} \otimes H^{\perp}_1$

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

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

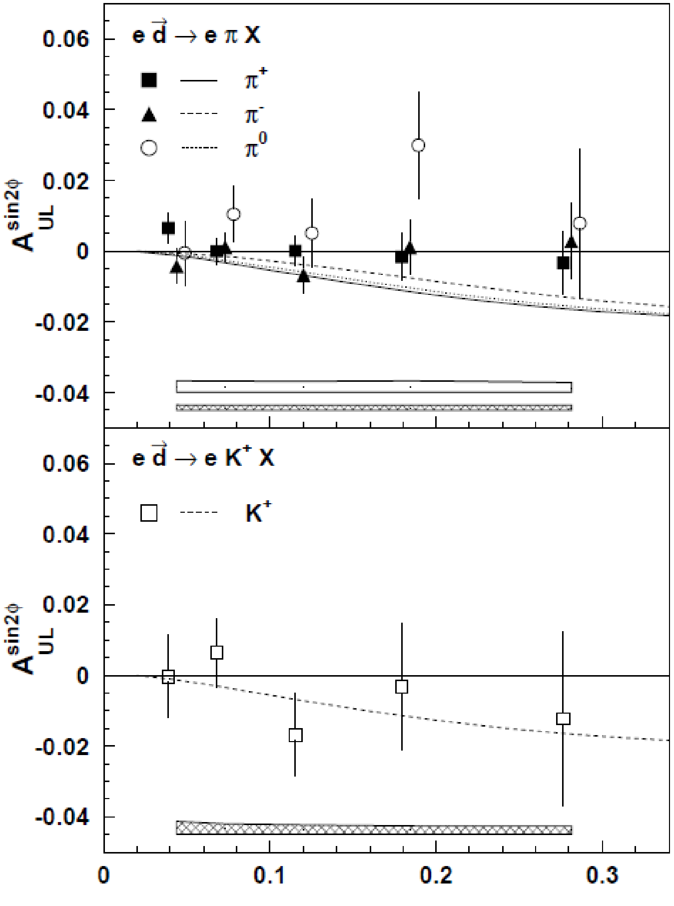
$\propto g_{1T} \otimes D_1$

The sin(2ϕ) amplitude

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

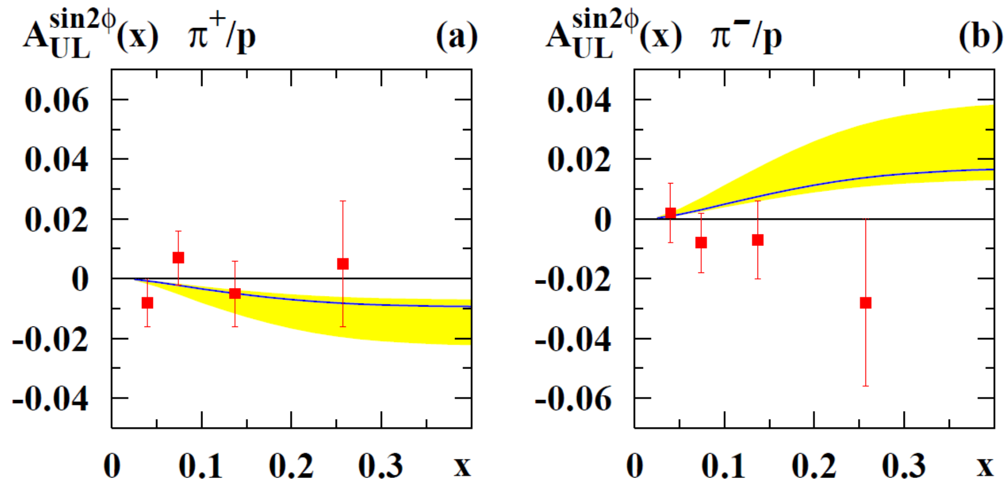
	U	L	T
U			
L			$h_{1L}^{\perp}$
T			

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.

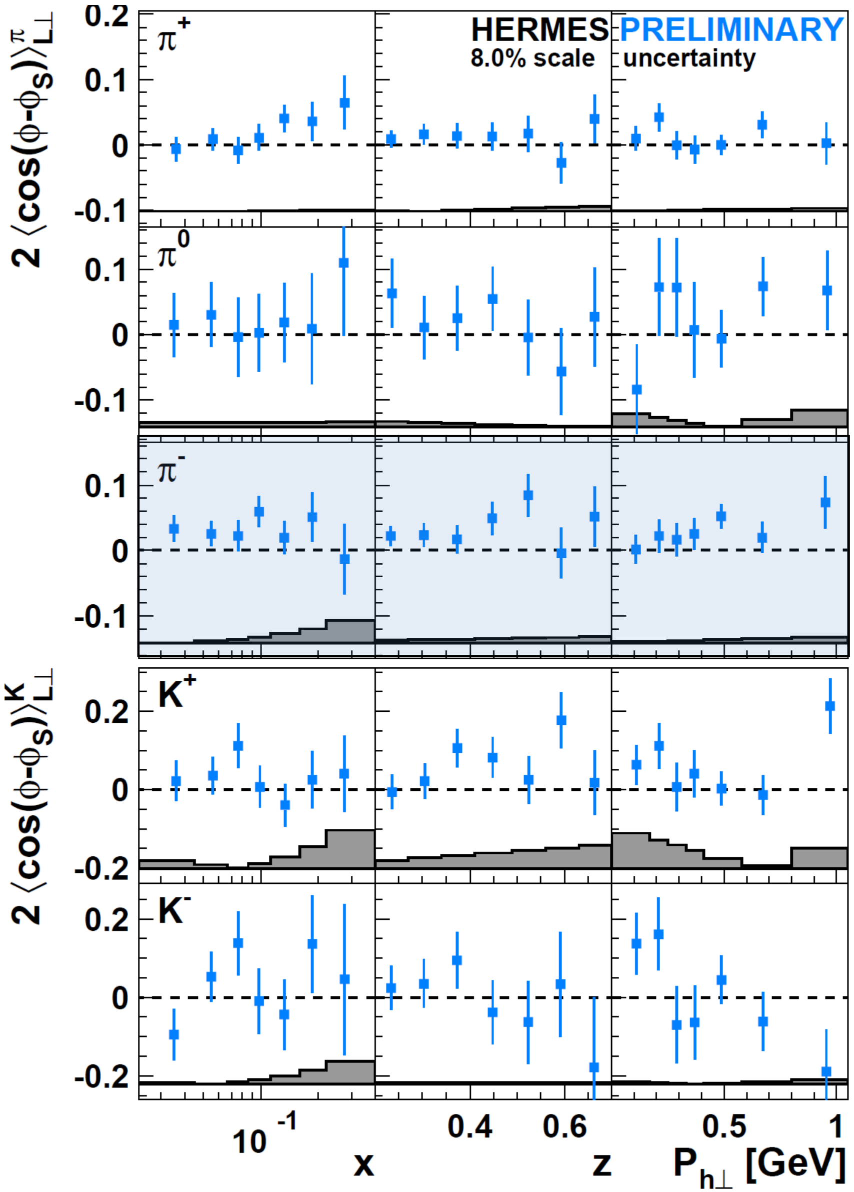
Similar observations by COMPASS on deuterium

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

Selected results (3)

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

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

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

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

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

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

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

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

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

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

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

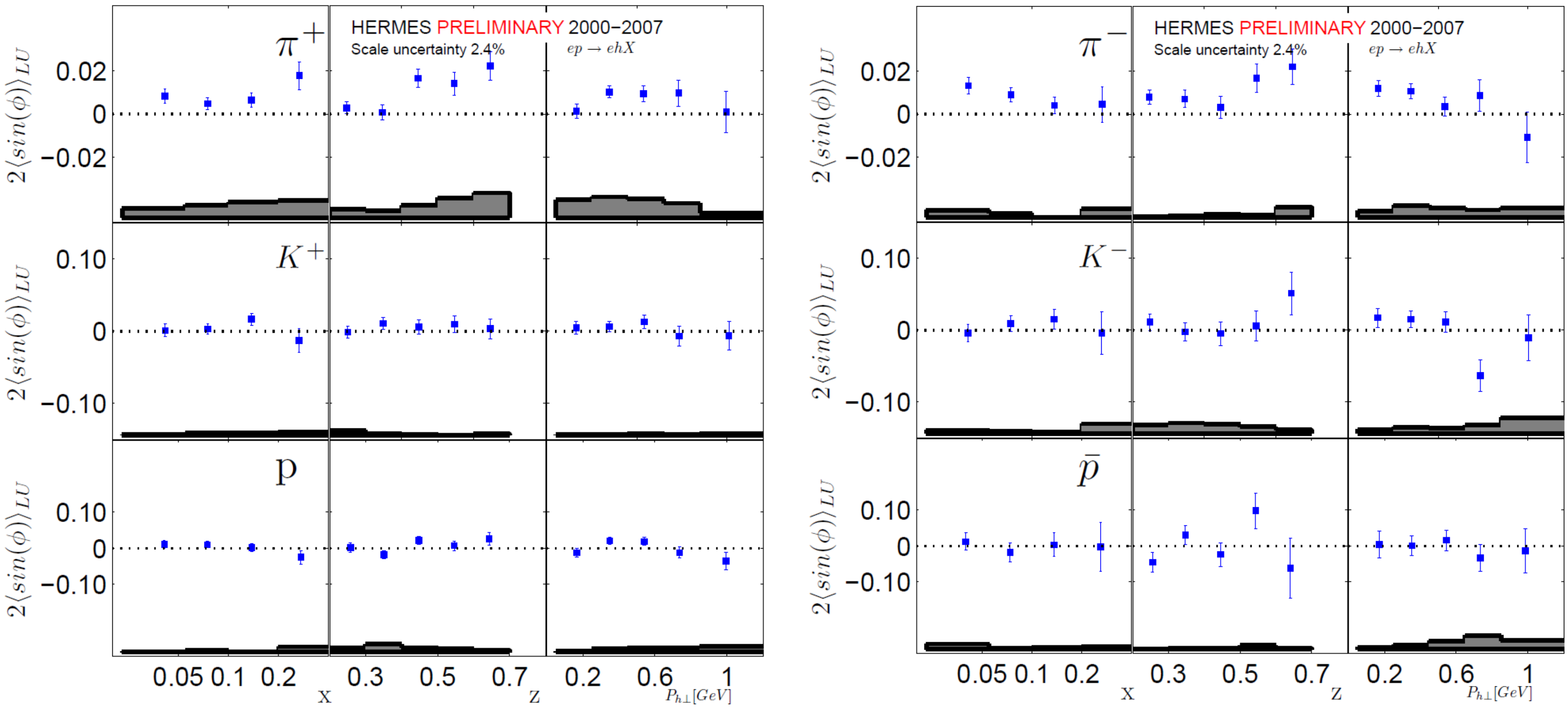
$$
\propto +\frac{1}{Q}\left[e \otimes H_1^\perp + \boldsymbol{f_1} \otimes \tilde{G}^\perp + g^\perp \otimes D_1 + \boldsymbol{h_1}^\perp \otimes \tilde{E}\right]
$$

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

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

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

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



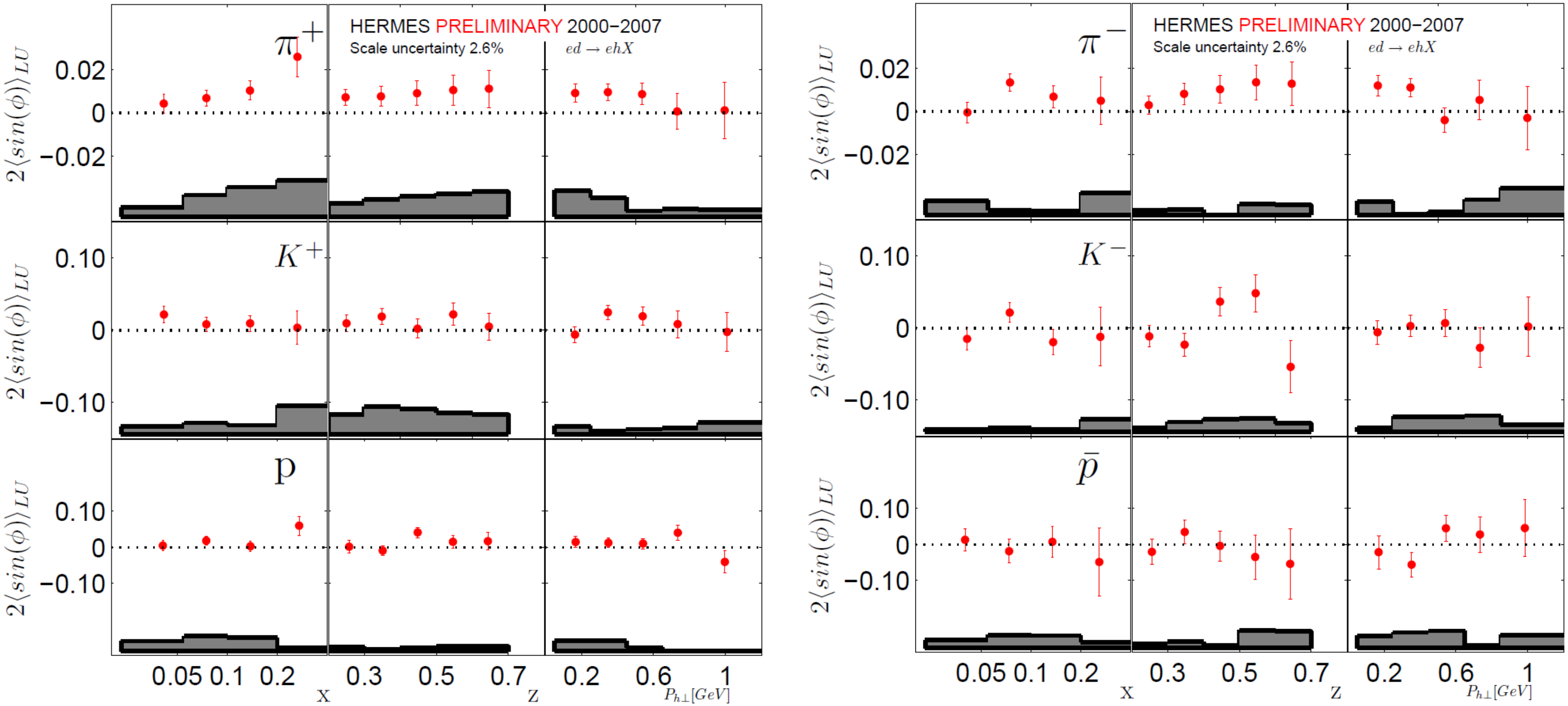
Amplitudes are positive for pions and consistent with zero for kaons and protons

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

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

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

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



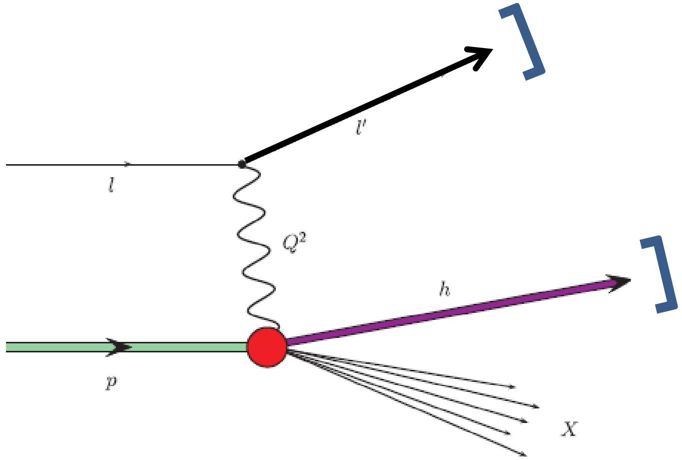
Amplitudes are positive for pions and consistent with zero for kaons and protons

Deuterium target: same features, less statistics

Part II

Inclusive electroproduction of hadrons

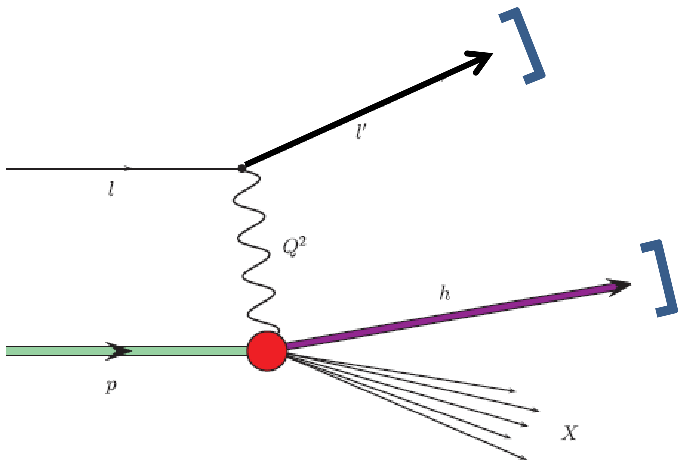
From SIDIS to inclusive hadron production

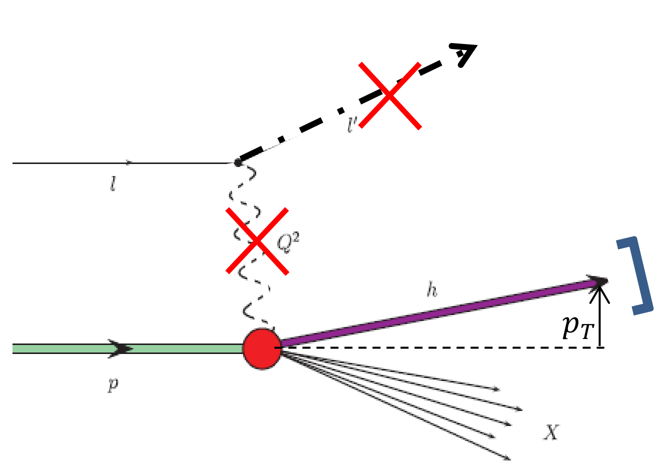


SIDIS: $\boldsymbol{lp^{\uparrow} \rightarrow l'hX}$

- 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





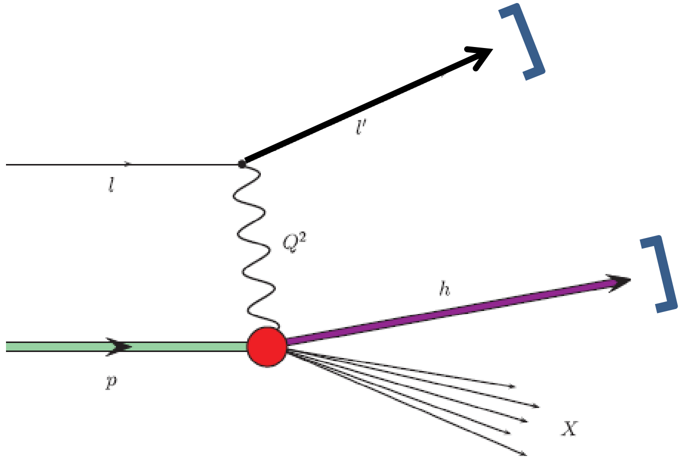
SIDIS: $lp^{\uparrow} \rightarrow l'hX$

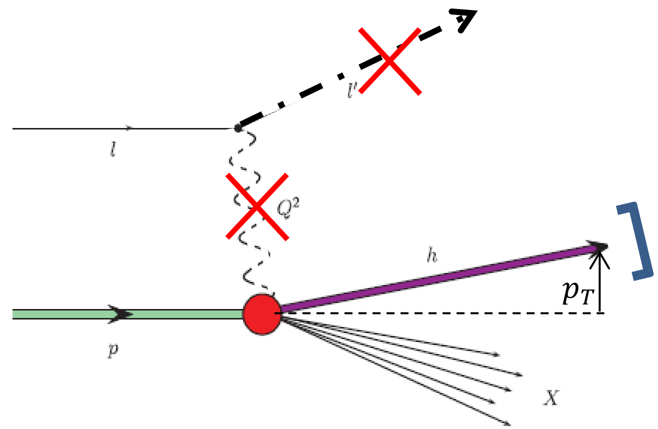
- Hadron detected in coincidence with lepton
- DIS regime ($Q^2 > 1\ GeV^2$)
- Hard scales: Q^2, $P_{h\perp}$ (w.r.t. γ^*)
- Factorization valid for ${P_{h\perp}}^2 \ll Q^2$

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 ${P_{h\perp}}^2 \ll Q^2$

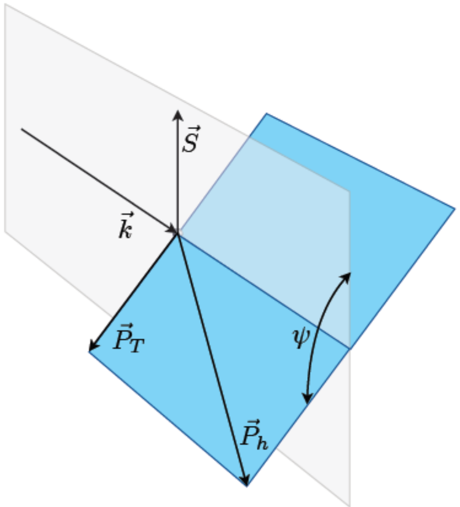
Hadron yields for UT data

	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

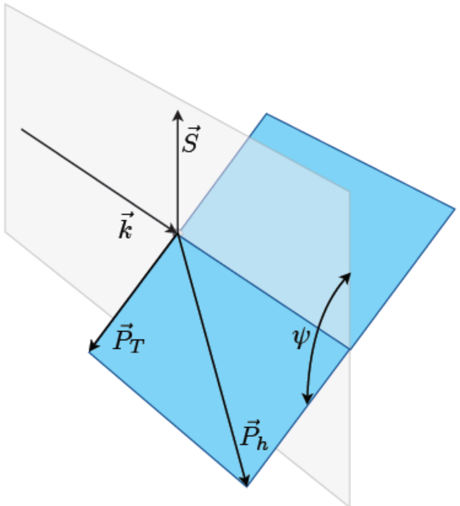


$$d\sigma = d\sigma_{UU}\left[1 + S_{\perp} A_{UT}^{\sin\psi} \sin\psi\right]$$

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

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

Cross section and azimuthal asymmetries



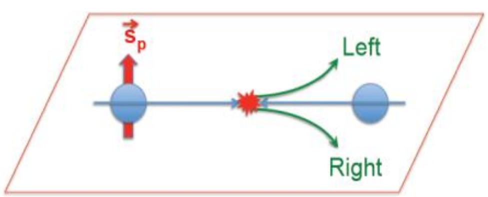
$$d\sigma = d\sigma_{UU}\left[1 + S_\perp A_{UT}^{\sin\psi}\sin\psi\right]$$

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

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

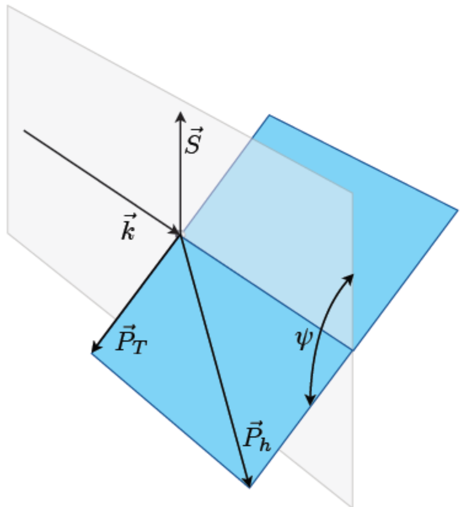
For an ideal detector with full 2π coverage in ψ:

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



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

Cross section and azimuthal asymmetries



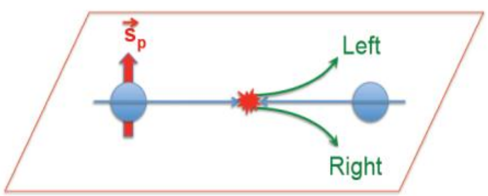
$$d\sigma = d\sigma_{UU}\left[1 + S_\perp A_{UT}^{\sin\psi} \sin\psi\right]$$

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

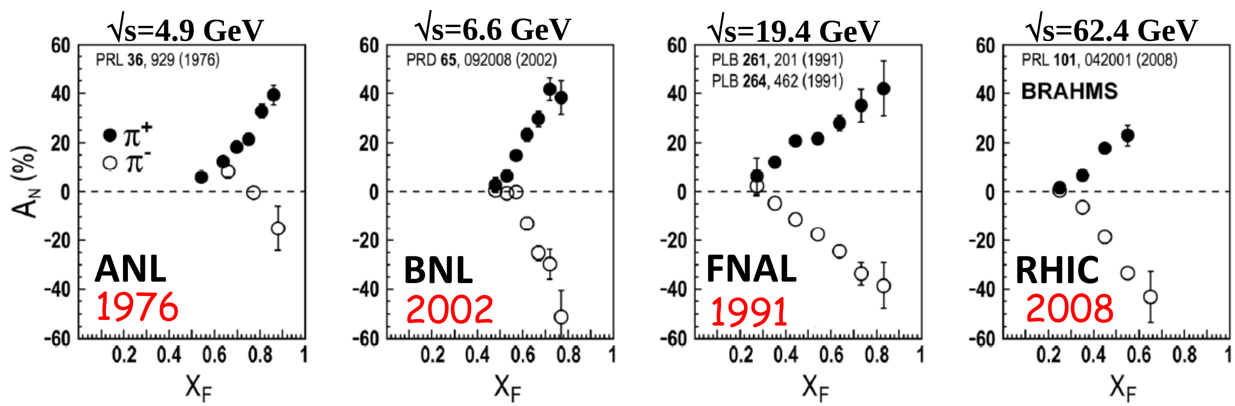
$\boldsymbol{\psi}$: azimuthal angle between the upwards target spin direction and hadron production plane around the beam direction

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

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



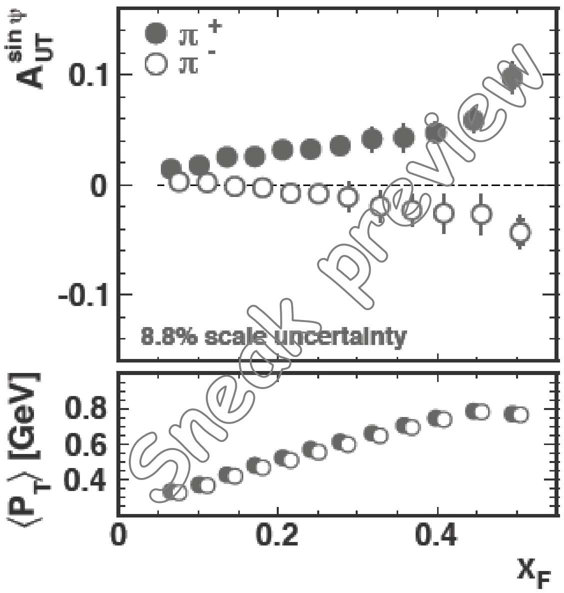
$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$



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**

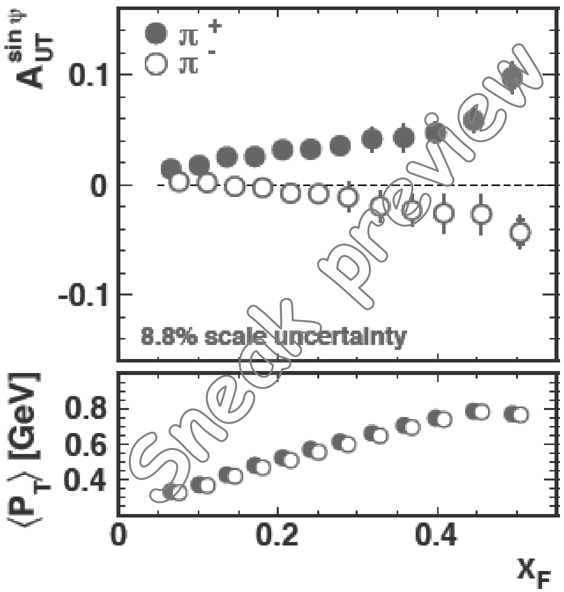
Inclusive hadrons results



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

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

Inclusive hadrons results



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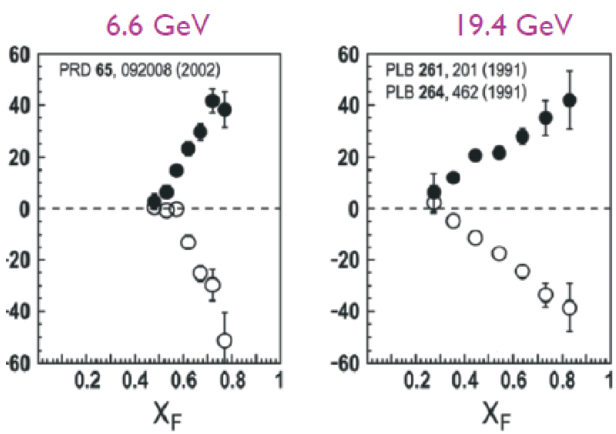
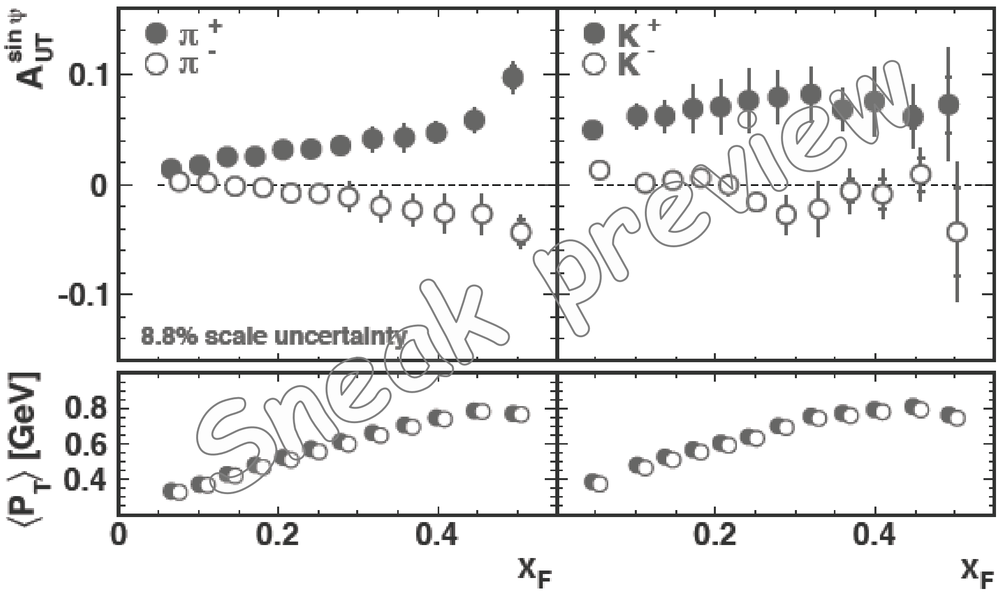
General trend very similar to A_N in $pp^{\uparrow}$ hard scattering



- 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^-

Inclusive hadrons results



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

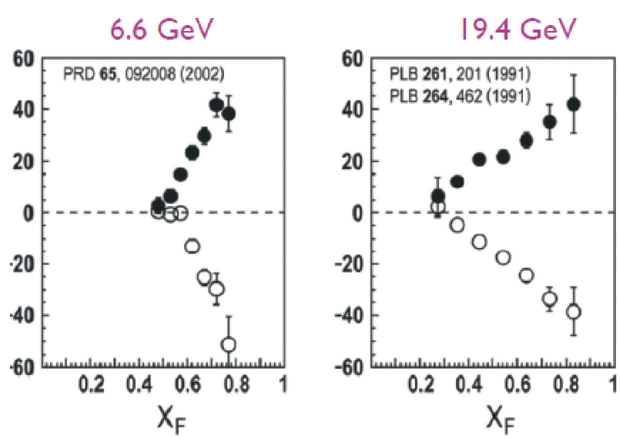
π^{-} **is negative, similar trend, smaller (up to 4%)**

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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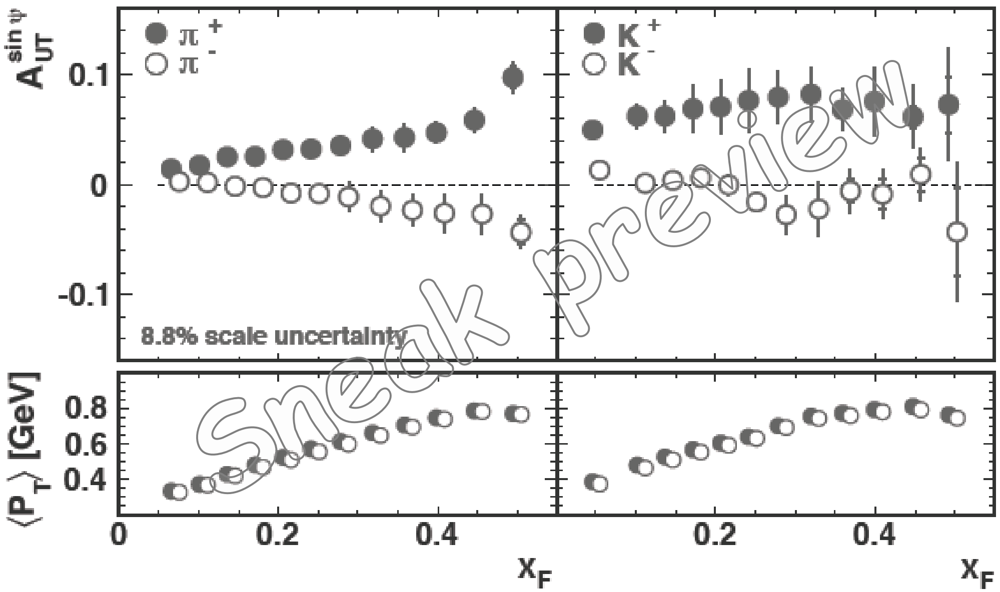

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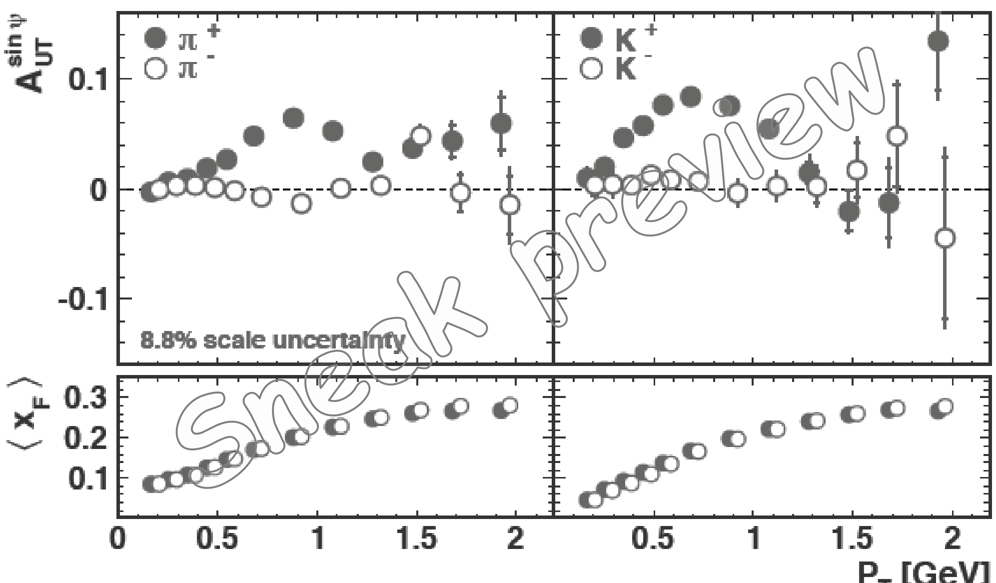
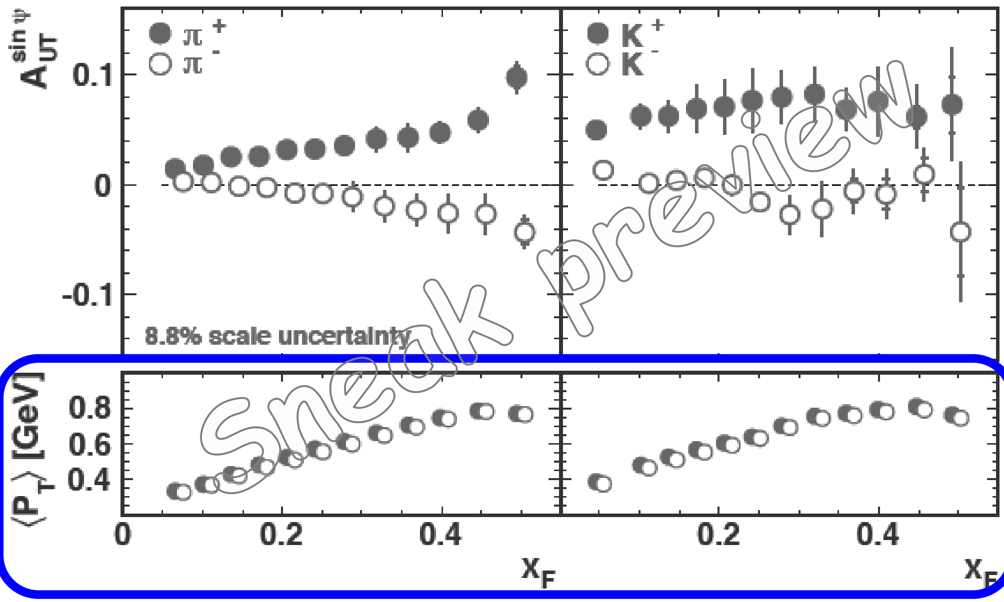


π^+ and K^+ amplitudes rise linearly up to $P_T \approx 0.8\ GeV$ then decrease with increasing P_T

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 $P_T \approx 1.5\ GeV$

Inclusive hadrons results



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

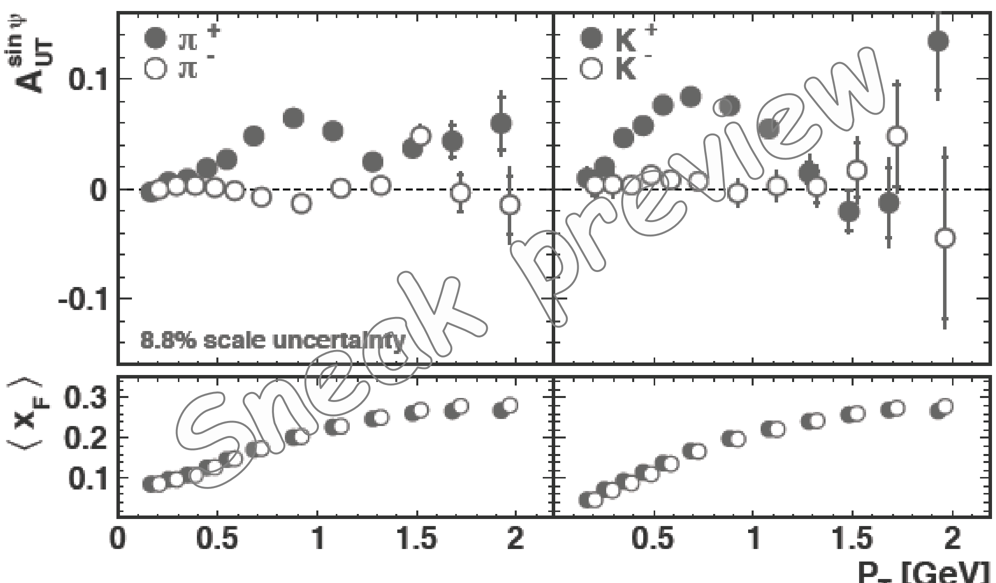
π^- is negative, similar trend, smaller (up to 4%)

K^+ is about constant around 7%

$K^- \approx 0$

Again kaon behave differently than pions!

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



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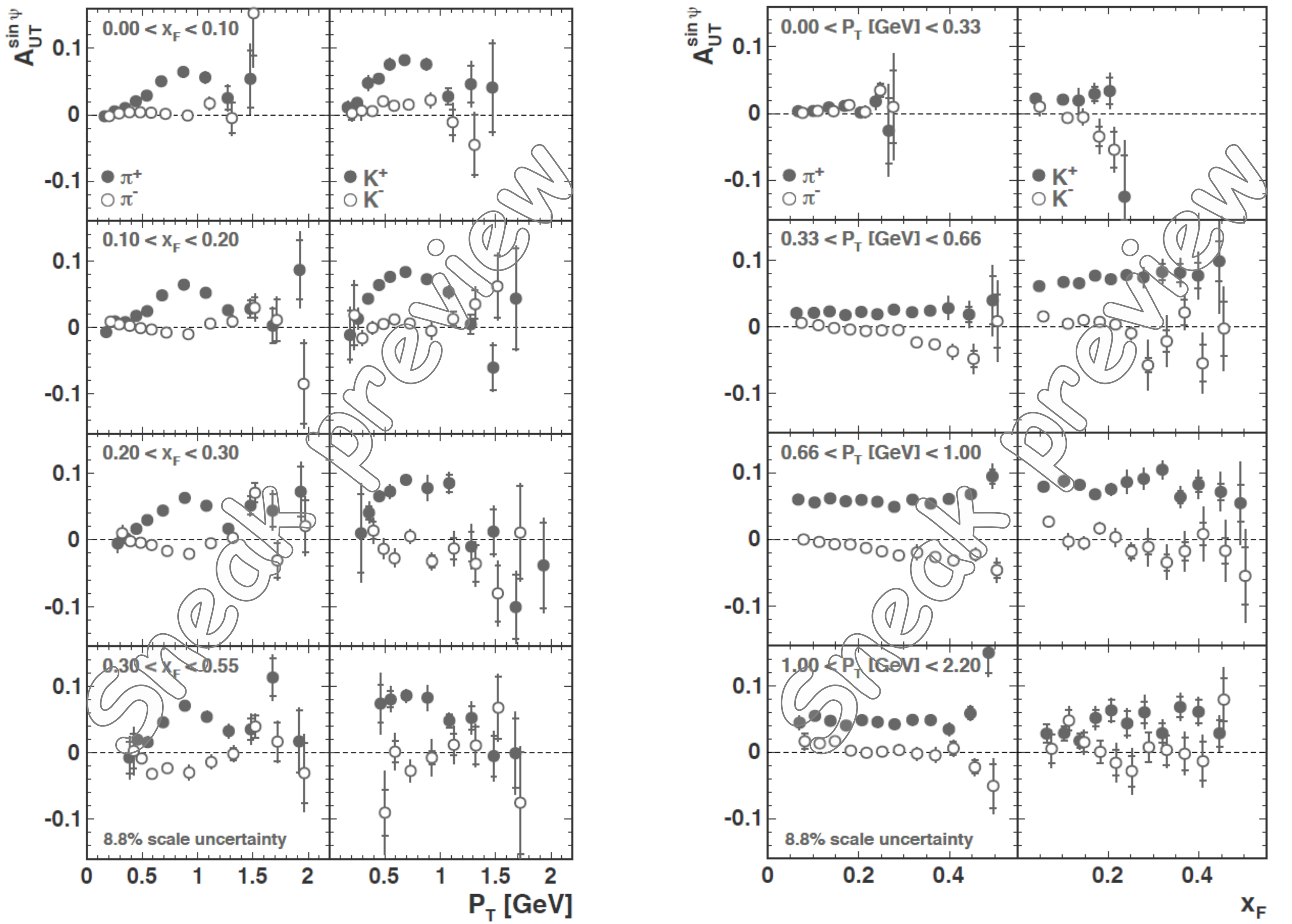

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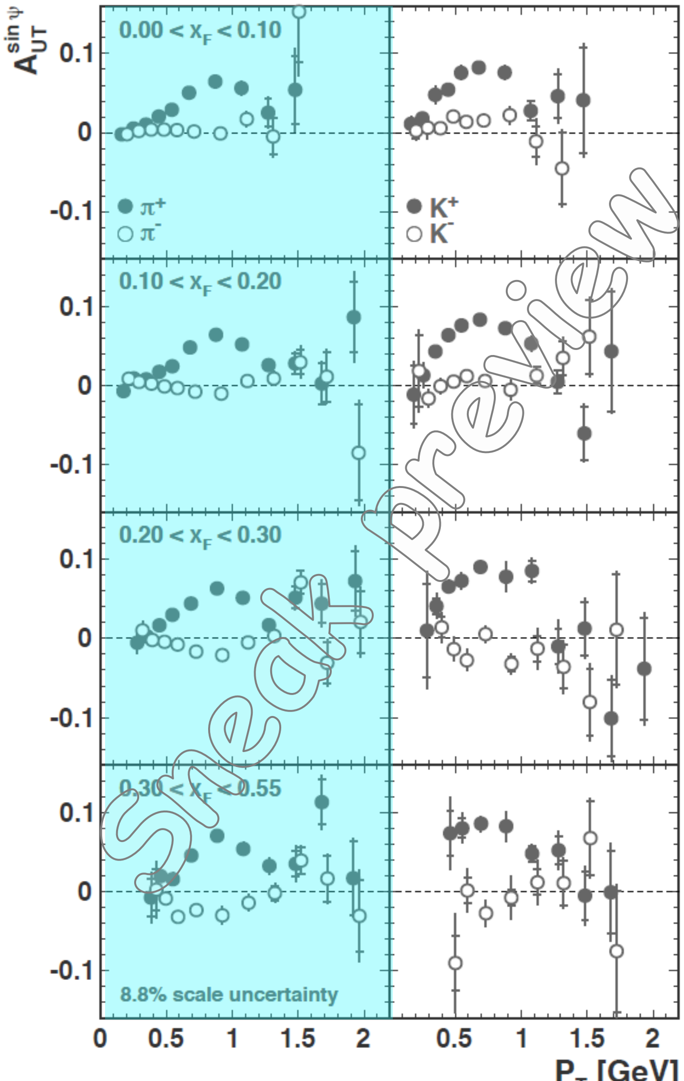
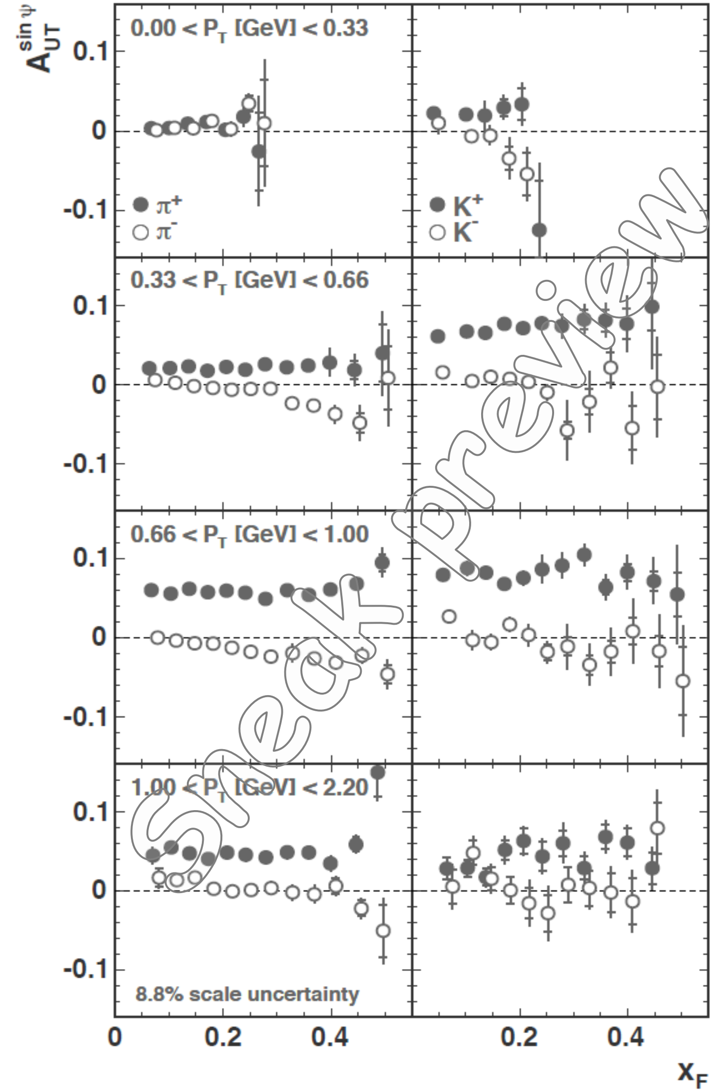
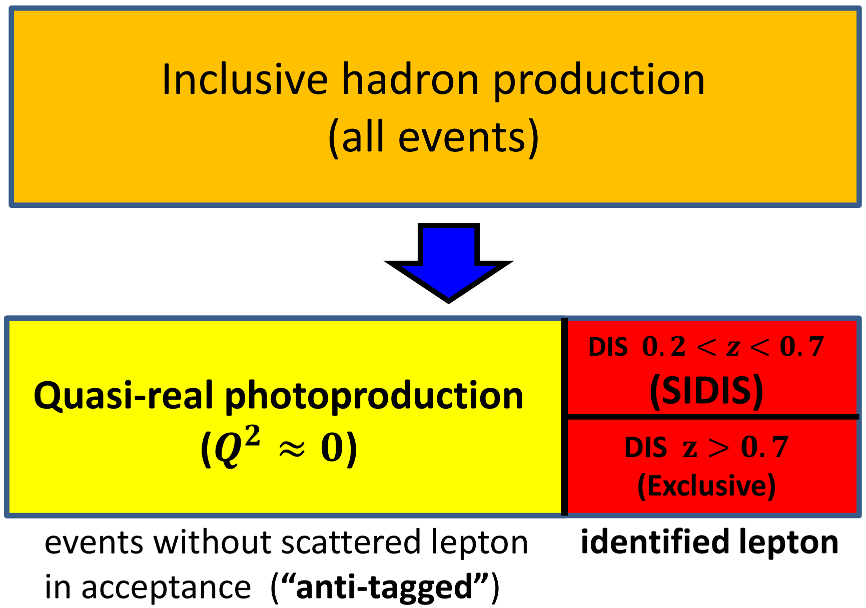




- π^+ amplitudes vs. P_T are basically the same in all x_F bins $\rightarrow$ apparent increase in magnitude vs. x_F in 1D projections is a reflection of underlying dependence on P_T
- π^- amplitudes vs. P_T are vanishing at low x_F and become negative at high x_F

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



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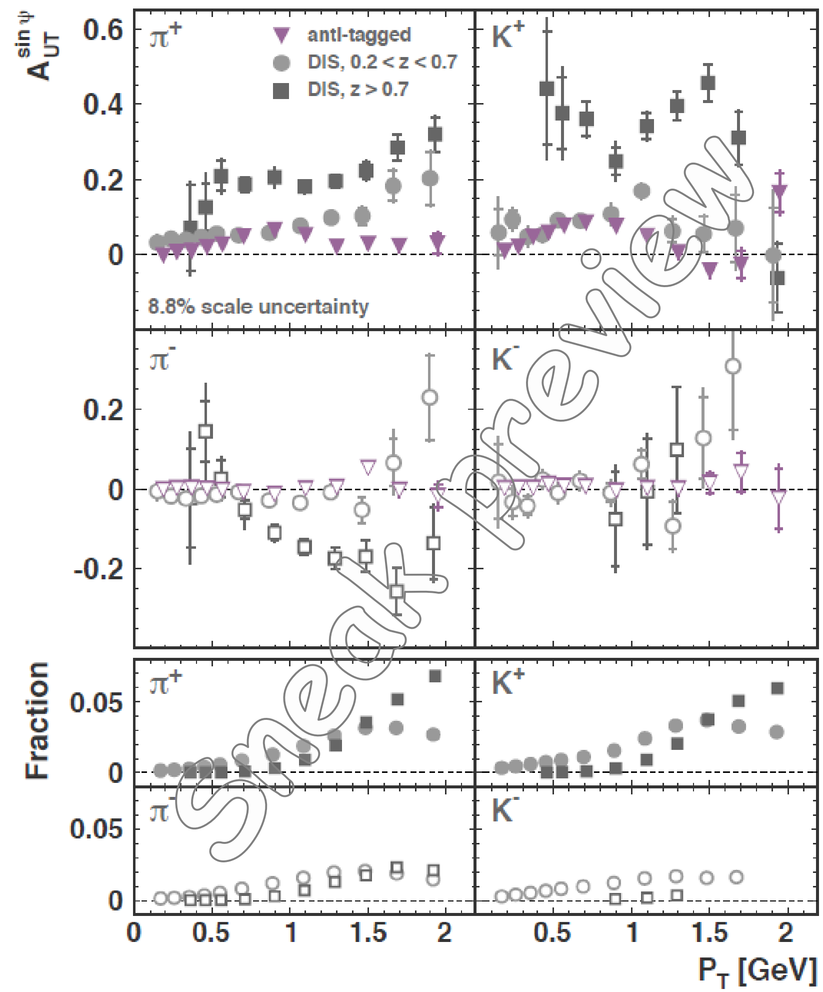
Inclusive hadron production
(all events)

⬇

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**



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

Interpretation

DIS $0.2 < z < 0.7$:

- π^+/π^- amplitudes larger than inclusive 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 $\boldsymbol{\psi}$ **and** $\boldsymbol{\phi - \phi_S}$ **are closely related** the observed P_T dependence might arise from the **Sivers effect**

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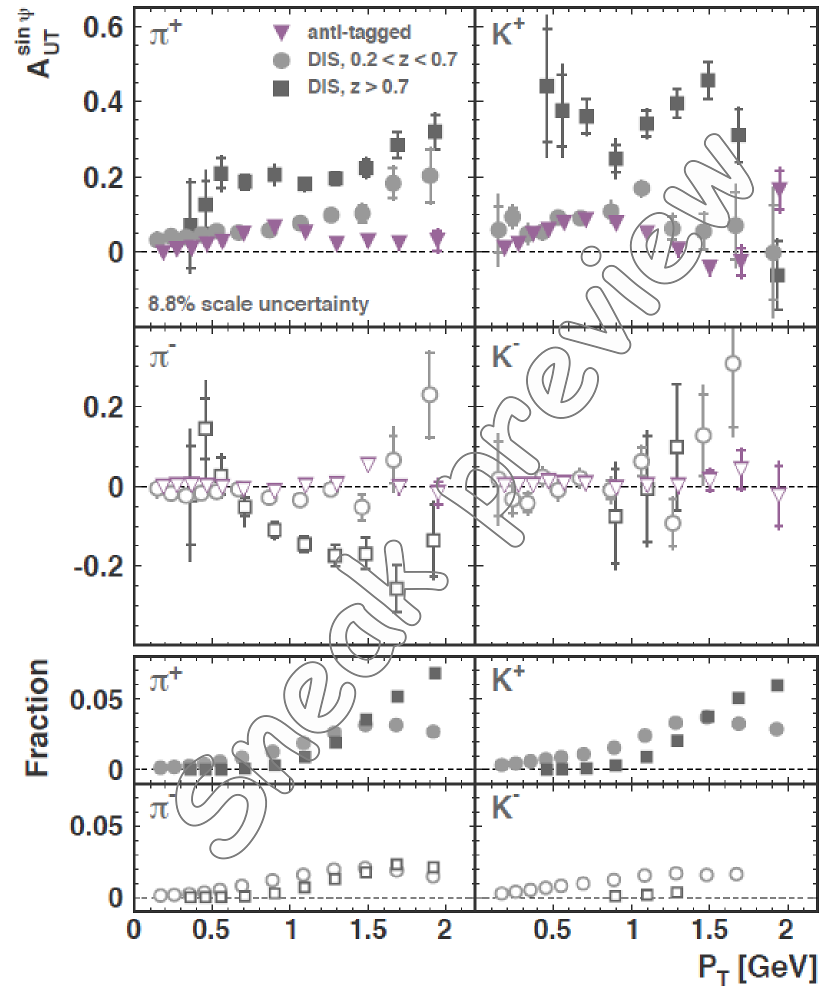

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- Since $\boldsymbol{\psi}$ **and** $\boldsymbol{\phi - \phi_S}$ **are closely related** the observed P_T dependence might arise from the **Sivers effect**

DIS $z > 0.7$:

- 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**

Anti-tagged:

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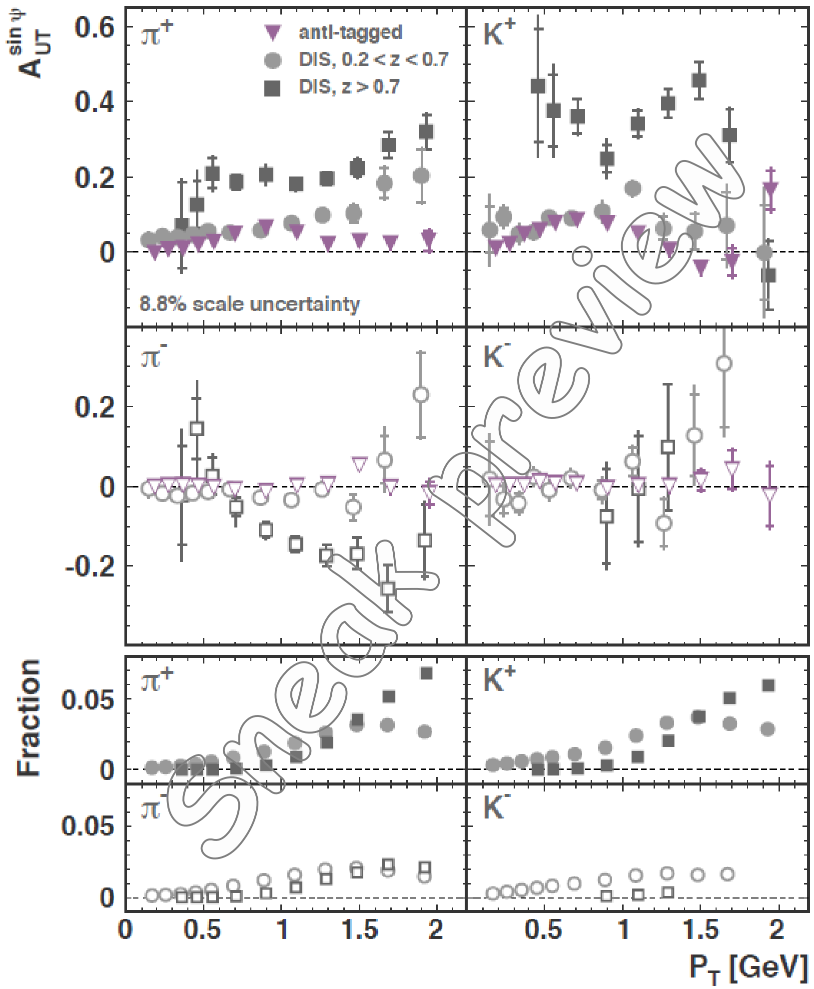

Conclusions

A rich phenomenology and surprising effects arise when intrinsic p_T is not integrated out!

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

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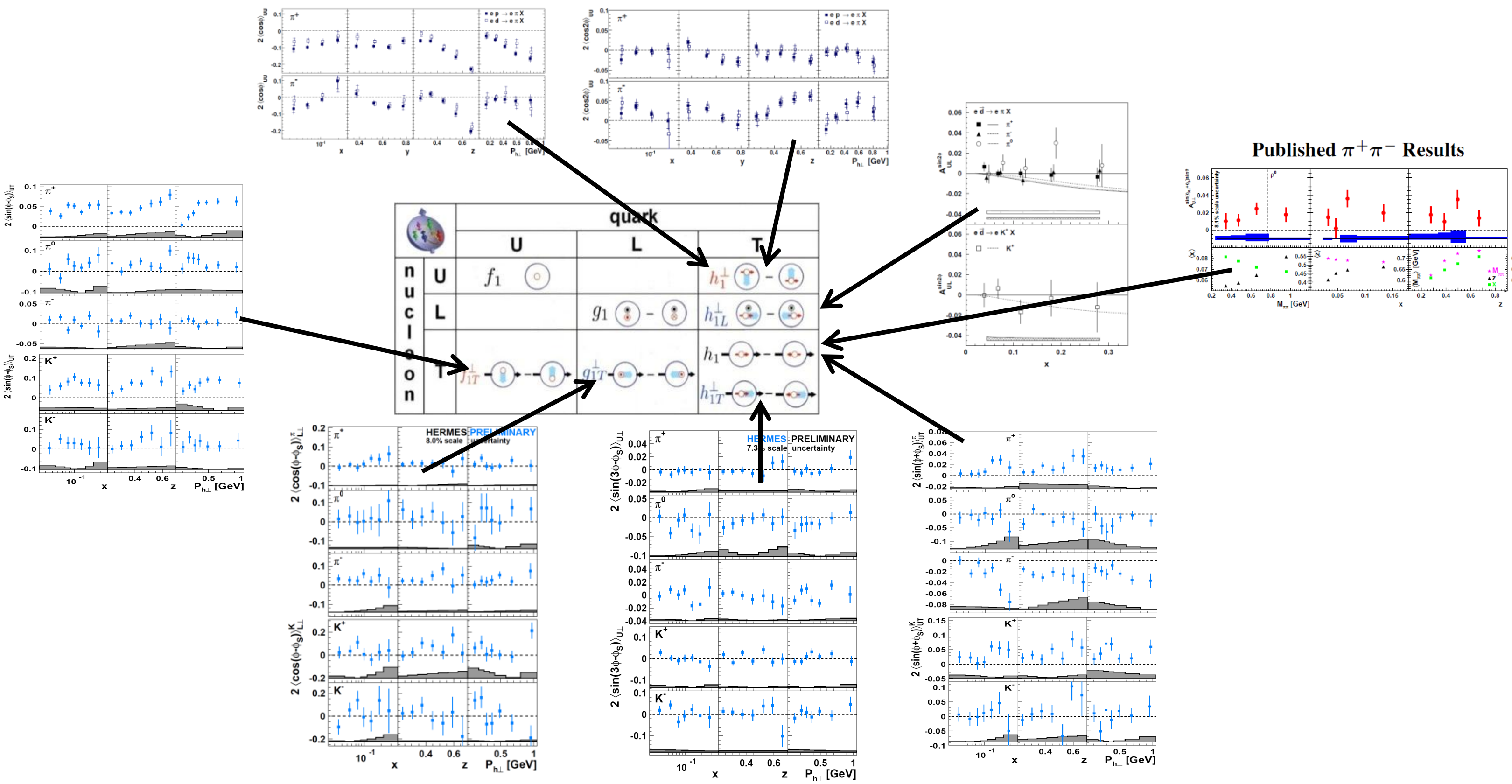
The HERMES experiment has played a pioneering role in these studies:



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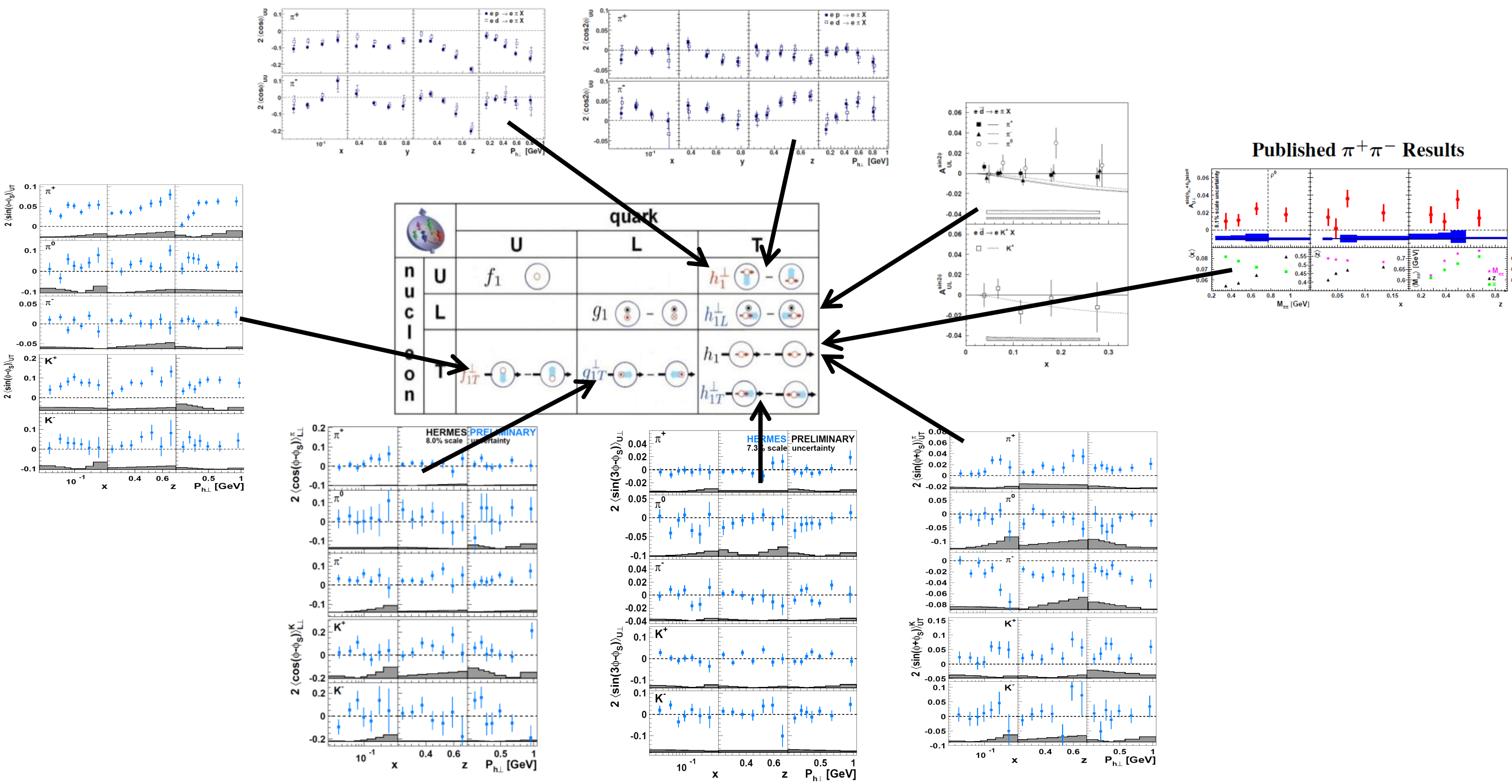


HERMES results in inclusive hadron electroproduction reveal interesting features in common with A_N in $pp^{\uparrow}$ scattering and with Sivers effect in SIDIS.
A rich phenomenology is revealed when the various subsamples are analyzed separately

Back-up

Transversity

$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}h_1 H_1^{\perp}\right]$$

Describes probability to find transversely polarized quarks in a transversely polarized nucleon

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

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

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

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

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

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

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

Distribution Functions

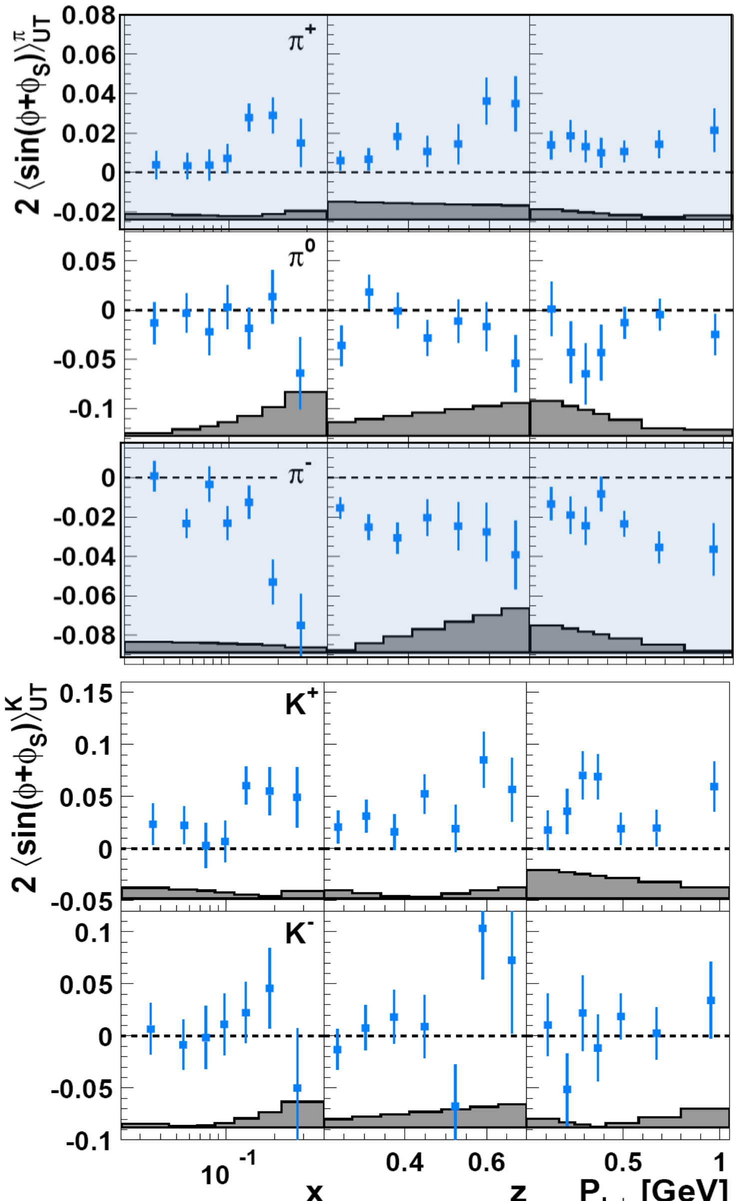
nucleon \ quark	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Fragmentation Functions

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

Collins amplitudes $\propto h_1(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

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



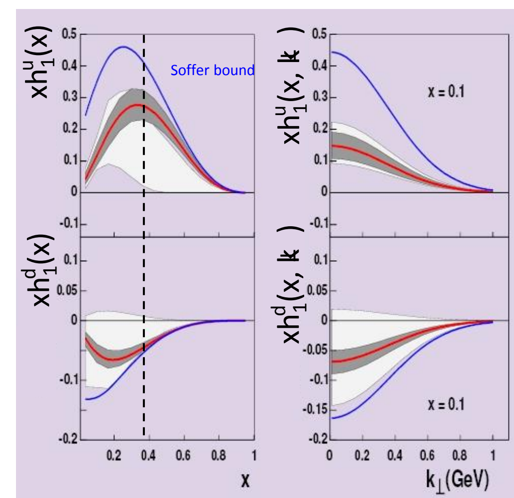
- π^+: positive
- π^0: consistent with zero (isospin-symmetry)
- π^-: large and negative!
- K^+: significantly positive
- K^-: consistent with zero

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

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

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

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



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

Subleading twist

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}\,\mathcal{C}\Big\{\Big(x f_T D_1 - \frac{M_h}{M}\,h_1\frac{\tilde{H}}{z}\Big) - \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\Big[\Big(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^{\perp}}{z}\Big) - \Big(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\Big)\Big]\Big\}$$

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

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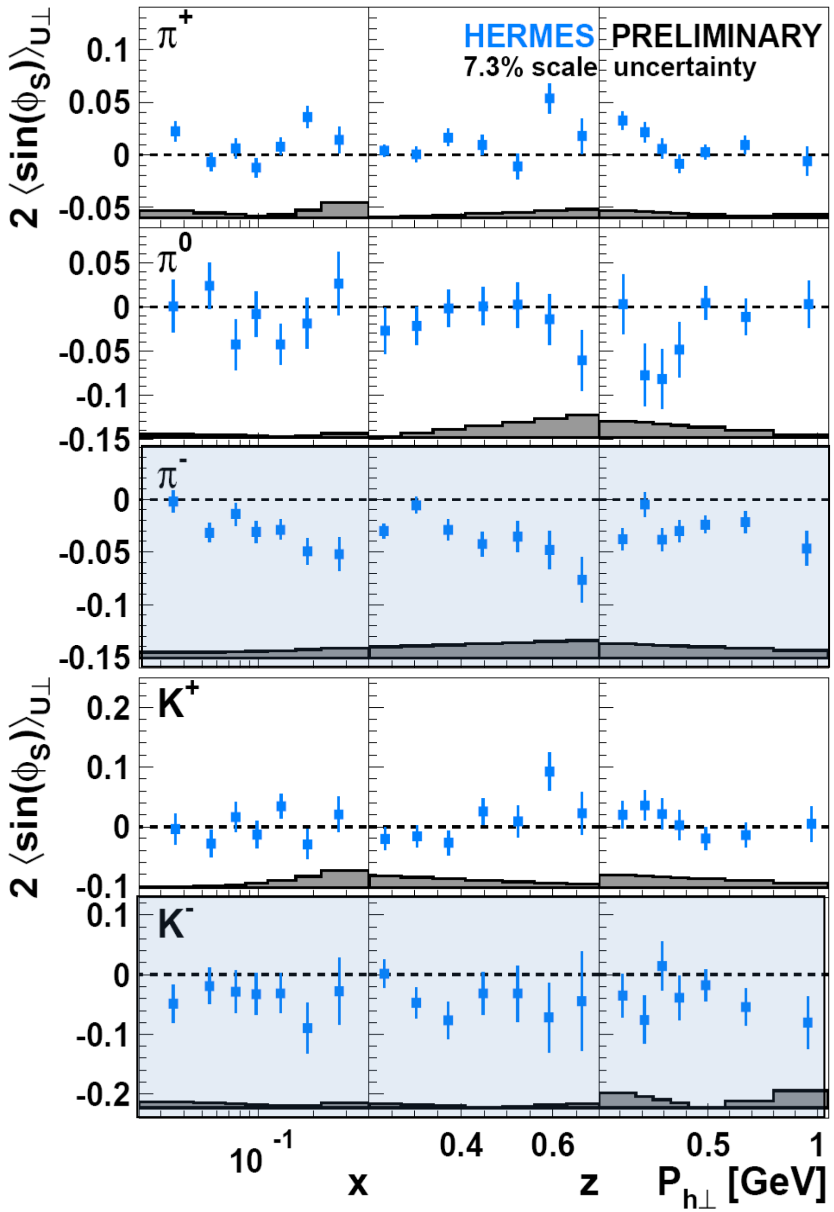
Sensitive to worm-gear $g_{1T}^{\perp}$, sivers, transversity + higher-twist DF and FF

Distribution Functions

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, $h_{1T}^{\perp}$

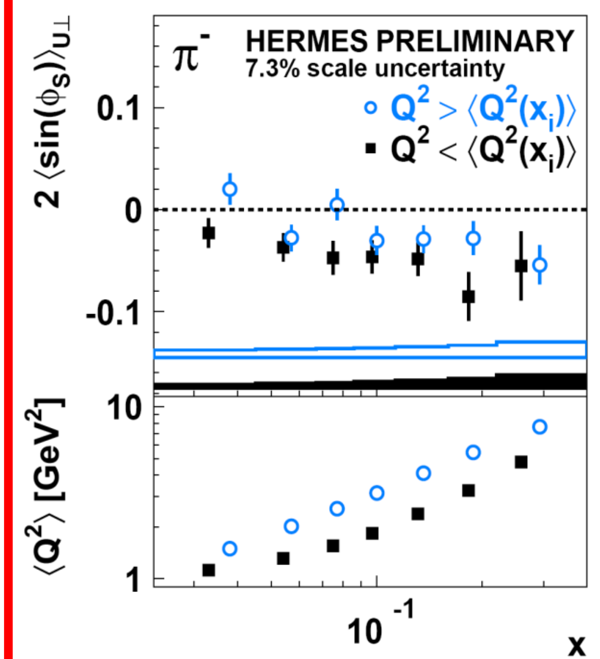
Subleading-twist sin(ϕ$_S$) Fourier component



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

Large and negative

negative



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

Pretzelosity

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

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

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

- Sensitive to **non-spherical shape** of the nucleon

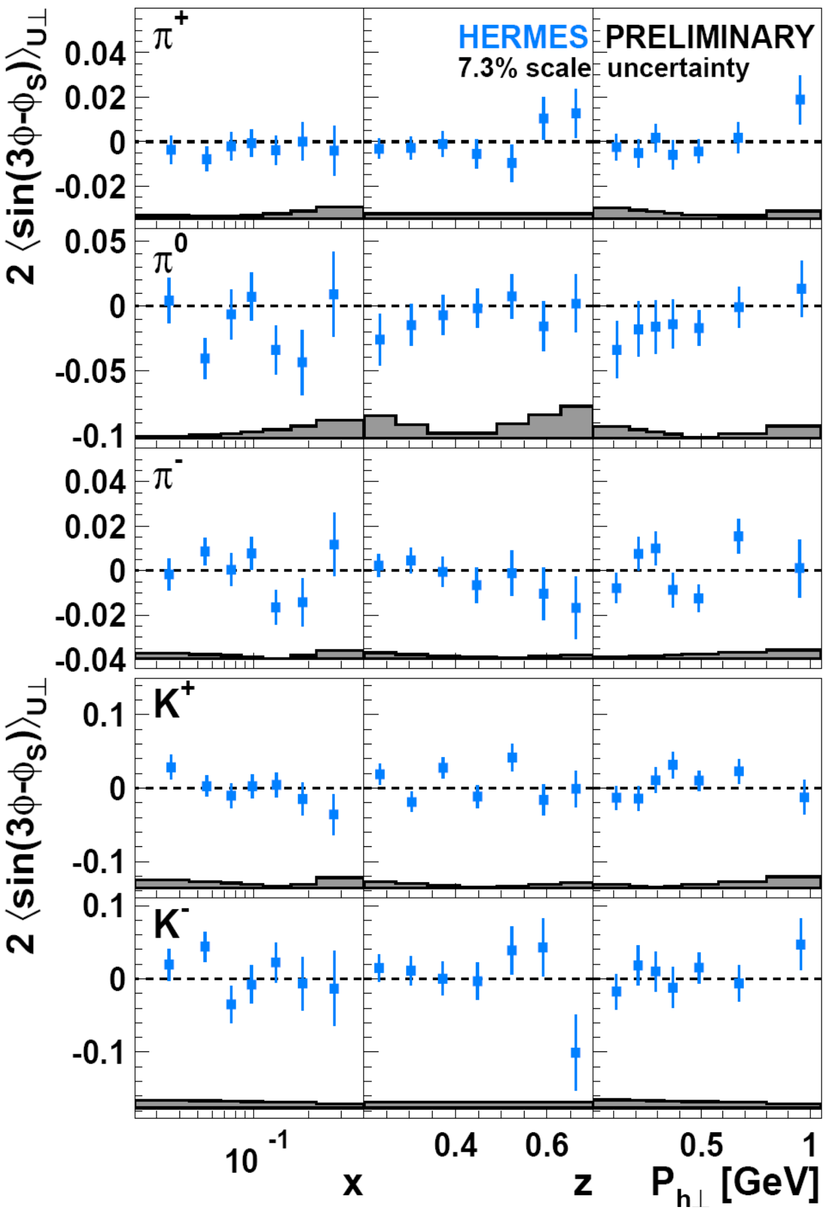
Distribution Functions

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

Fragmentation Functions

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

The sin(3ϕ-ϕ_s) amplitude $\propto h_{1T}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

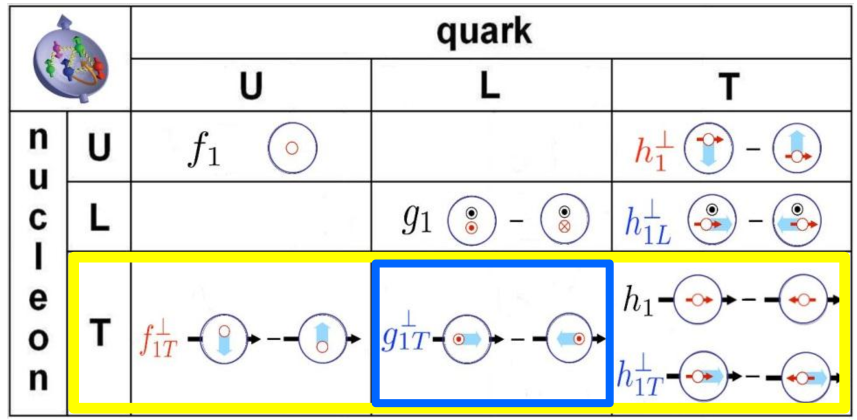


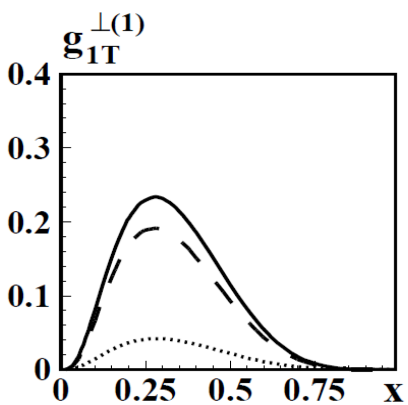
All amplitudes consistent with zero

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

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

- 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

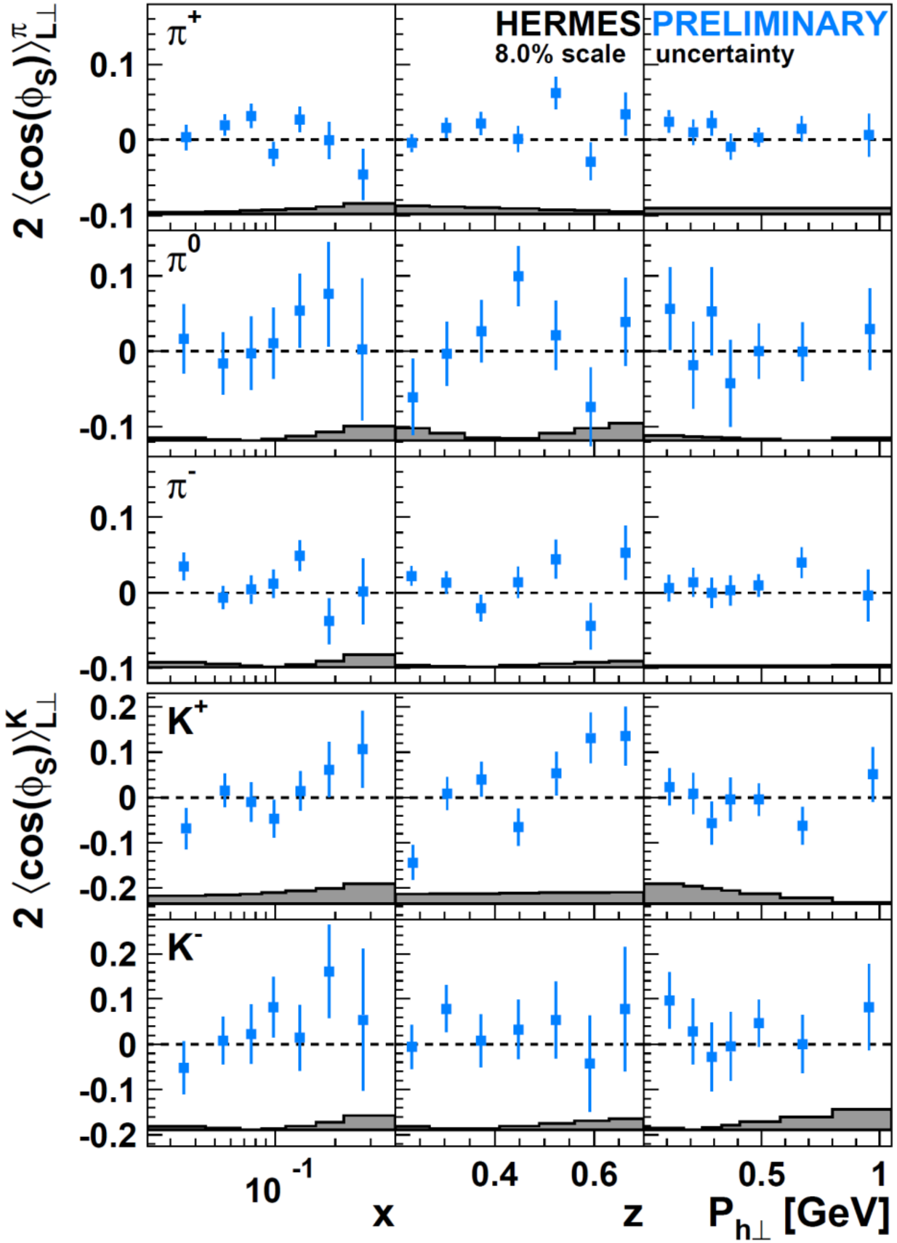
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} g_{1T} D_1\right]$$

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

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

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



π^+: ≈ 0

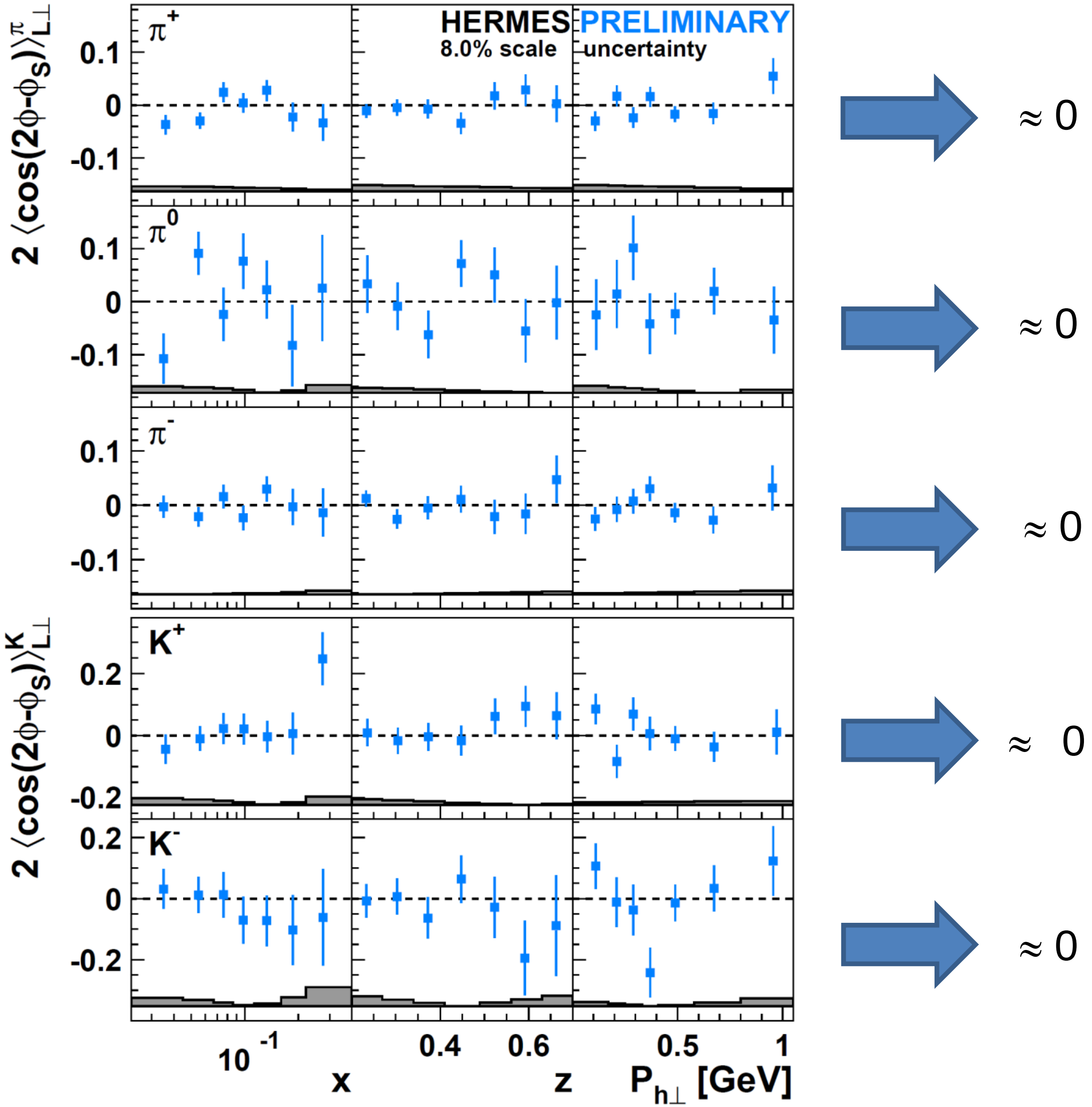
π^0: ≈ 0

π^-: ≈ 0

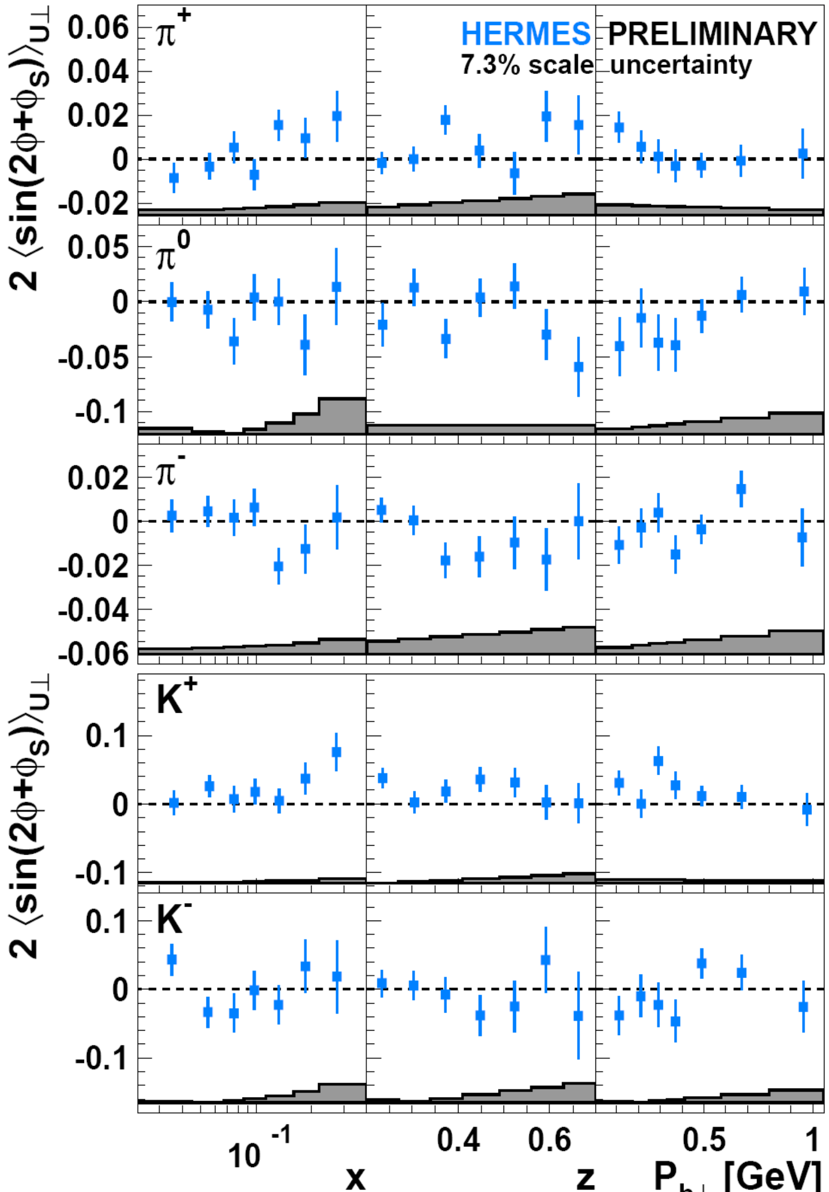
K^+: ≈ 0
sign change?

K^-: ≈ 0

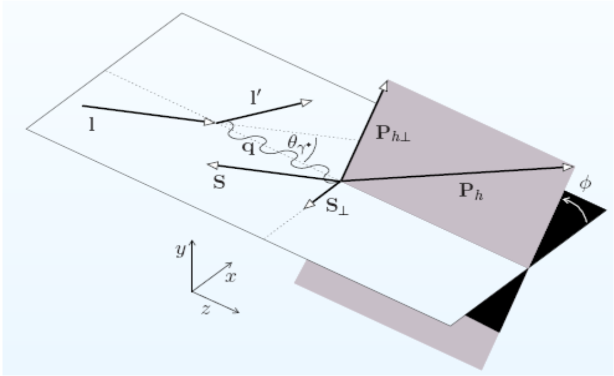
The cos(2ϕ-ϕ_S) Fourier component



The sin(2ϕ+ϕ$_S$) Fourier component



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

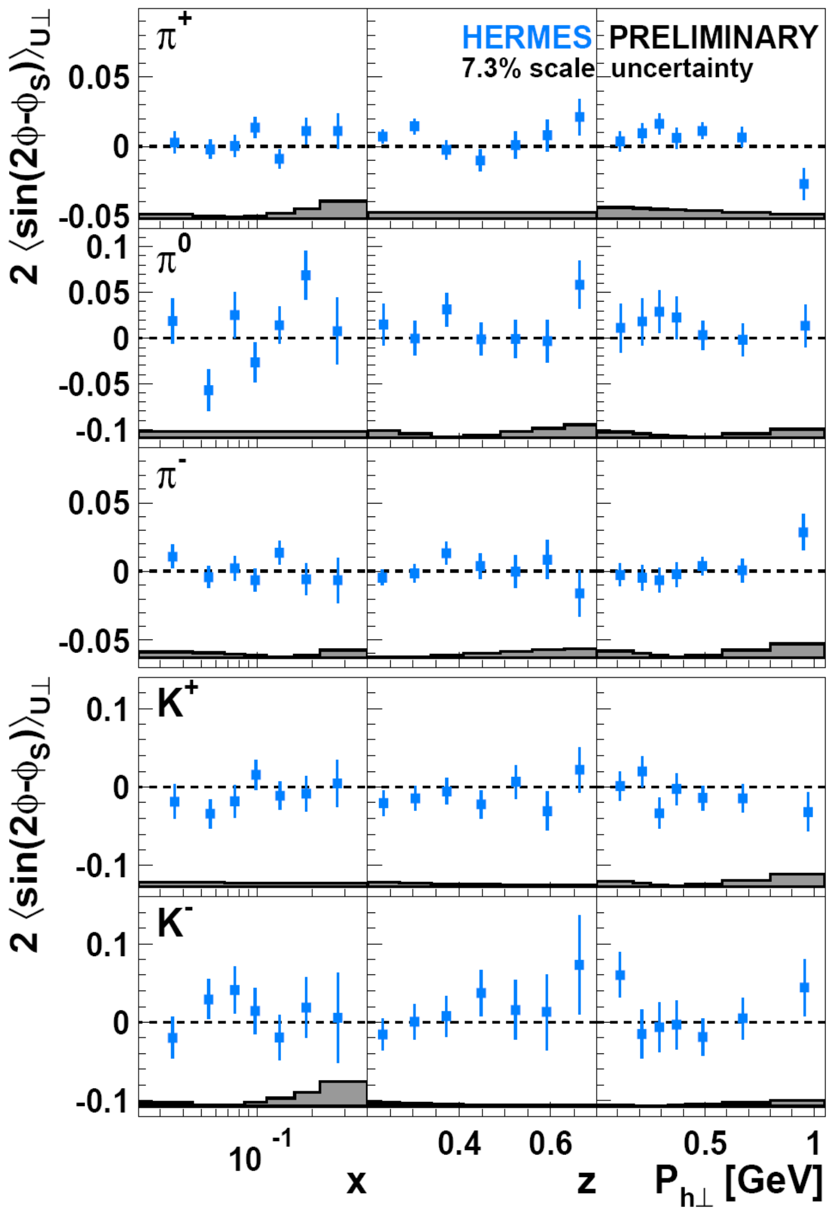


- related to <sin(2ϕ)>$_{UL}$ Fourier comp:

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

- 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 $\sin(2\phi-\phi_S)$ Fourier component



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

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

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

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

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

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

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

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

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

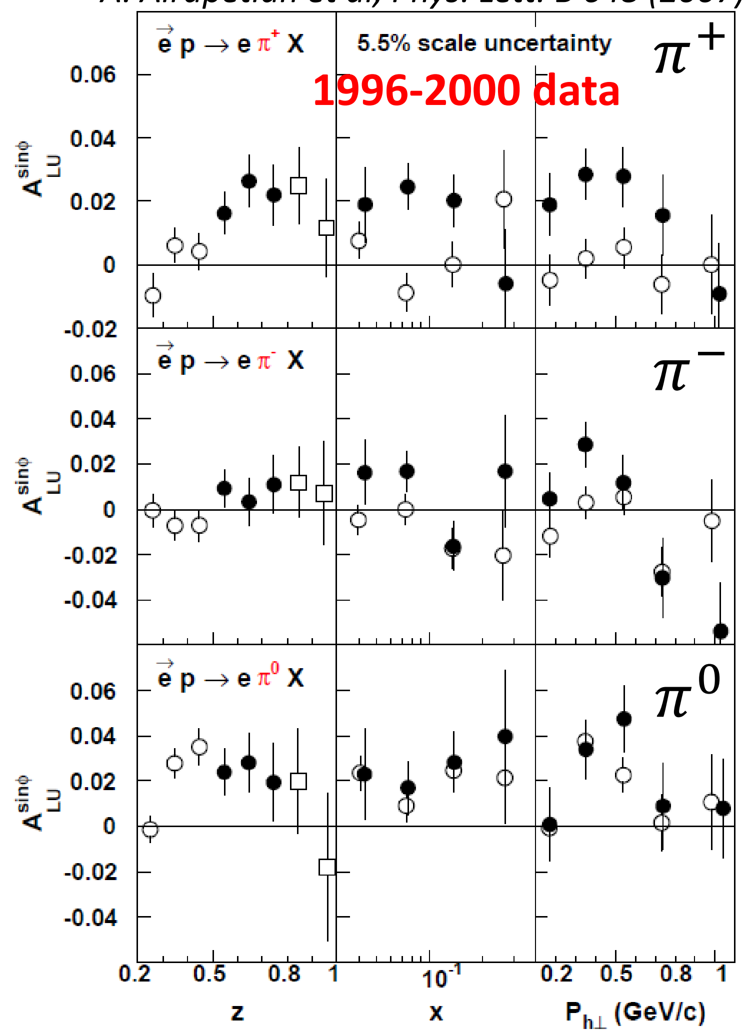
$$+\ S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

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

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

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

A. Airapetian et al, Phys. Lett. B 648 (2007)

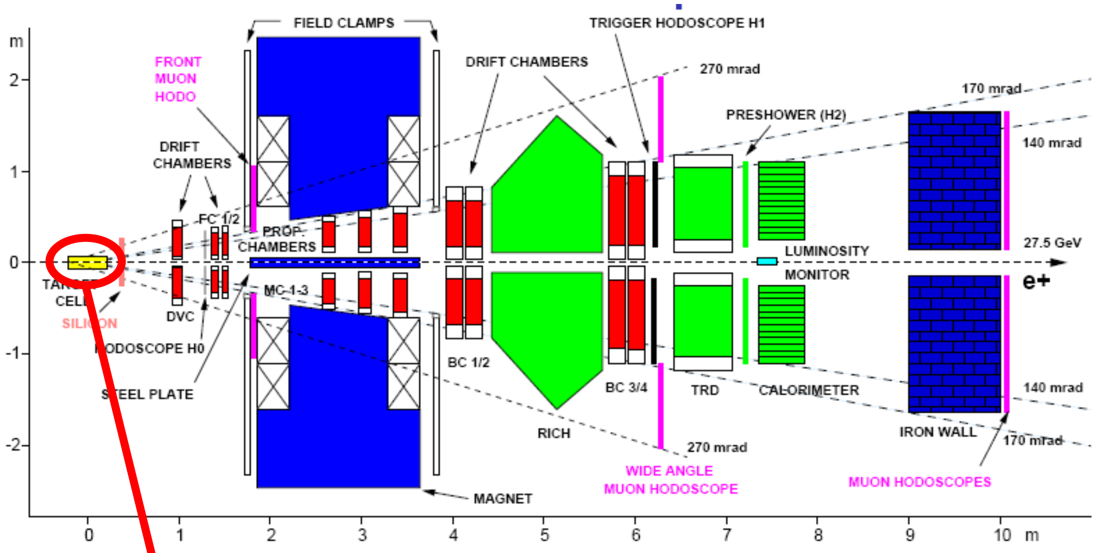


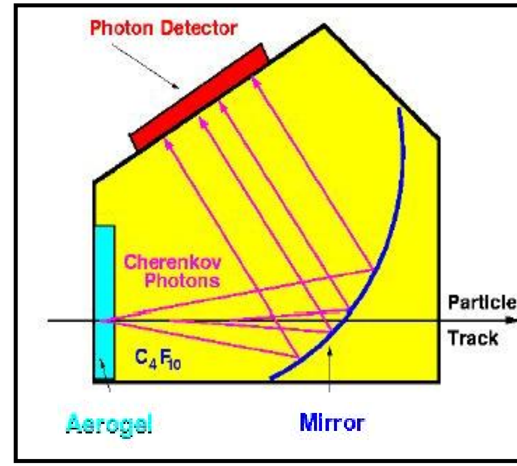
open circles 0.2<z<0.5

full circles 0.5<z<0.8

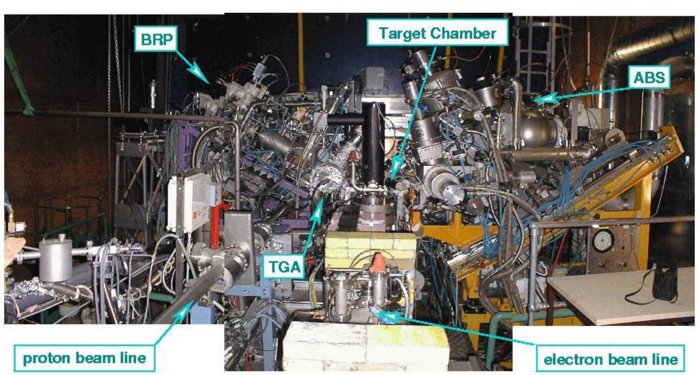
open squares: 0.8<z<1.0

The HERMES experiment at HERA



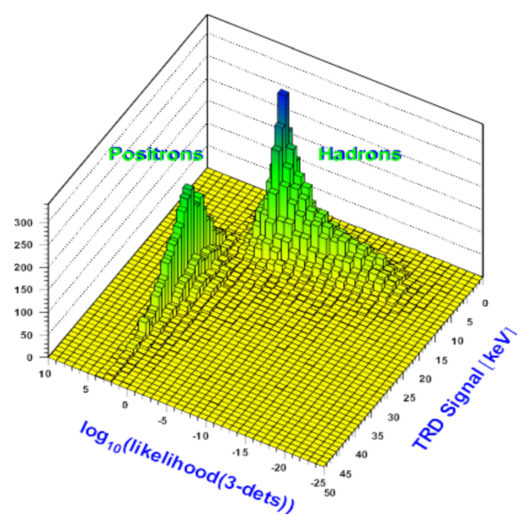


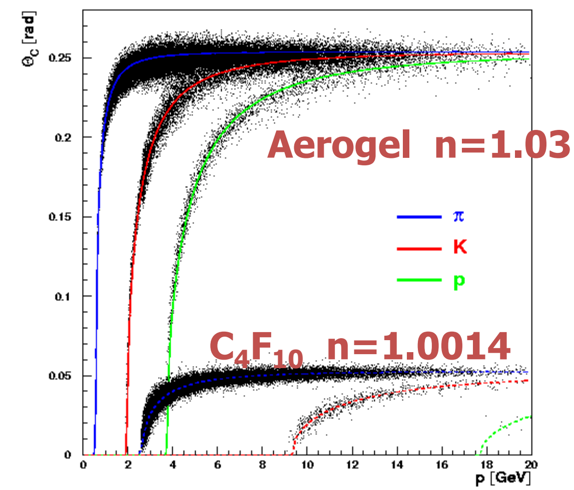
hadron separation



TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%





π ~ 98%, K ~ 88% , P ~ 85%

2-hadron SIDIS results

Following formalism developed by **Steve Gliske**

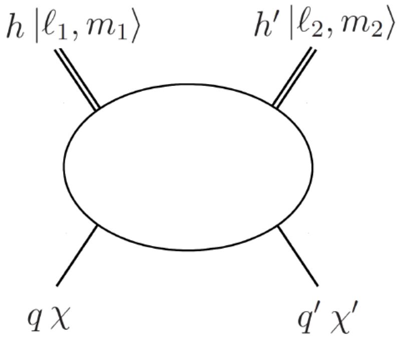
Find details in

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:

$$\begin{aligned}
D_1^{|0,0\rangle} &= D_{1,OO} = \left(\frac{1}{4}D_{1,OO}^{s} + \frac{3}{4}D_{1,OO}^{p}\right)\\
D_1^{|1,0\rangle} &= D_{1,OL},\\
D_1^{|1,\pm1\rangle} &= D_{1,OT} \mp \frac{|\boldsymbol{k}_T|\,|\boldsymbol{R}|}{M_h^2} G_{1,OT}^{\perp},\\
D_1^{|2,0\rangle} &= \frac{1}{2} D_{1,LL},\\
D_1^{|2,\pm1\rangle} &= \frac{1}{2}\left(D_{1,LT} \mp \frac{|\boldsymbol{k}_T|\,|\boldsymbol{R}|}{M_h^2} G_{1,LT}^{\perp}\right),\\
D_1^{|2,\pm2\rangle} &= D_{1,TT} \mp \frac{1}{2}\frac{|\boldsymbol{k}_T|\,|\boldsymbol{R}|}{M_h^2} G_{1,TT}^{\perp},
\end{aligned}$$

$$\begin{aligned}
H_1^{\perp|0,0\rangle} &= H_{1,OO}^{\perp} = \frac{1}{4}H_{1,OO}^{\perp s} + \frac{3}{4}H_{1,OO}^{\perp p},\\
H_1^{\perp|1,1\rangle} &= H_{1,OT}^{\perp} + \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|}\bar{H}_{1,OT}^{\sphericalangle} = \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} H_{1,OT}^{\sphericalangle}\\
H_1^{\perp|1,0\rangle} &= H_{1,OL}^{\perp}\\
H_1^{\perp|1,-1\rangle} &= H_{1,OT}^{\perp}\\
H_1^{\perp|2,2\rangle} &= H_{1,TT}^{\perp} + \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|}\bar{H}_{1,TT}^{\sphericalangle} = \frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} H_{1,TT}^{\sphericalangle},\\
H_1^{\perp|2,1\rangle} &= \frac{1}{2}H_{1,LT}^{\perp} + \frac{1}{2}\frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|}\bar{H}_{1,LT}^{\sphericalangle} = \frac{1}{2}\frac{|\boldsymbol{R}|}{|\boldsymbol{k}_T|} H_{1,LT}^{\sphericalangle},
\end{aligned}$$

$$\begin{aligned}
H_1^{\perp|2,0\rangle} &= \frac{1}{2} H_{1,LL}^{\perp},\\
H_1^{\perp|2,-1\rangle} &= \frac{1}{2} H_{1,LT}^{\perp},\\
H_1^{\perp|2,-2\rangle} &= H_{1,TT}^{\perp}.
\end{aligned}$$

The di-hadron SIDIS cross-section

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

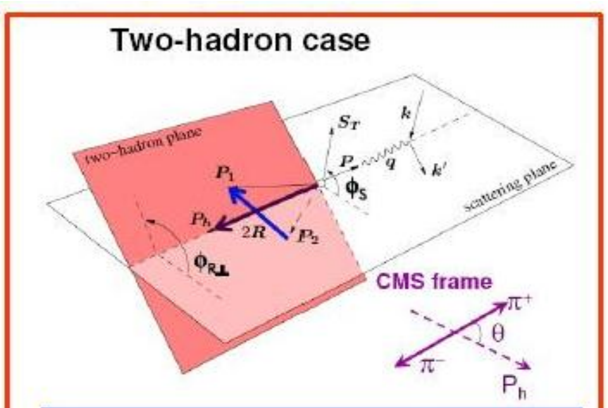
l and m correspond to $|lm\rangle$ angular momentum state of the hadron

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

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

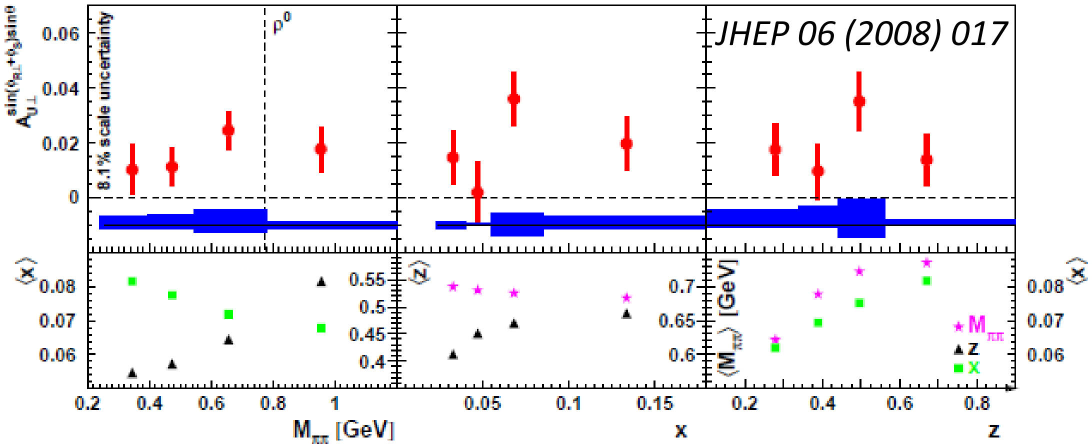
which for $l = 1$ and $m = 1$ reduces to the well known collinear $F_{UT}{}^{\sin\vartheta\,\sin(\phi_R+\phi_S)}$ related to transversity

The di-hadron SIDIS cross-section



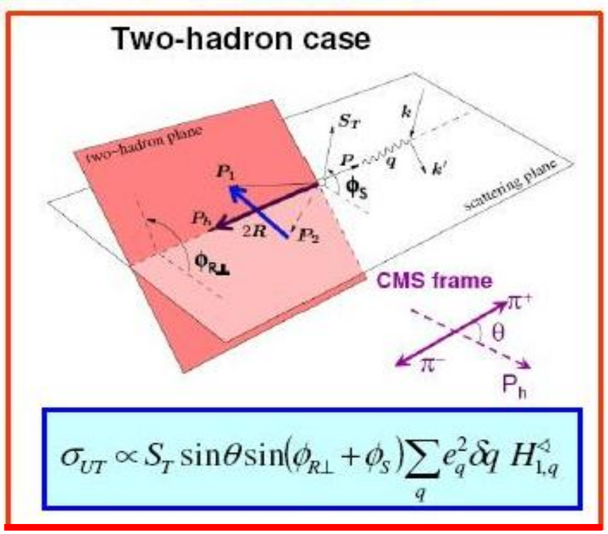
$$\sigma_{UT} \propto S_T \sin\theta \sin(\phi_{R\perp} + \phi_S) \sum_q e_q^2 \delta q \, H_{1,q}^{\sphericalangle}$$

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

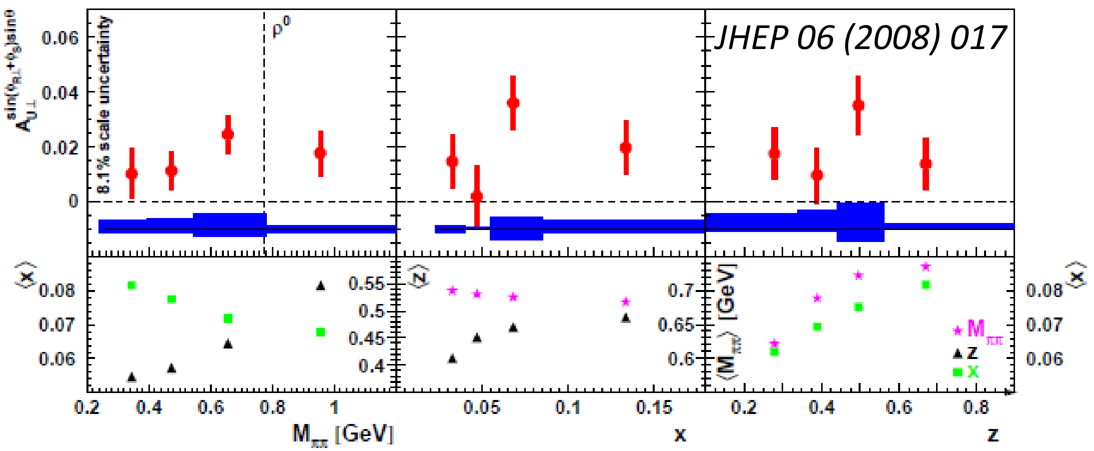


- independent way to access transversity
- Collinear → no convolution integral
- significantly positive amplitudes
- 1^{st} evidence of non zero dihadron FF
- limited statistical power (v.r.t. 1 hadron)

The di-hadron SIDIS cross-section

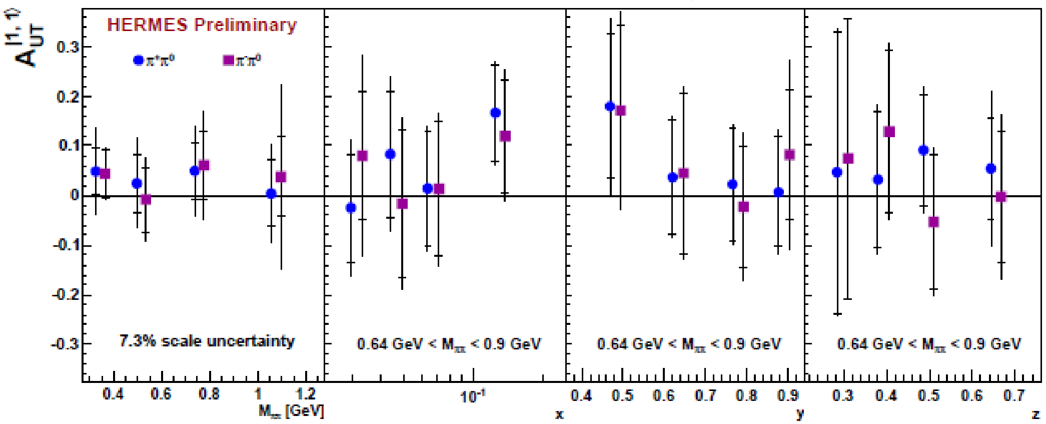


Published $\pi^+\pi^-$ Results



- 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 $\pi^{\pm}\pi^0$ Results

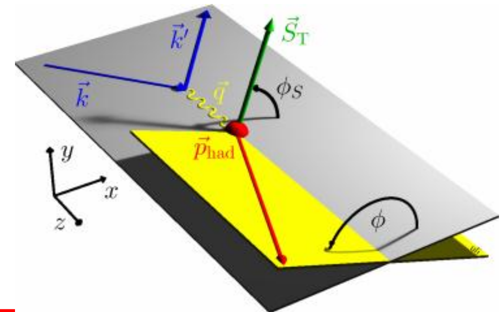


- New tracking, new PID, use of ϕ_R rather than $\phi_{R\perp}$
- Different fitting procedure and function
- Acceptance correction

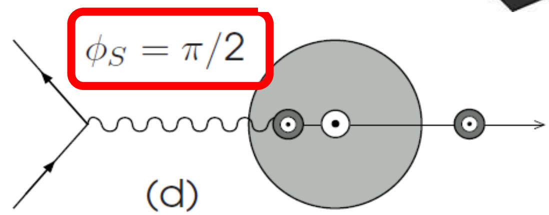
A short digression on the Lund/Artru string fragmentation model

(a phenomenological explanation of the Collins effect)

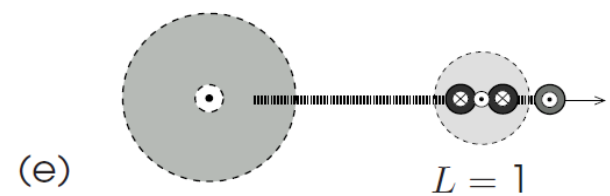
In the cross-section the Collins FF is always paired withy a distrib. function involving a transv. pol. quark.



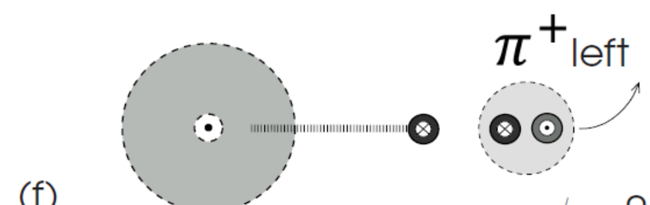
1. Assume u quark and proton have (transverse) spin alligned in the direction $\phi_S = \pi/2$. The model assumes that the struck quark is initially connected with the remnant via a gluon-flux tube (string)



2. When the string breaks, a $q\bar{q}$ pair is created with vacuum quantum numbers $J^P = 0^+$. The positive parity requires that the spins of q and $\bar{q}$ are aligned, thus an OAM $\boldsymbol{L} = \mathbf{1}$ has to compensate the spins



3. This OAM generates a transverse momentum of the produced pseudo-scalar meson (e.g. $\boldsymbol{\pi}^+$) and deflects the meson to the **left side** w.r.t. the struck quark direction, generating left-righ azimuthal asymmetries



A short digression on the Lund/Artru string fragmentation model

Relative to the proton transv. spin, the fragmenting quark can have spin parallel or antiparallel to $\left|\frac{1}{2}, \pm\frac{1}{2}\right\rangle$

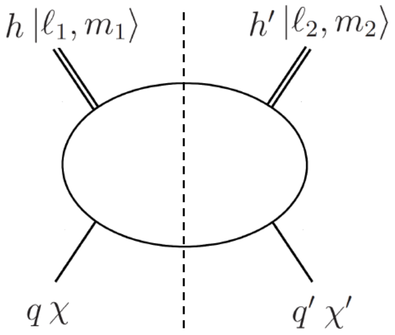
Then combining the spins of the formed di-quark systems one can get:

$$\frac{1}{2} \otimes \frac{1}{2} = 1 \oplus 0 \;\Rightarrow \begin{cases} 1\ spin\ 0\ state\ |0,0\rangle & \text{1 pseudo-scalar meson (PSM)} \\ 3\ spin\ 1\ states \begin{cases} |1,0\rangle \\ |1,\pm1\rangle \end{cases} & \begin{array}{l}\text{1 Longitudinal VM} \\ \text{2 transvrse VM}\end{array} \end{cases}$$

Lund/Artru prediction at the amplitude level: the asymmetry for PSM has opposite sign to that for transversely polarized VM (left vs. right side), and the amplitude for $|1,0\rangle$ is 0

Lund/Artru model makes predictions for the individual di-hadrons, but the Collins function includes pairs of di-hadrons

→ to make predictions for the Collins function one needs to consider the cross-section level, i.e. the sum of contributing amplitudes times their complex conjugate



Using the Clebsch-Gordan algebra one obtains: $|1,\pm1\rangle\,|1,\pm1\rangle \equiv |2,\pm2\rangle$

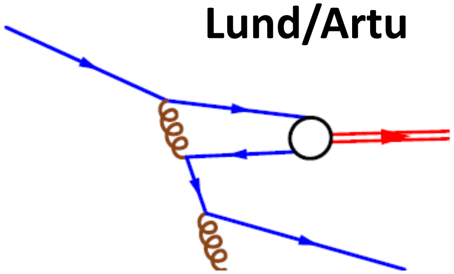
Lund/Artru prediction at the cross-section level: the $|2,\pm2\rangle$ partial waves of the Collins func. for SIDIS VM production have the opposite sign as the respective PS Collins func.

“gluon radiaton model” vs. Lund/Artru model

The Lund/Artru model only accounts for favored Collins fragmentation. An extension of the model (the **gluon radiation model**), elaborated by **S. Gliske** accounts for the disfavored case

1. Struck quark emits a gluon in such a way that most of its momentum is transferred to the gluon
2. The struck quark then becomes part of the remnant
3. The radiated gluon produces a $q\bar{q}$ pair that eventually converts into a meson
4. For PSM the di-quark must interact further with the remnant to get the PSM quantum numbers. In case of VM the di-quark directly forms the meson

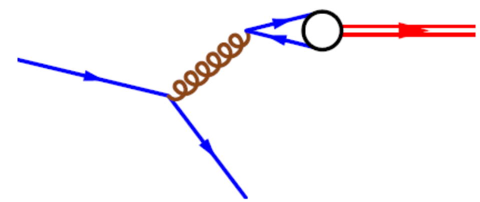
Lund/Artu



- Di-quark has q.n. of vacuum
- **Struck quark** joins the anti-quark in the final state $\rightarrow$ **favored fragment.**

Prediction: the $|2, \pm 2\rangle$ partial wave of the Collins funct. for SIDIS VM production have the opposite sign as the respective PS Collins function

Gluon radiation



- Di-quark has q.n. of observed final state
- **Produced quark** joins the anti-quark in the final state $\rightarrow$ **disfavored fragment.**

Prediction: the disfavored $|2, \pm 2\rangle$ Collins frag. also is expected to have opposite sign as the respective PS Collins function.

⇨ Models predict: fav = disfav for VM

Data say: fav $\cong -$ disfav for PSM (Collins π^+ $vs.$ π^-)

…and now let's look at the results

Fragment. process	Fav/disfav	Deflection	Sign of amplitude
$\boldsymbol{u} \rightarrow \boldsymbol{\pi}^+$	fav PSM	left $(\phi_h \rightarrow 0)$	> 0 (Collins π^+)
$\boldsymbol{u} \rightarrow \boldsymbol{\pi}^-$	disfav PSM	ight $(\phi_h \rightarrow \pi)$	< 0 (Collins π^-)
$\boldsymbol{u} \rightarrow \boldsymbol{\rho}^+ \rightarrow \pi^+\pi^0$	fav VM	right $(\phi_h \rightarrow \pi)$	< 0
$\boldsymbol{u} \rightarrow \boldsymbol{\rho}^- \rightarrow \pi^-\pi^0$	disfav VM	right $(\phi_h \rightarrow \pi)$	< 0
$\boldsymbol{u} \rightarrow \boldsymbol{\rho}^{\mathbf{0}} \rightarrow \pi^+\pi^-$	mixed VM	right $(\phi_h \rightarrow \pi)$	0 or < 0

u dominance

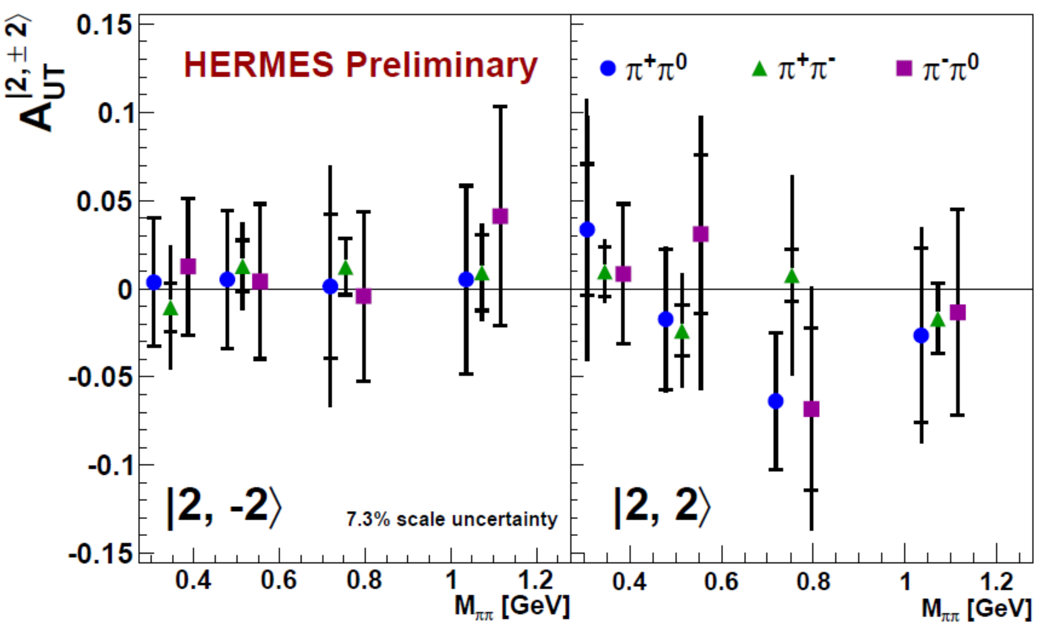
from data

from models

…and now let's look at the results

Fragment. process	Fav/disfav	Deflection	Sign of amplitude
$u \rightarrow \pi^+$	fav PSM	left ($\phi_h \rightarrow 0$)	> 0 (Collins π^+)
$u \rightarrow \pi^-$	disfav PSM	ight ($\phi_h \rightarrow \pi$)	< 0 (Collins π^-)
$u \rightarrow \rho^+ \rightarrow \pi^+\pi^0$	fav VM	right ($\phi_h \rightarrow \pi$)	< 0
$u \rightarrow \rho^- \rightarrow \pi^-\pi^0$	disfav VM	right ($\phi_h \rightarrow \pi$)	< 0
$u \rightarrow \rho^0 \rightarrow \pi^+\pi^-$	mixed VM	right ($\phi_h \rightarrow \pi$)	0 or < 0

u dominance (all rows); from data (rows 1–2); from models (rows 3–5)

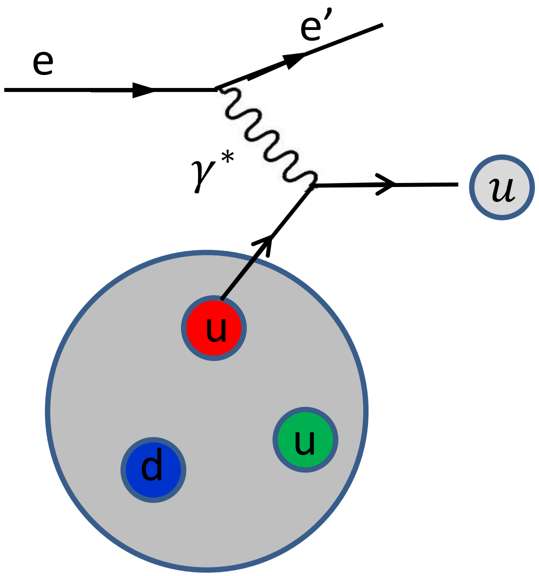


$|2,-2\rangle$ consistent with zero for all flavors
Not in contraddiction with models: if the transversity function causes the fragmenting quark to have positive polarization than Collins $|2,-2\rangle$ must be zero as this partial wave requires fragmenting quark with negative polarization

$|2,+2\rangle$ consistent with model expect:

- No signal outside ρ-mass bin
  $\rightarrow$ no non-resonant pion-pairs in p-wave
- Negative for $\rho^\pm$ (model predictions)
- very small for ρ^0 (consistent with small Collins π^0)

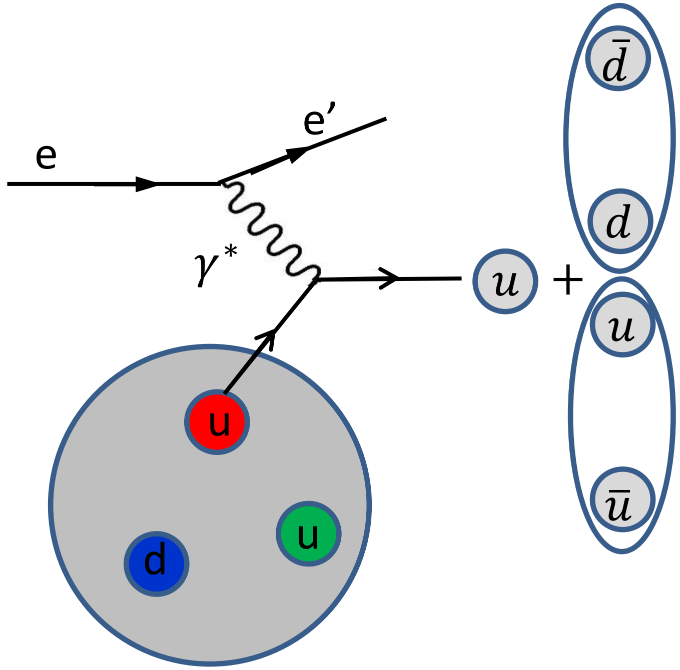
Proton production



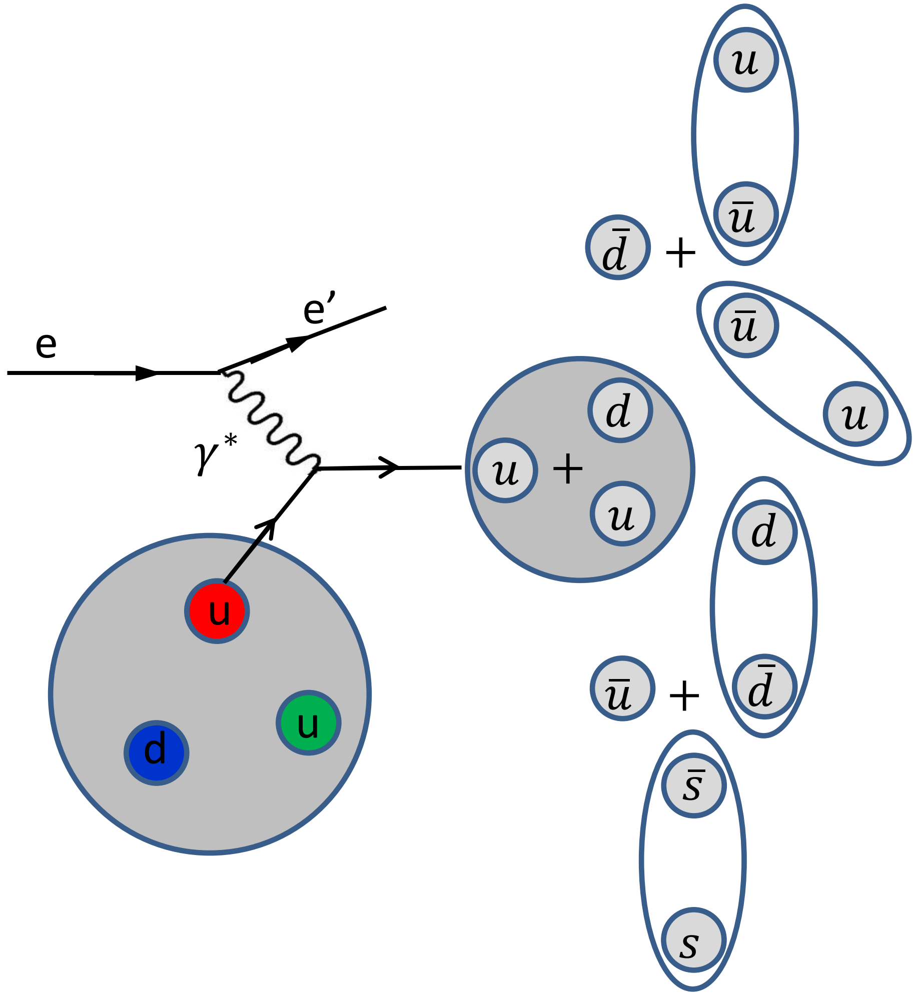
Assume scattering off a u quark

...in next 5 slides a *naive* representation of a fragmentation process that can lead to protons/antiprotons in the final states

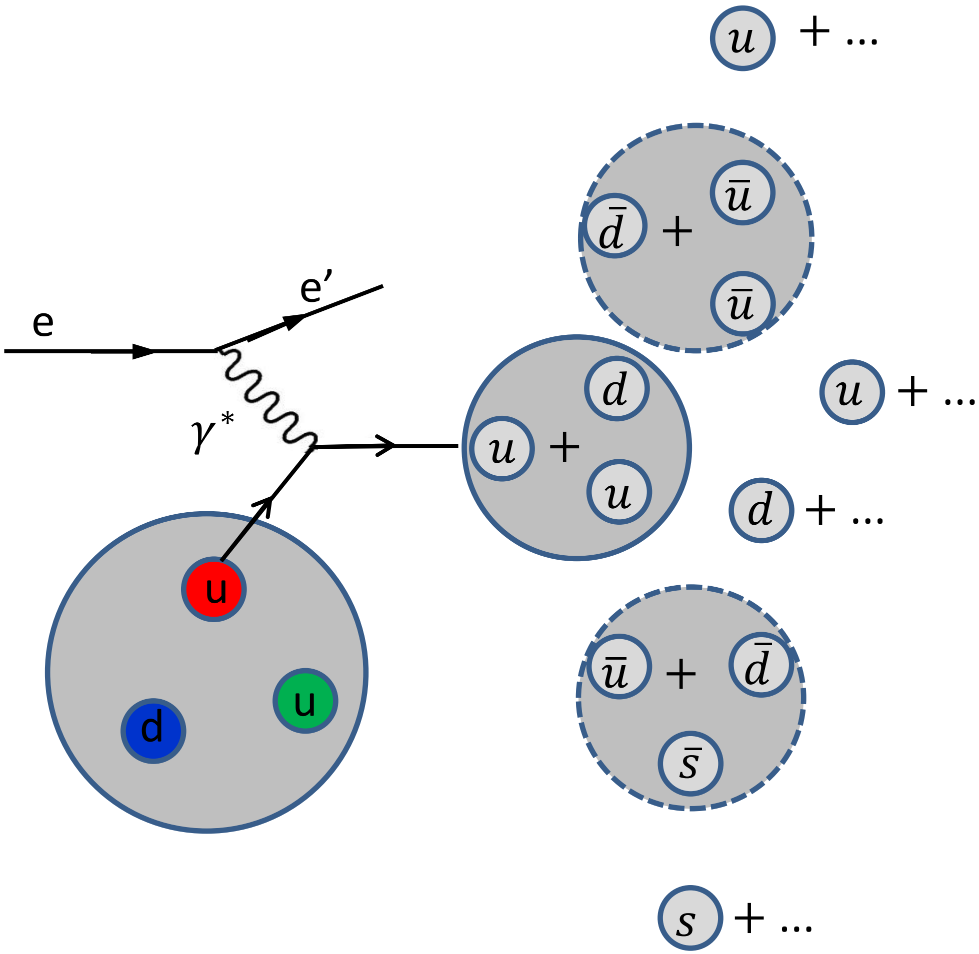
Proton production



Proton production



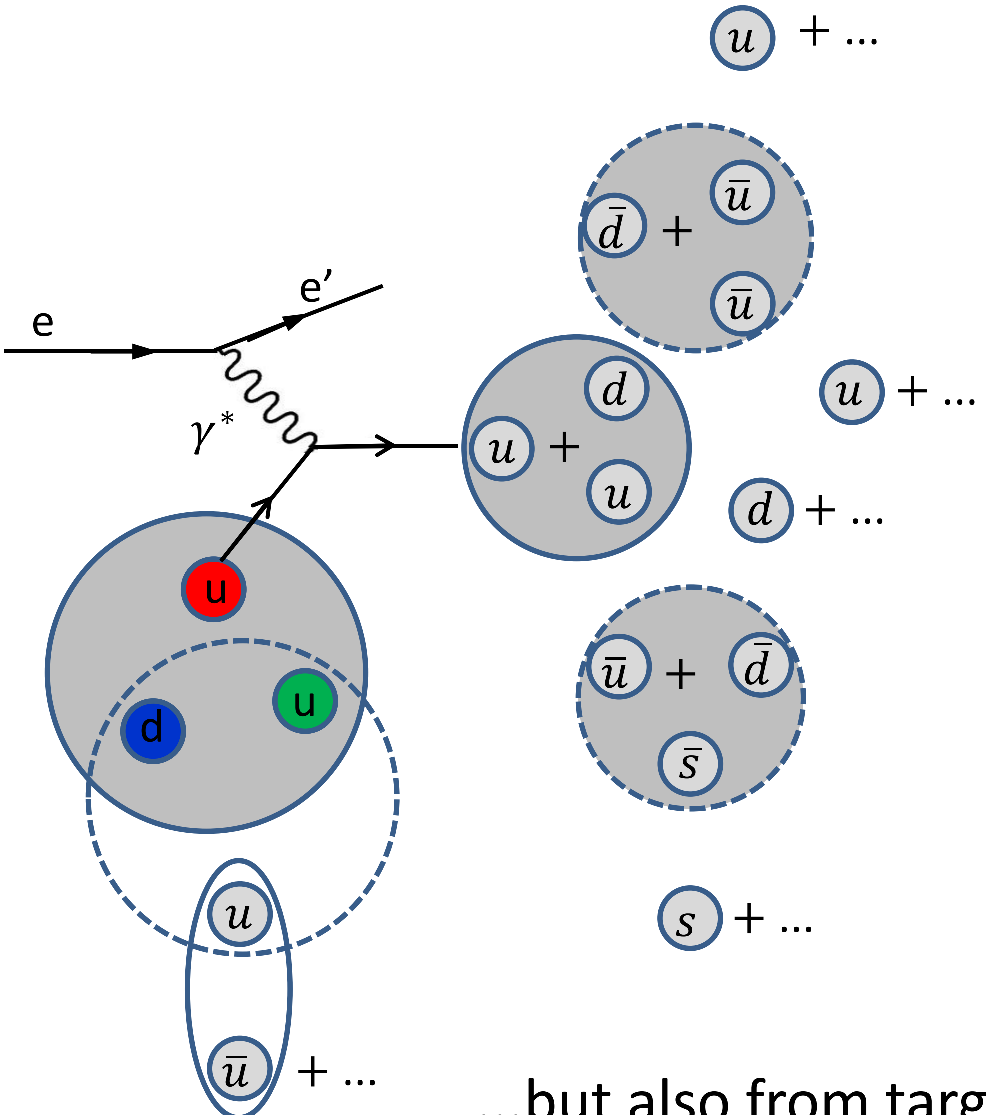
Proton production



$$= p + \bar{p} + \bar{\Lambda} + \ldots ?$$

$$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$$

Proton production



$$= p + \bar{p} + \bar{\Lambda} + \ldots ?$$

$$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$$

...but also from target fragmentation