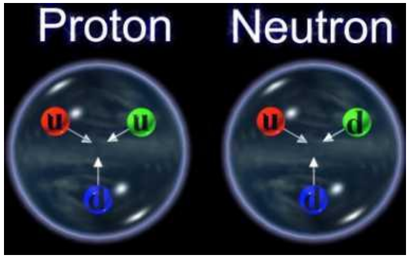
Hermes results on 3D imaging of the nucleon

Luciano L. Pappalardo

University of Ferrara

So popular, yet so misterious…

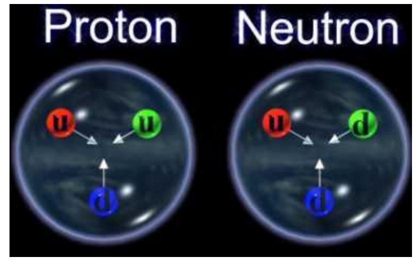
Building bloks of ordinary matter



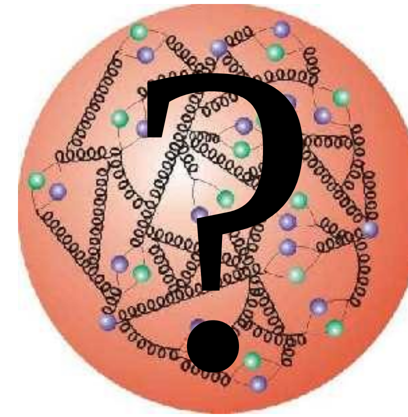
Mass of visible Universe

So popular, yet so misterious…

Building bloks of ordinary matter



Complex inner structure



Mass of visible Universe

npQCD, confinement,…

basic properties from first principles?

- **mass**
- **radius**
- **charge**
- **spin**
- **mag. moment**
- **…**

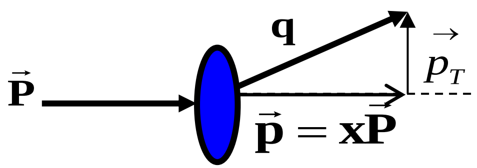
Describing the internal structure of hadrons is one of the most formidable challenges of QCD!

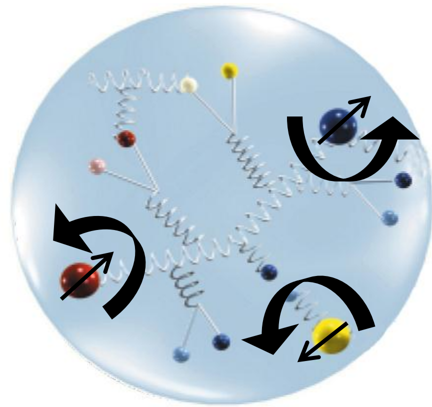
Looking deeply into the proton

What do we want to know? ...everything!

- where are the quarks/gluons located inside a proton? ($\longrightarrow x, y, z \equiv r$)
- how they move? ($\longrightarrow p_x, p_y, p_z \equiv x, p_T$)

Orbital Angular Momentum





Full quantum phase-space distribution of partons

Looking deeply into the proton

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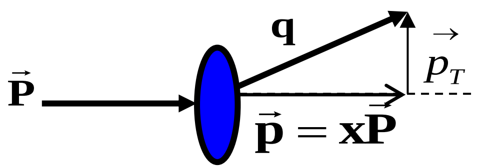
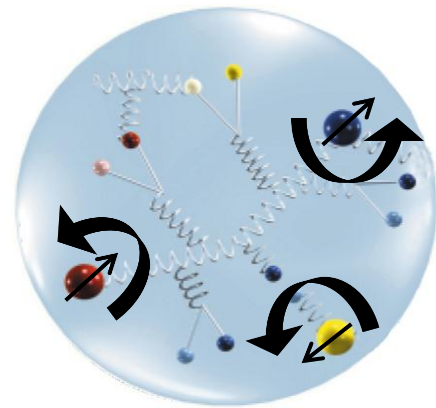
} **Orbital Angular Momentum**





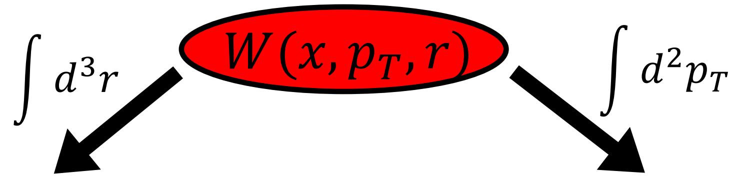
Full quantum phase-space distribution of partons

$W(x, p_T, r)$ **Wigner function**

- represents the maximal knowledge of the partonic structure of nucleons
- equivalent to knowing the complete wave function of partons inside the nucleon
- can be used in principle to compute expectation values of any physical observable

The phase-space distribution of partons

...but $\Delta x \Delta p \geq \frac{\hbar}{2}$ $\rightarrow$ cannot be accessed experimentally $\rightarrow$ **integrated quantities**



The phase-space distribution of partons

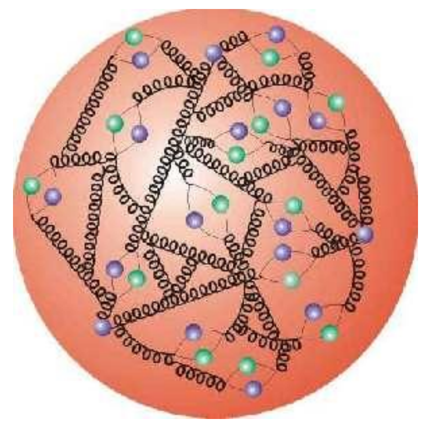
...but $\Delta x \Delta p \geq \frac{\hbar}{2}$ $\rightarrow$ cannot be accessed experimentally $\rightarrow$ **integrated quantities**

$W(x, p_T, r)$

$\int d^3r$ $\rightarrow$ TMDs $f(x, p_T)$

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

3D descriptions



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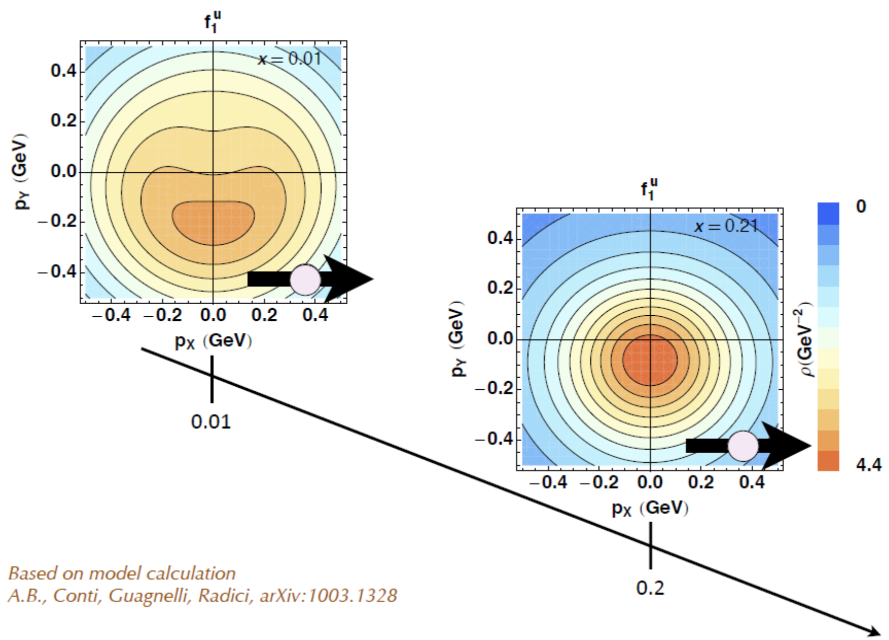
3D descriptions

Nucleon tomography!



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

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3D descriptions

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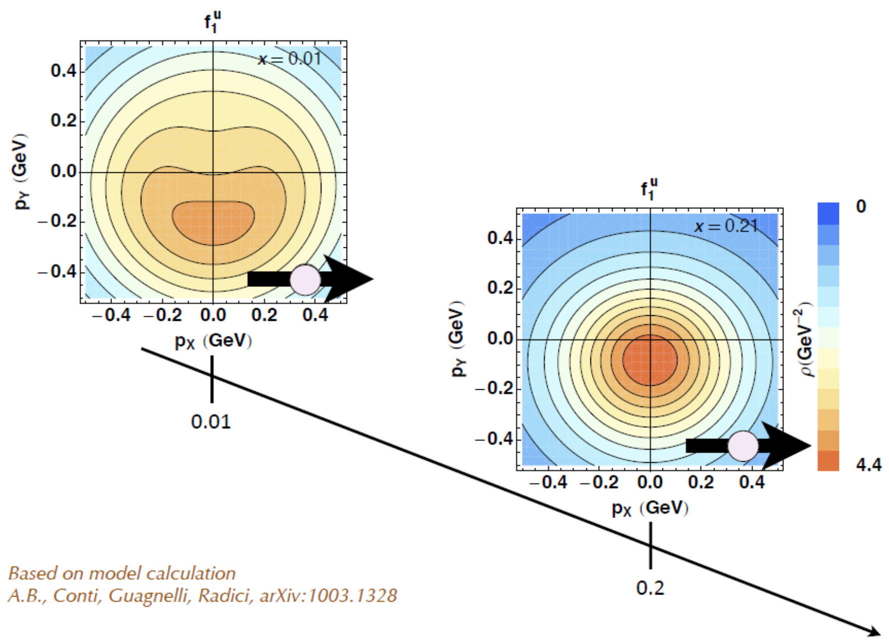

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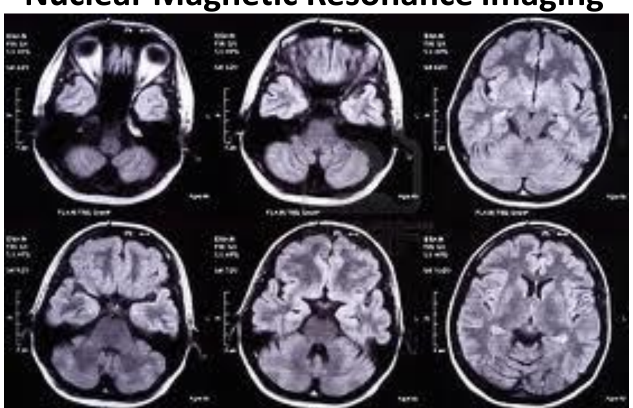
Nuclear Magnetic Resonance imaging



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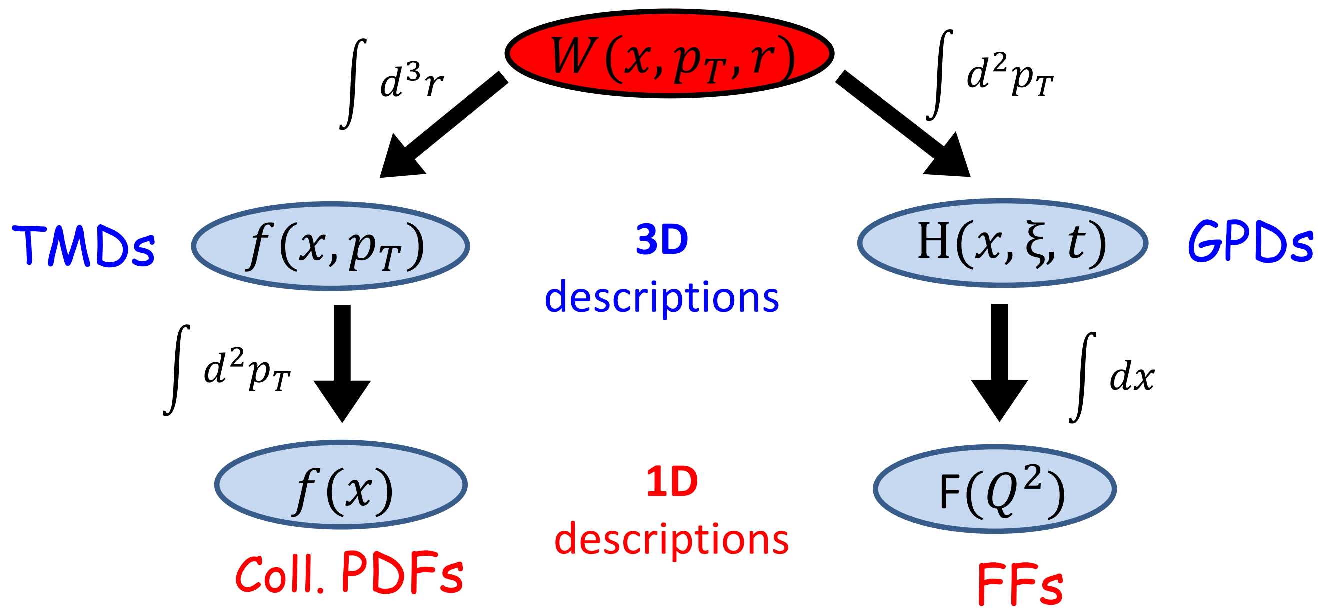

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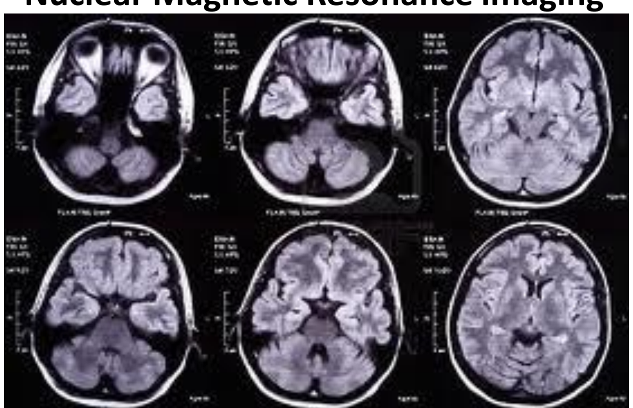
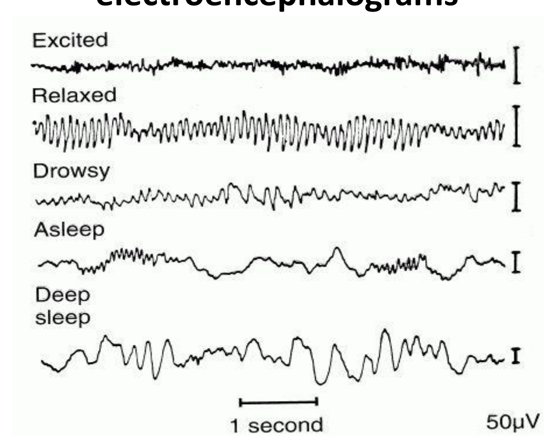


electroencephalograms



The phase-space distribution of partons

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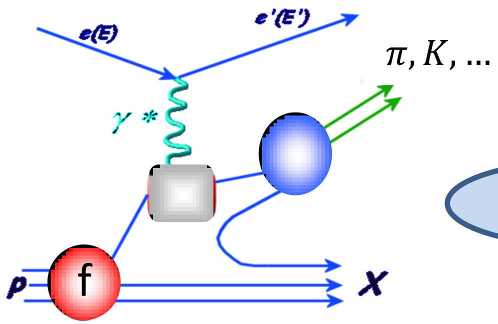


$W(x, p_T, r)$

$\int d^3r \rightarrow f(x, p_T)$ — TMDs

$\int d^2p_T \rightarrow H(x, \xi, t)$ — GPDs

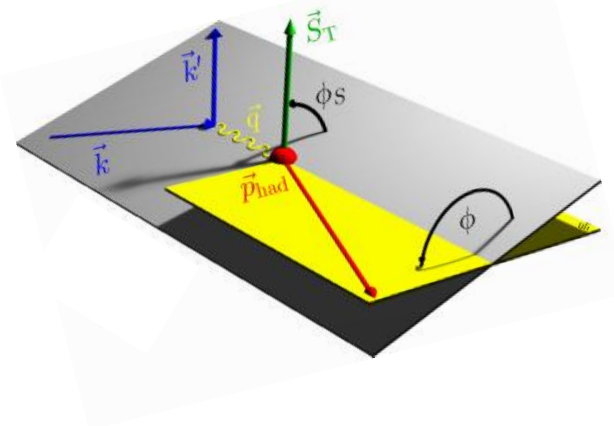
quark polarisation (columns) / **nucleon polarisation** (rows)

	U	L	T
U	f_1 number density PRD 87 (2013) 074029		$h_1^{\perp}$ Boer-Mulders PRD87 (2013) 012010
L		g_1 helicity PRD 75 (2007) 012007	$h_{1L}^{\perp}$ worm-gear PLB 562 (2003) 182 PRL 84 (2000) 4047
T	$f_{1T}^{\perp}$ Sivers PRL 94 (2005) 012002 PRL 103 (2009) 152002	g_{1T} worm-gear released	h_1 transversity PRL 94 (2005) 012002 PLB 693 (2010) 11 $h_{1T}^{\perp}$ pretzelosity released

Semi-inclusive processes (SIDIS)

- Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)
- Sensitive to quark OAM!

The SIDIS cross-section



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

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

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

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

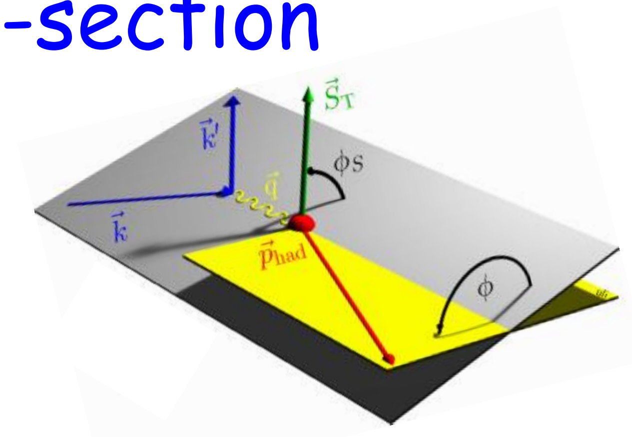
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\Big]$$

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

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

The SIDIS cross-section

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



Fragmentation Functions

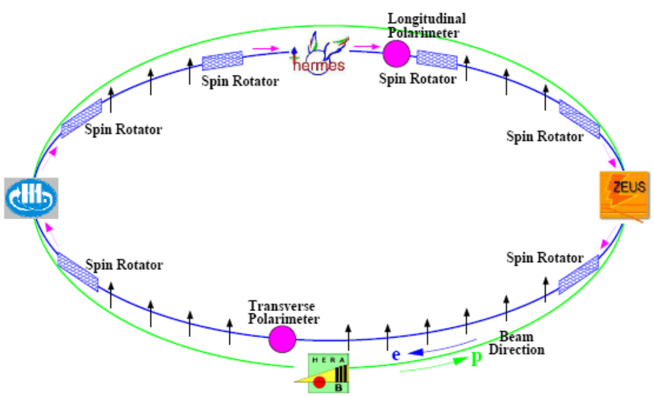
		quark U	quark L	quark T
h	U	D_1		$H_1^\perp$

$F \propto DF \otimes FF$

Distribution Functions

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

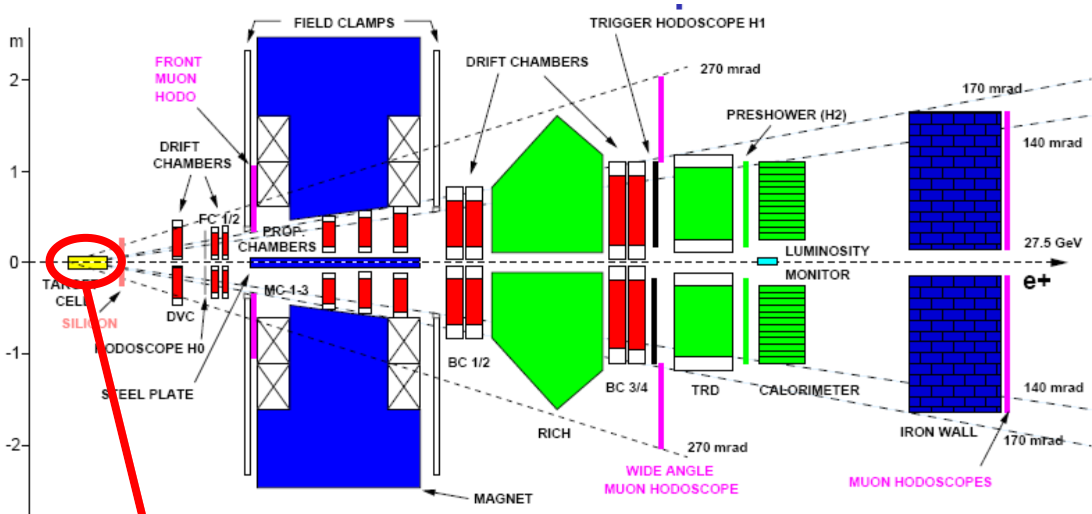
The HERA storage ring (DESY)

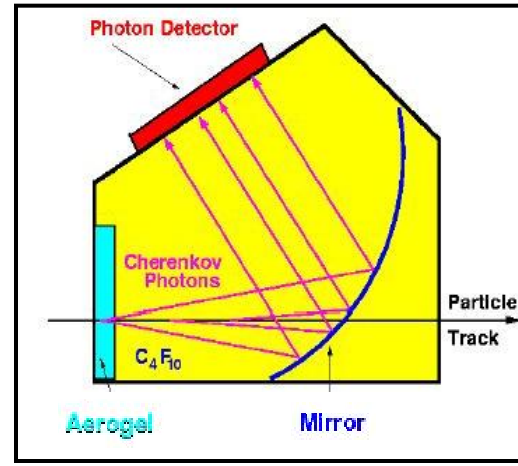


- 27.5 GeV e^+/e^- beam
- Self-polarizing through Sokolov-Ternov-Effect
- Average beam polarization of about 55%

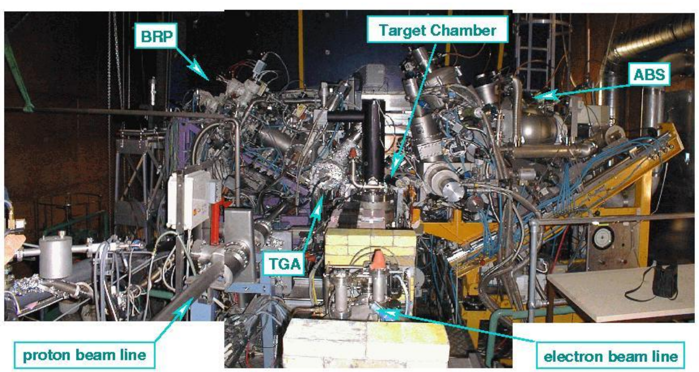
The HERMES Spectrometer (1995-2007)

The HERMES experiment at HERA



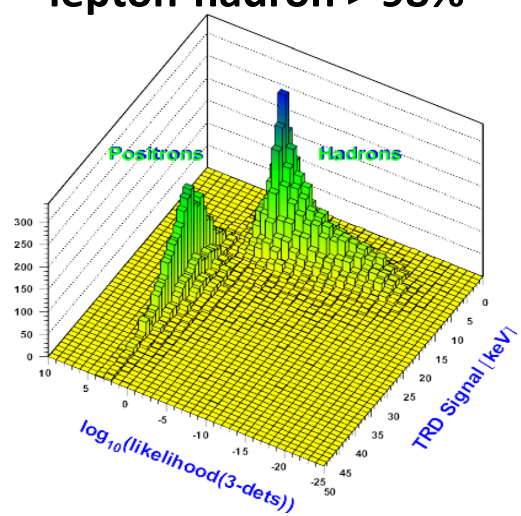


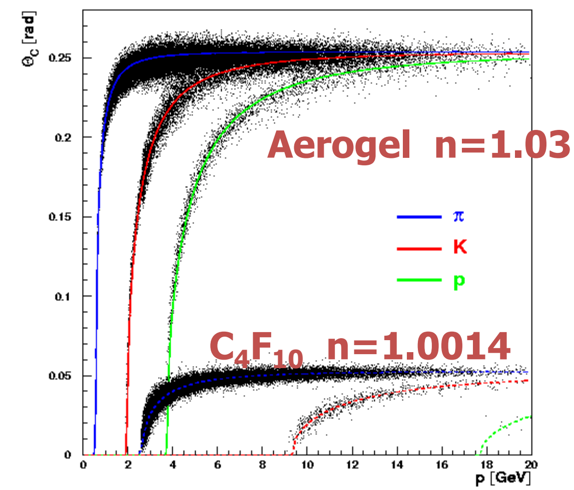
hadron separation



TRD, Calorimeter, preshower, RICH:

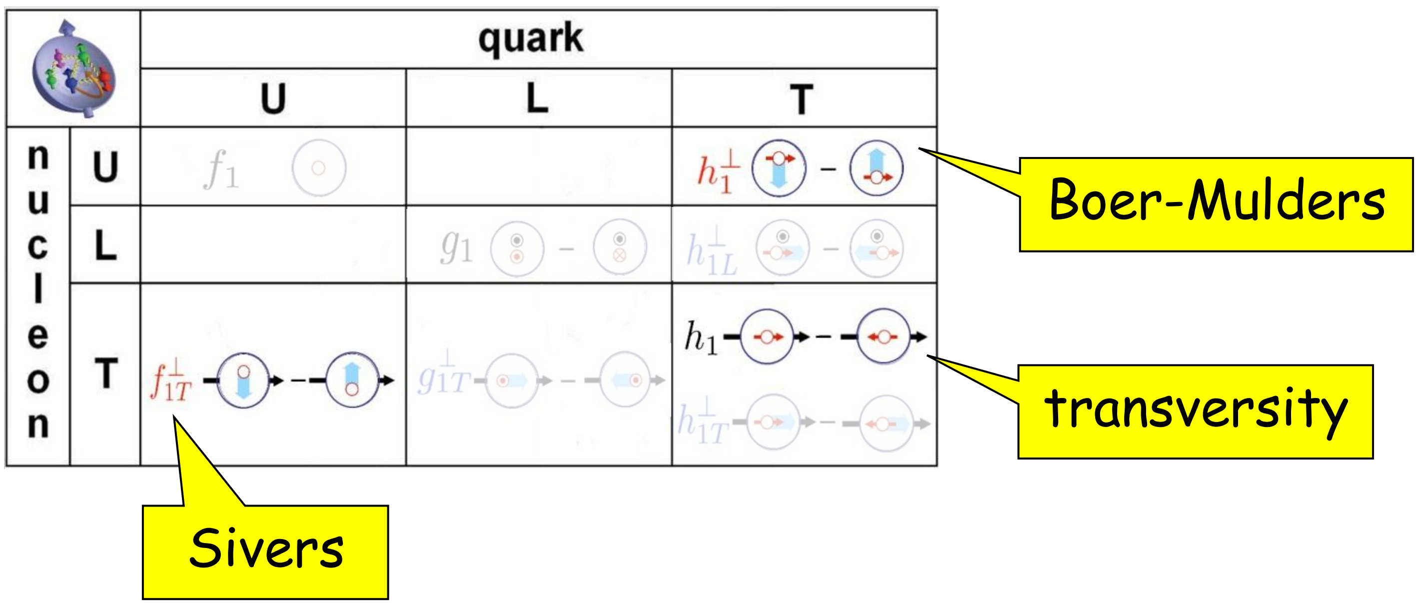
lepton-hadron > 98%





π ~ 98%, K ~ 88% , P ~ 85%

Selected TMDs results



Transversity

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

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

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

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

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

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

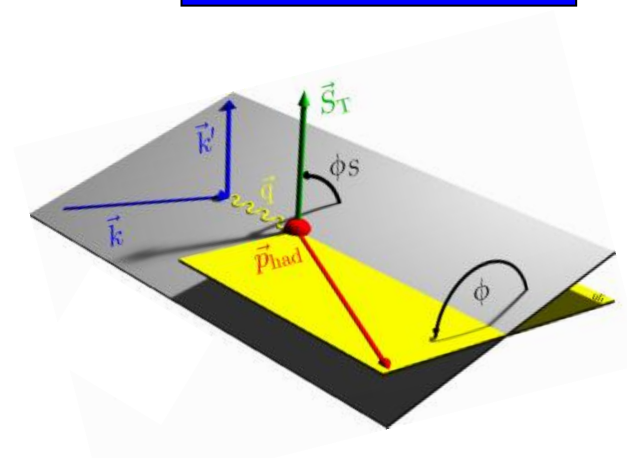
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

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

Transversity

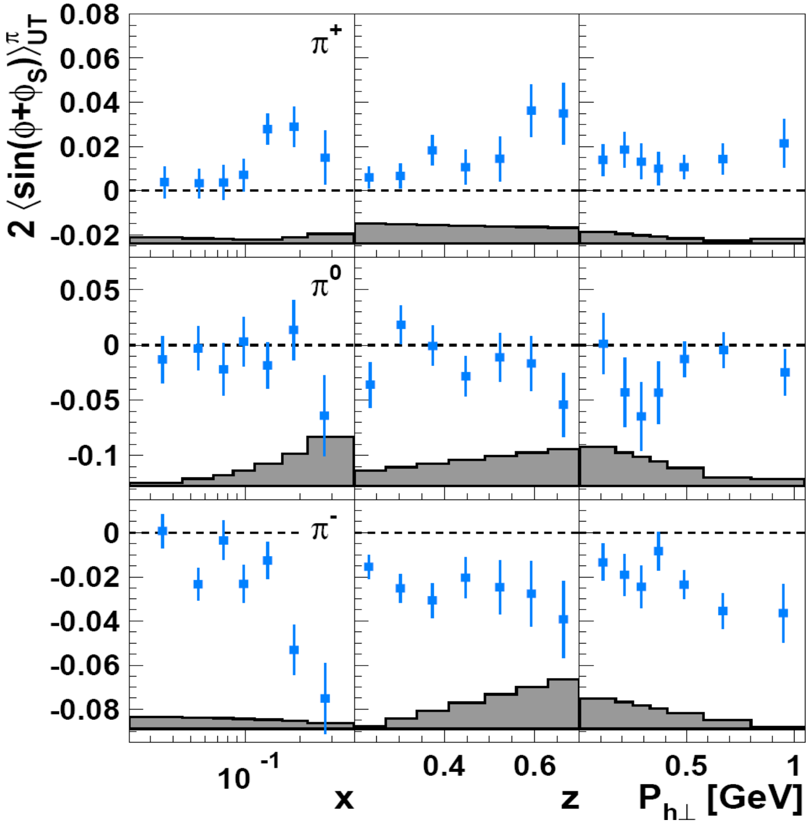
$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^\perp\right]$$

Collins FF



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]



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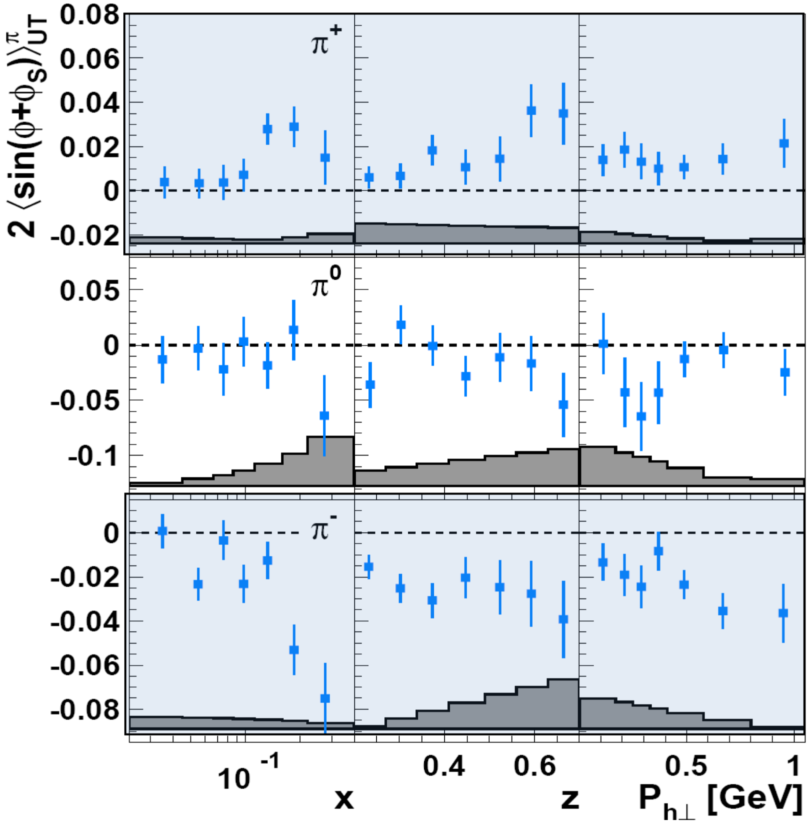

- **positive**
- **~ zero** (isospin-symmetry)
- **large & negative!**

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

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

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

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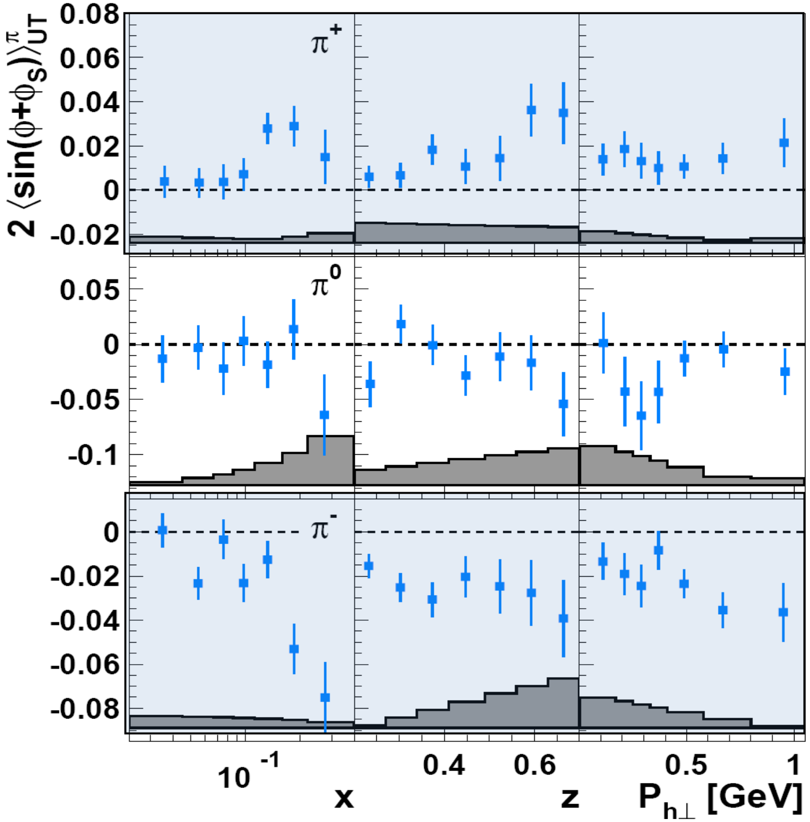

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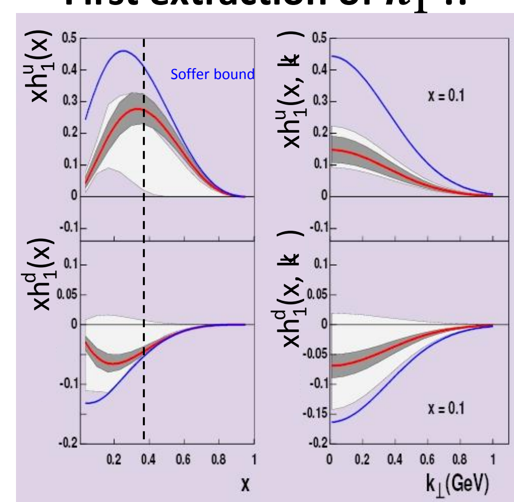
First extraction of h_1 !!



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

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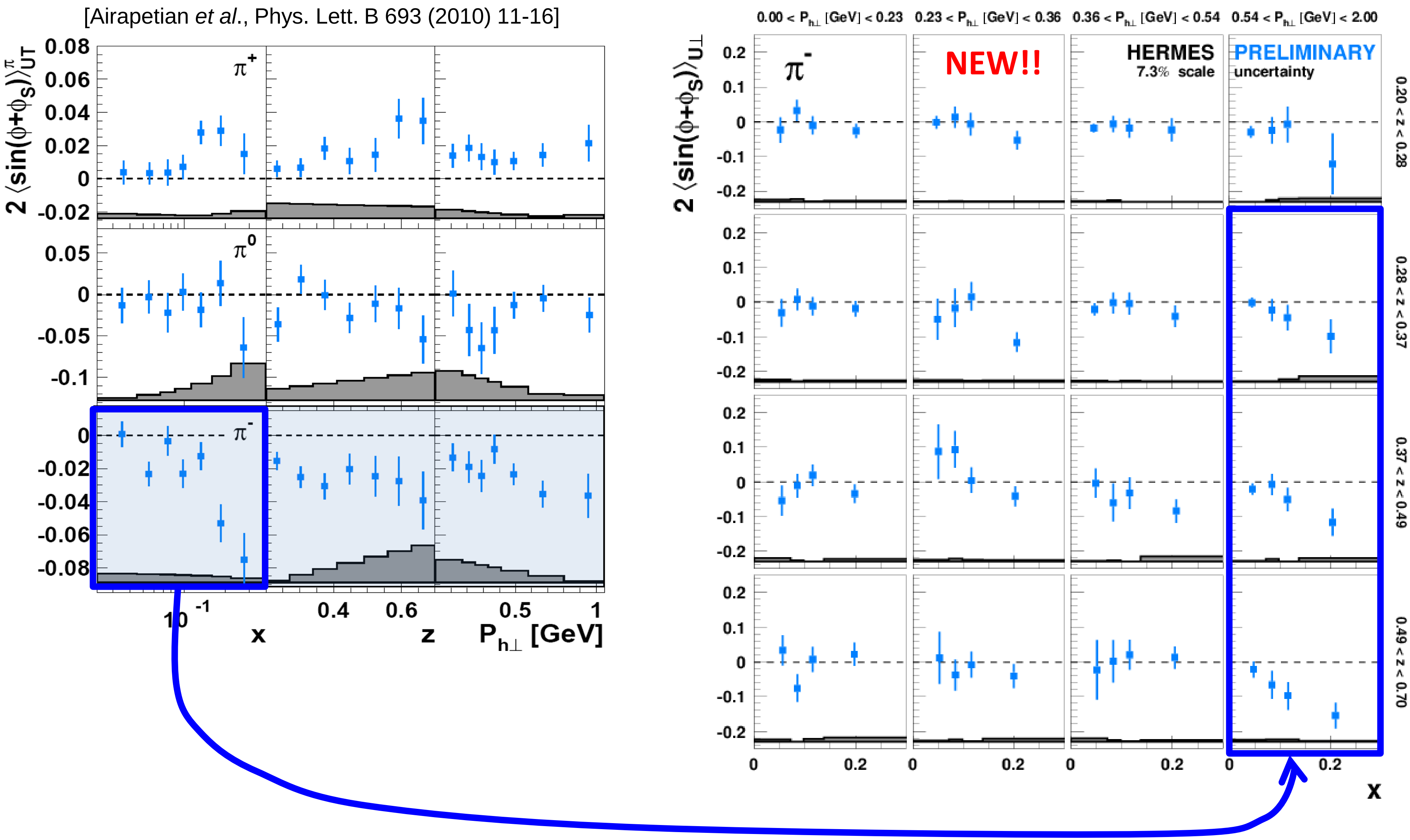
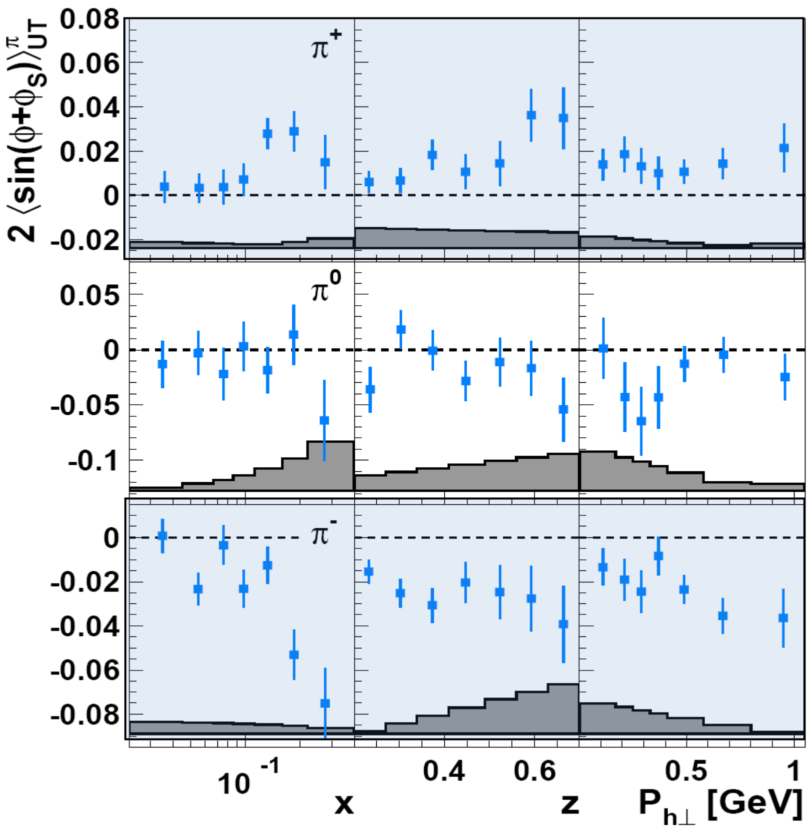
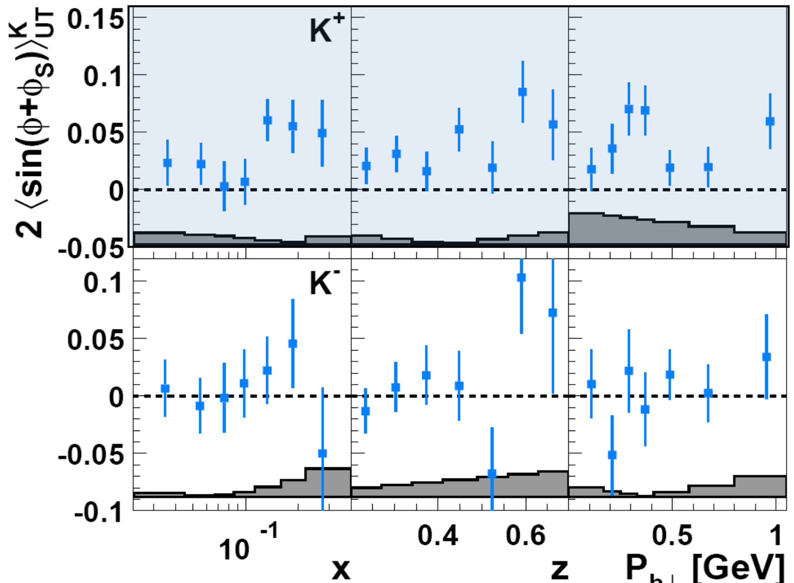


3D projections allow to constrain global fits in a more profound way!

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]

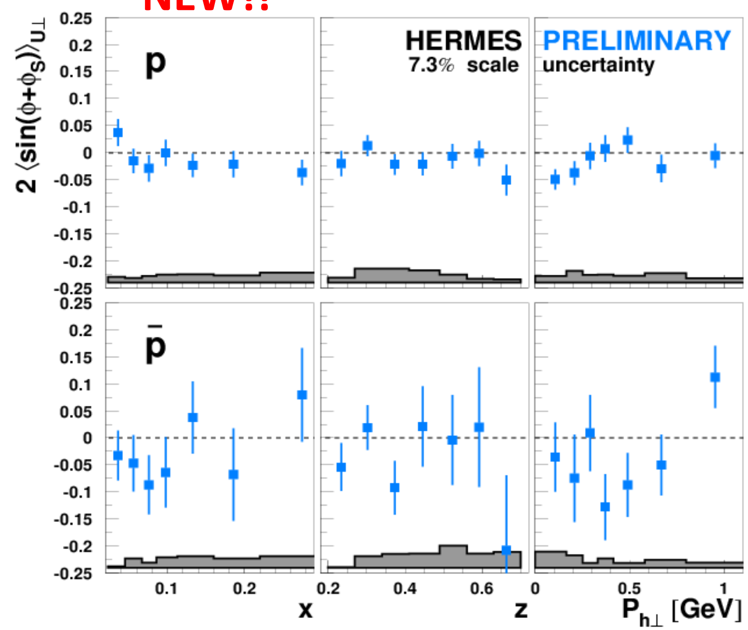




☛ positive

☛ ~ zero

NEW!!



☛ ~ zero

☛ ~ zero

Sivers function

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

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

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

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

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

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

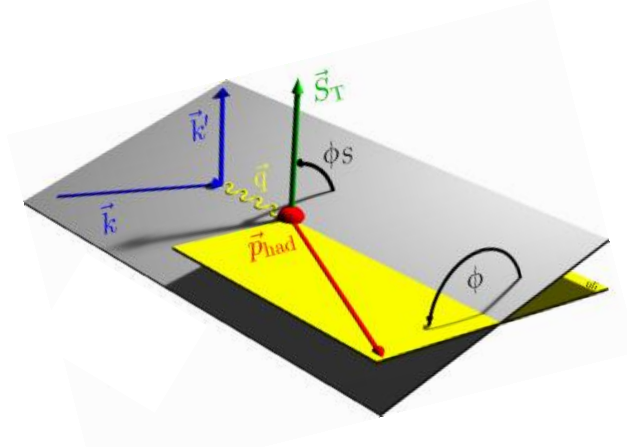
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\rm LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\rm LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\rm LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Describes correlation between quark transverse momentum and nucleon transverse polarization

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

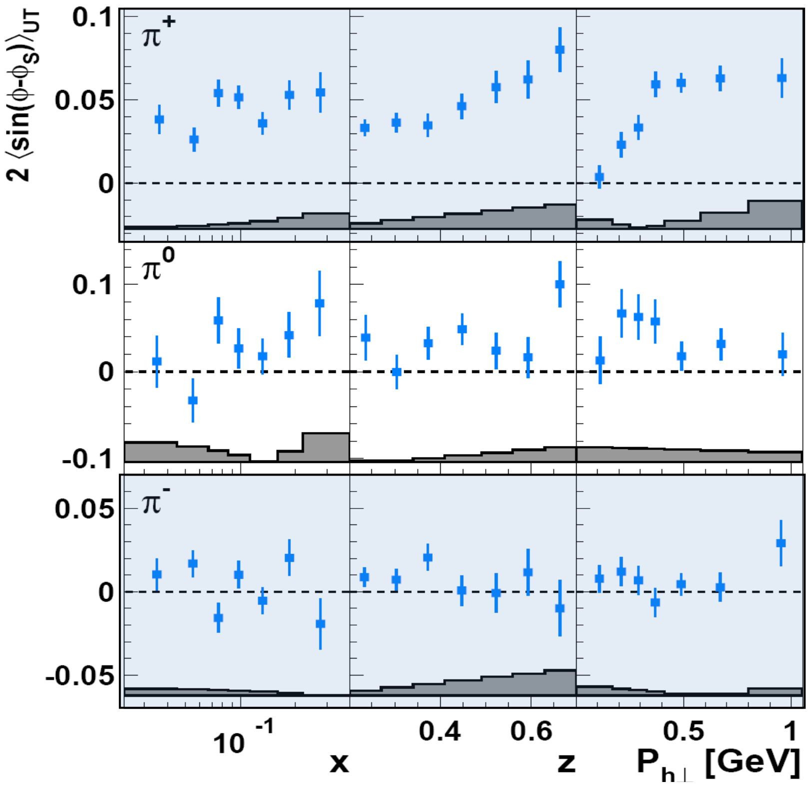
Sivers

Unpol. FF



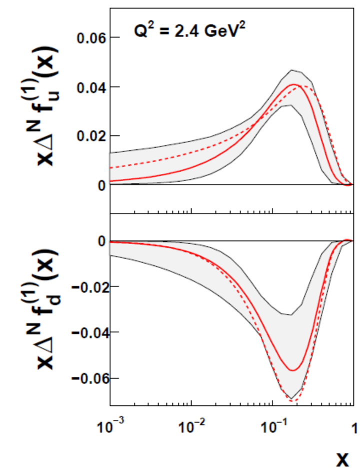
Sivers amplitudes $\propto f_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$

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



- **Large & positive**
- **slightly positive** (isospin-symmetry)
- **~ zero**

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

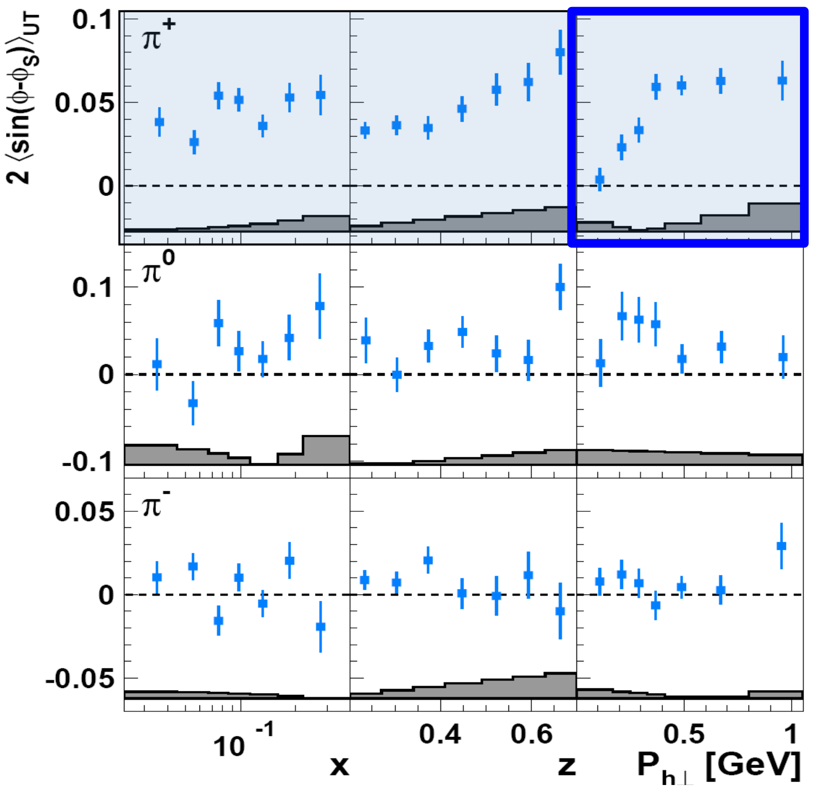


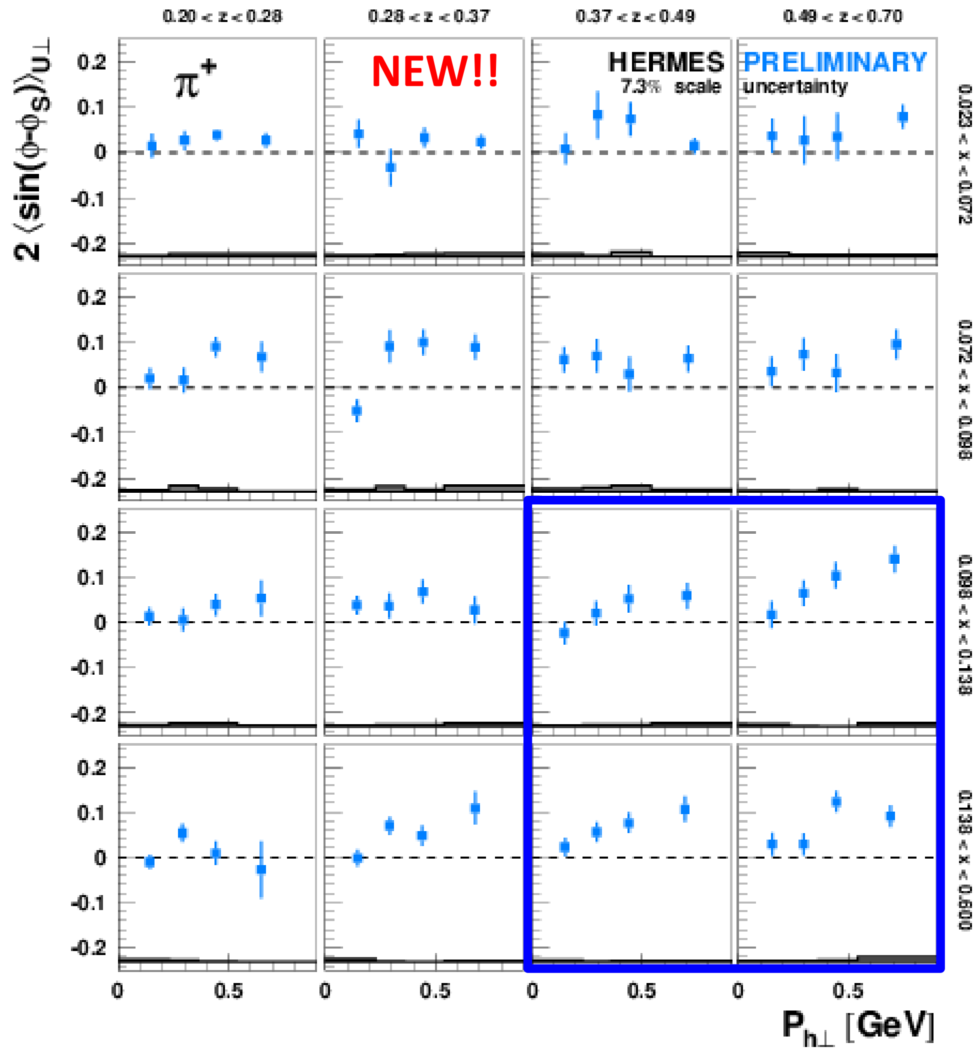
[Anselmino *et al.*,Eur.Phys.J.A3,2009]

***u* and *d* quark have opposite OAM!!**

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

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





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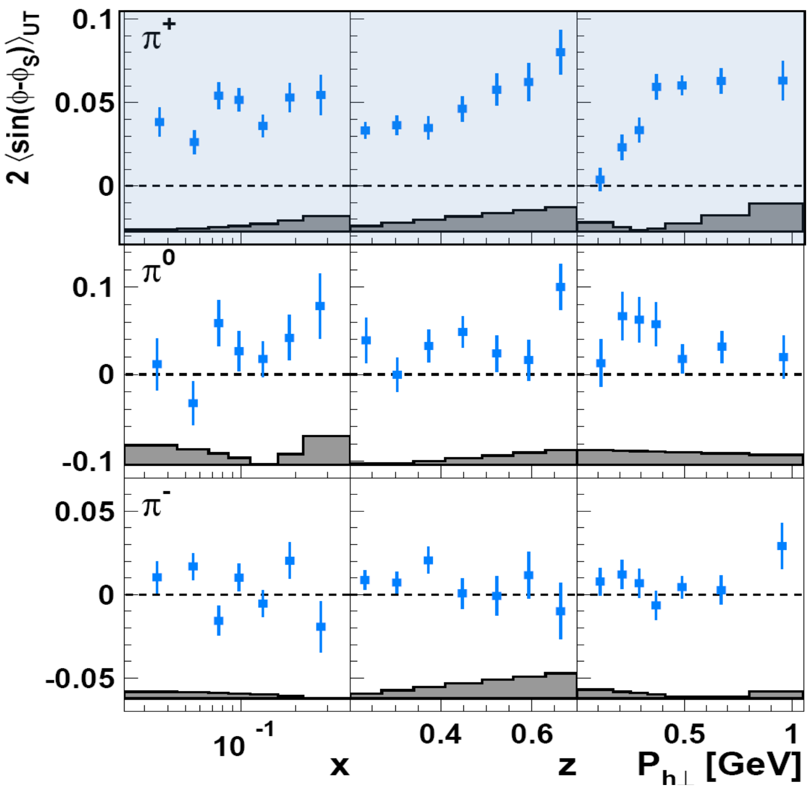

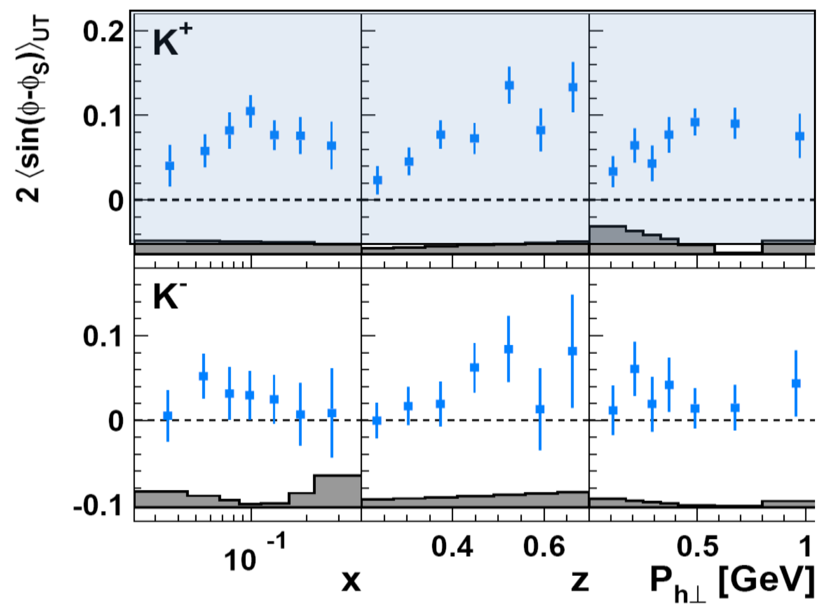

K^+ amplitude larger than π^+!!

- Unexpected!
- role of sea quarks ?
- Difference mainly from low Q^2
- Higher-twist contrib for K^+ ?

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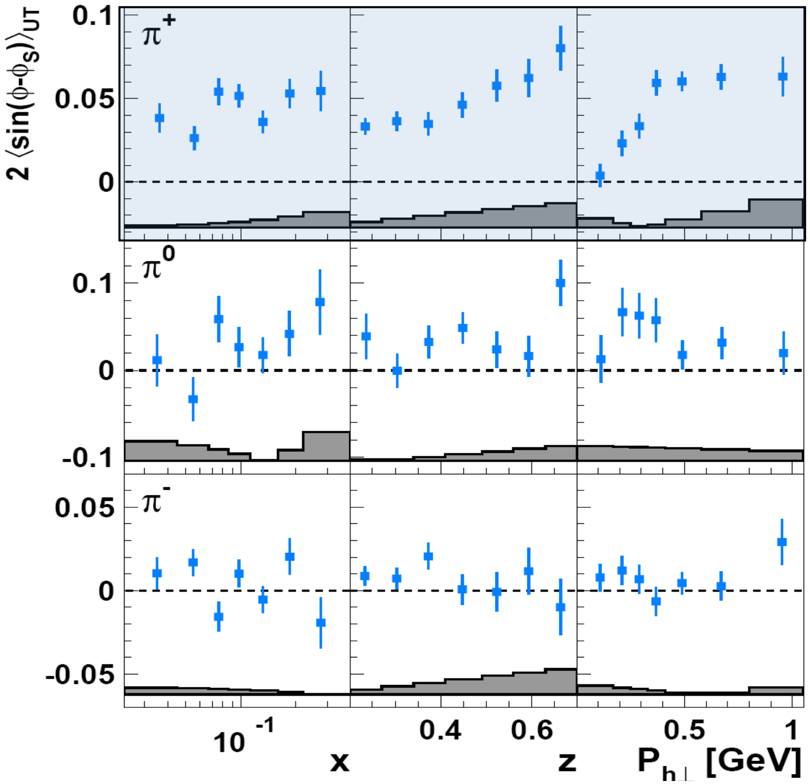

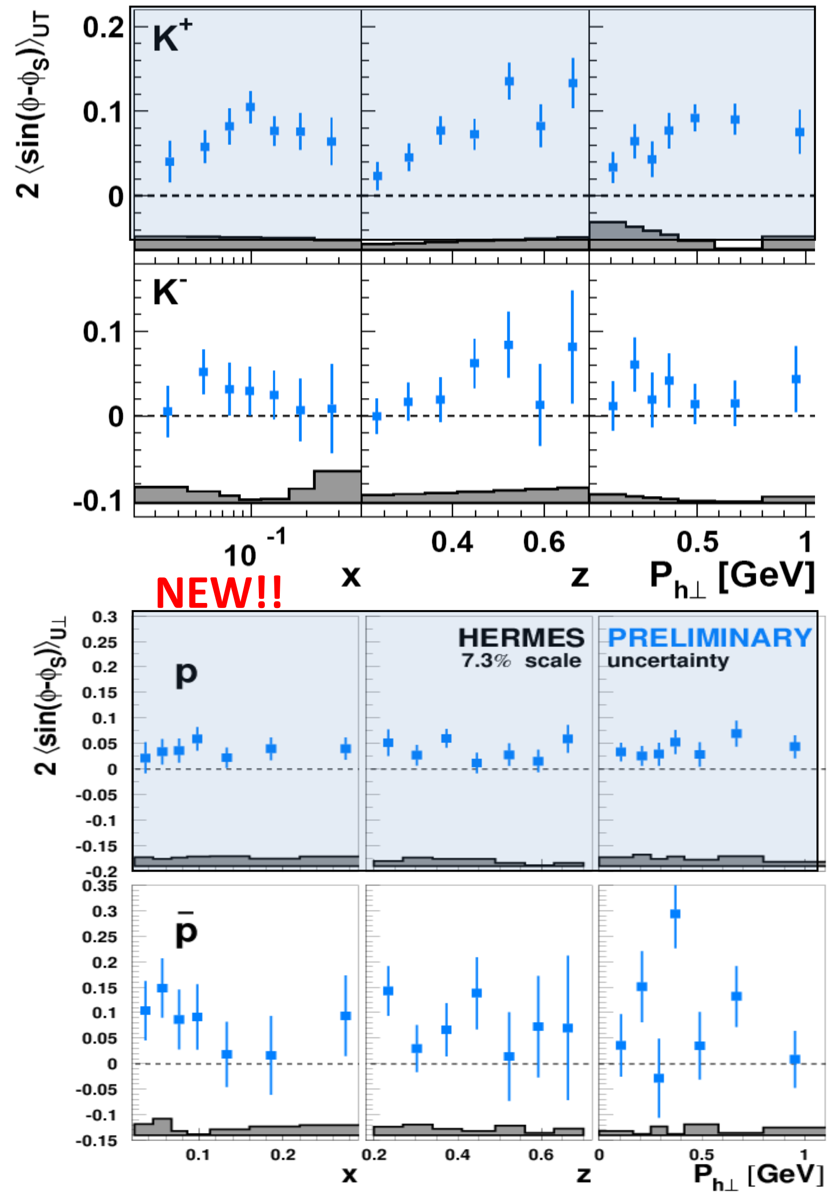

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Boer-Mulders function

Describes correlation between quark transverse momentum and transverse spin in unpolarized nucleon

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

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

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

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

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

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

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

$$F_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2}[f_1 \otimes D_1 + \cdots]$$

Boer-Mulders

Collins FF

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

$$F_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2}[f_1 \otimes D_1 + \cdots]$$

Cahn effect

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$$

Cahn effect

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Boer-Mulders

Collins FF

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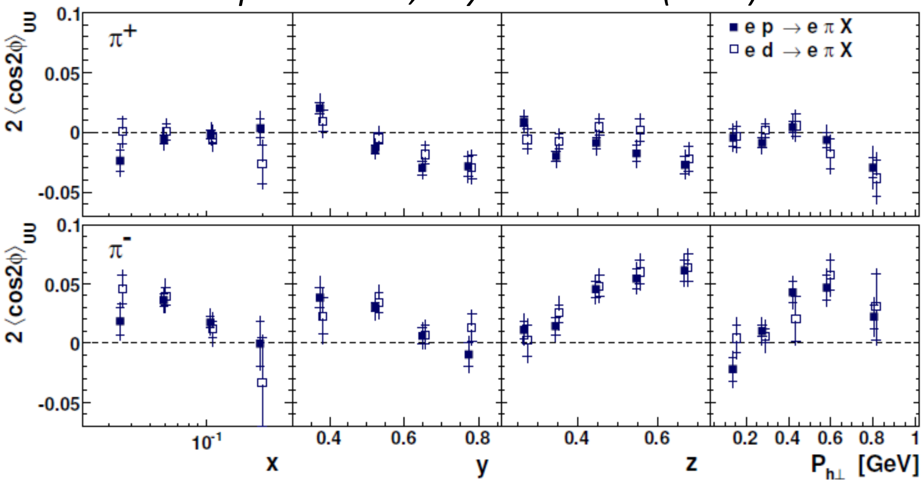
Cahn effect

Interaction dependent terms

The cos2ϕ amplitudes $\propto h_1^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

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



negative

positive

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

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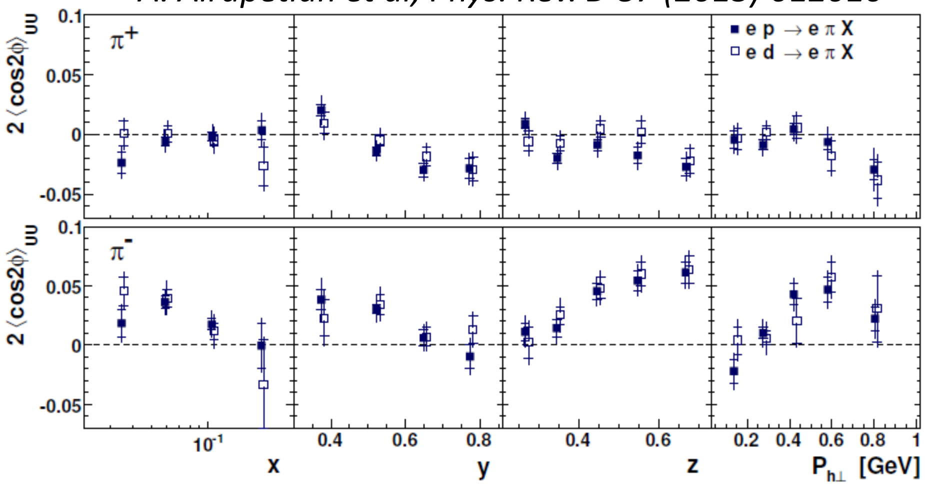

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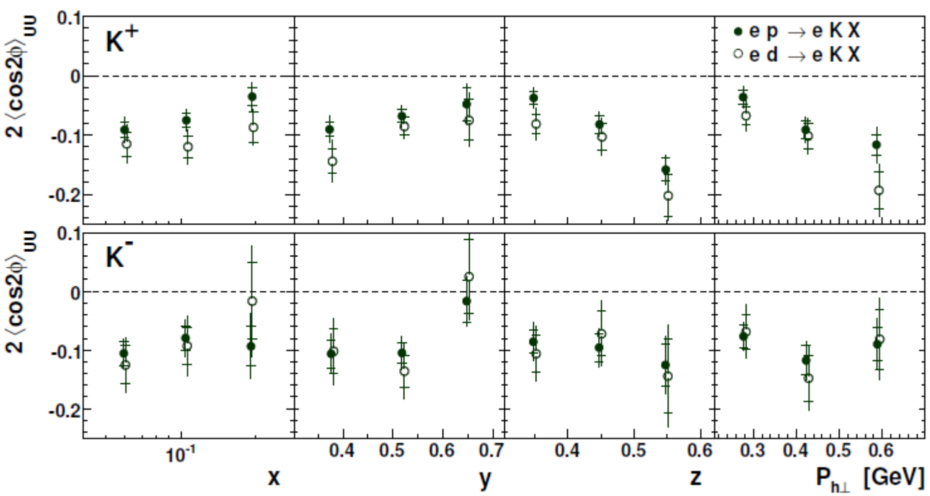


Large and negative

Large and negative

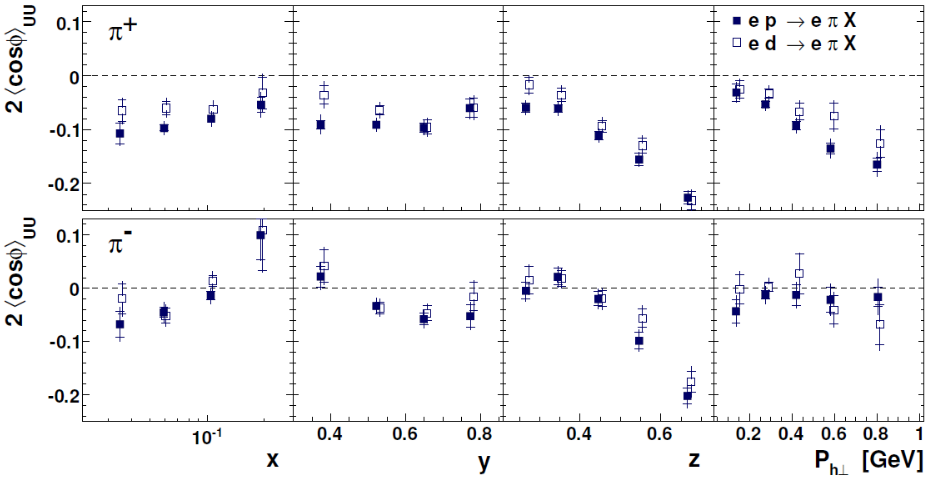
- **K^+/K^- amplitudes larger than for pions , have different kinematic dependencies than pions and have same sign**

→ different role of Collins FF for pions and kaons?

→ significant contribution from scattering off strange quarks**?**

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



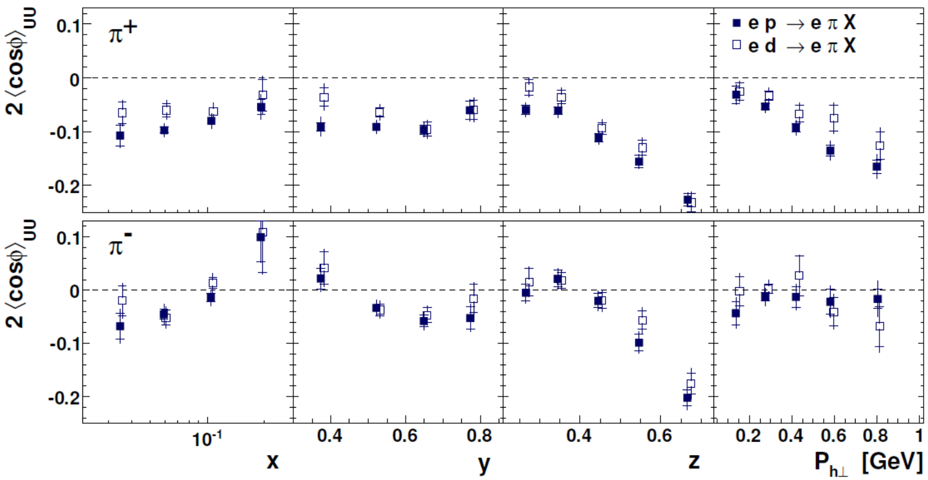
negative

negative

- **Significant and of same sign** → Chan effect weekly flavor dependent?
- **Clear rise with z for π^+ & π^- and $P_{h\perp}$ for π^+**
- **Different $P_{h\perp}$ dependence** → contrib. of flavor dependent effects (e.g. BM) for π^-?

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



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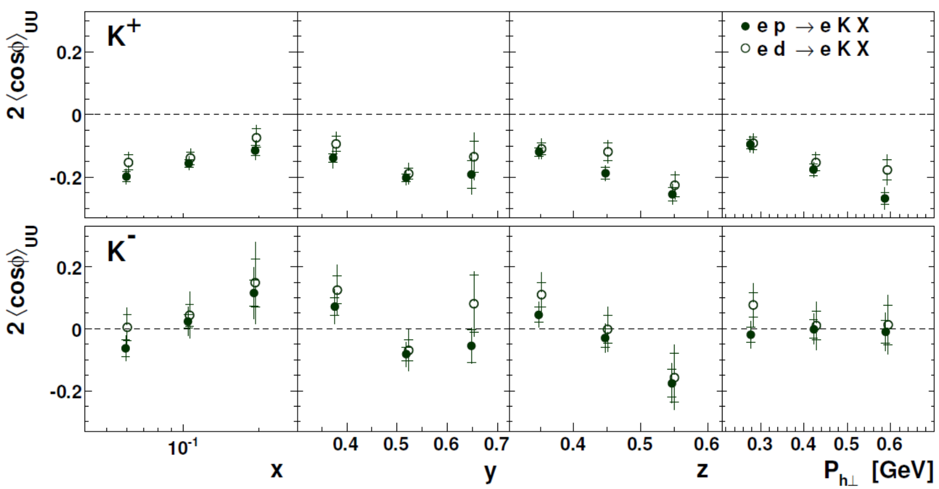
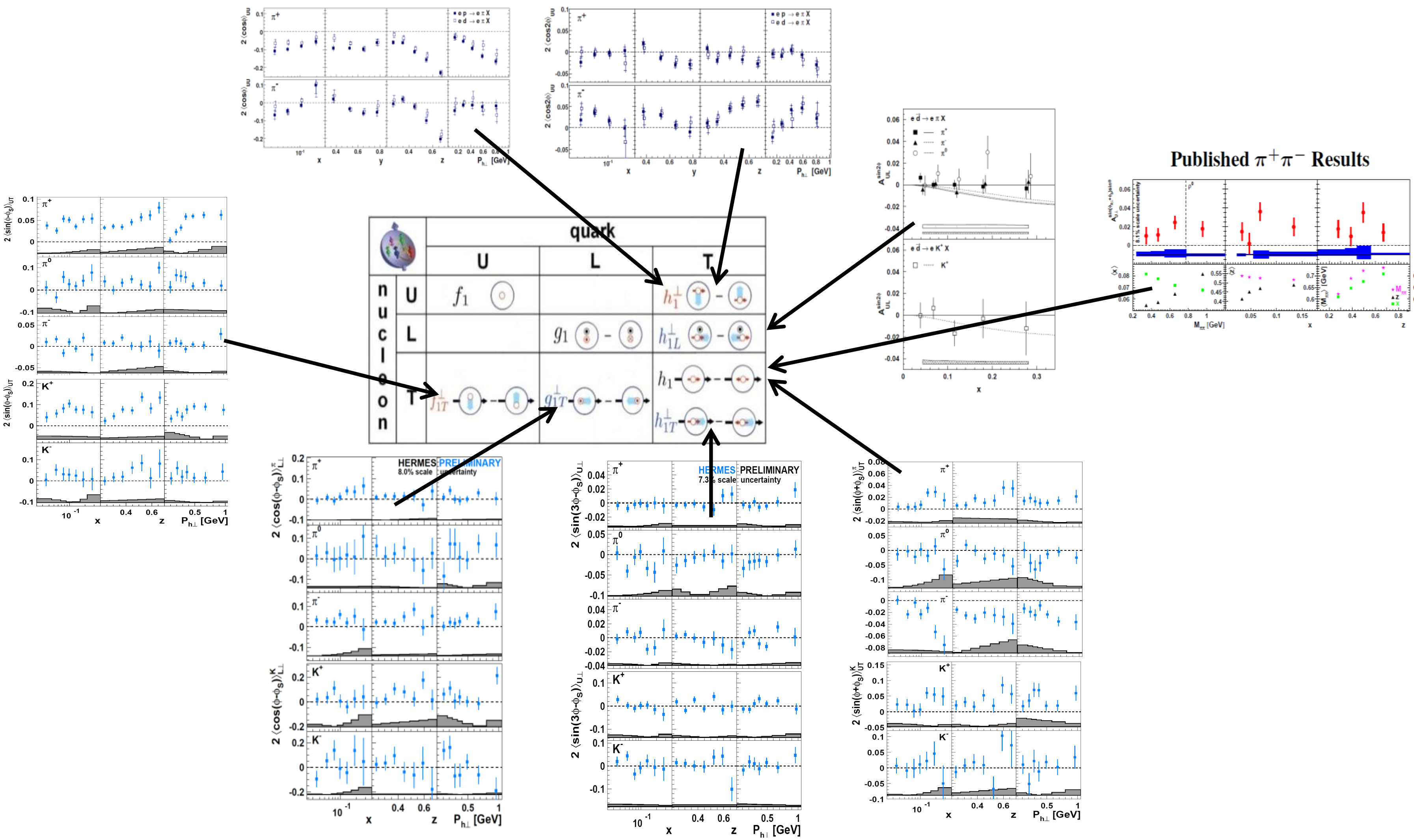


Large and negative

Consist. with 0

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



Published π+π− Results
quark
U
L
T
nucleon
HERMES PRELIMINARY
8.0% scale uncertainty
7.3% scale uncertainty

The phase-space distribution of partons

...but $\Delta x \Delta p \geq \frac{\hbar}{2}$ $\rightarrow$ cannot be accessed experimentally $\rightarrow$ **integrated quantities**

$W(x, p_T, r)$

$\int d^3r$ → $f(x, p_T)$ — TMDs

$\int d^2p_T$ → $H(x, \xi, t)$ — GPDs

		Chiral-even		Chiral-odd	
		conserve quark spin		*quark spin flip*	
nucleon helicity	*non-flip*	H	$\widetilde{H}$	H_T	$\widetilde{H}_T$
	flip	E	$\widetilde{E}$	E_T	$\widetilde{E}_T$

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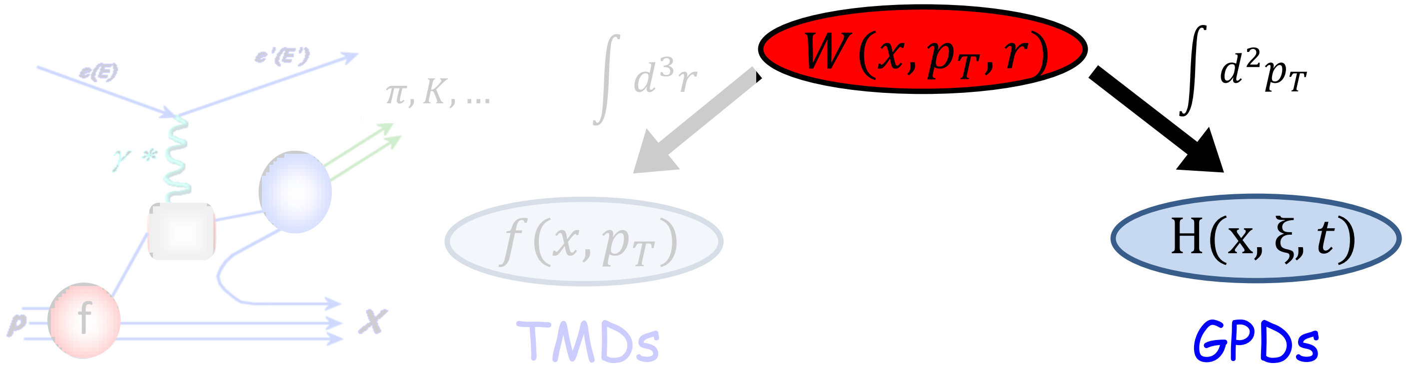

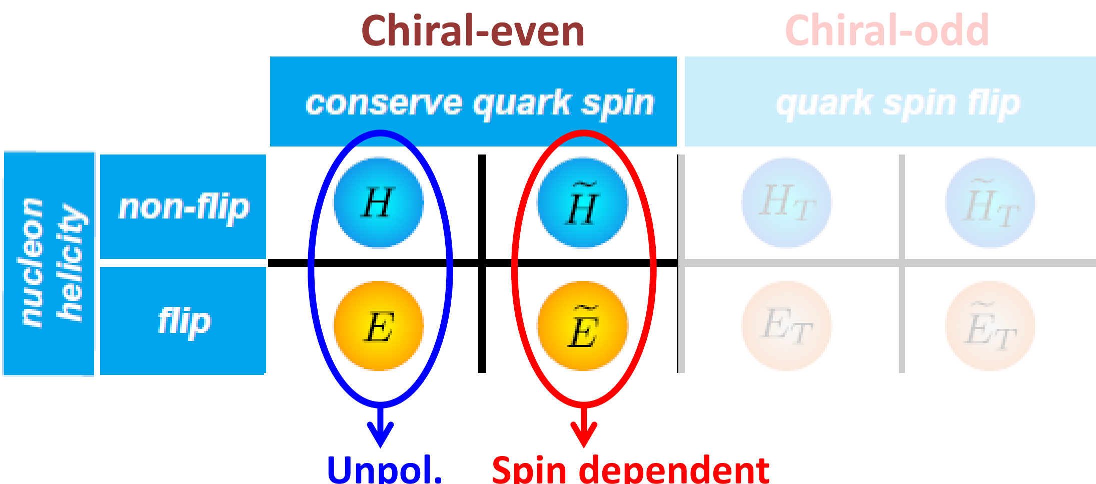

Ji relation

$$\lim_{t\to 0} \int_0^1 \mathrm{d}x\ x\,(H_q(x,\xi,t) + E_q(x,\xi,t)) = J_q$$

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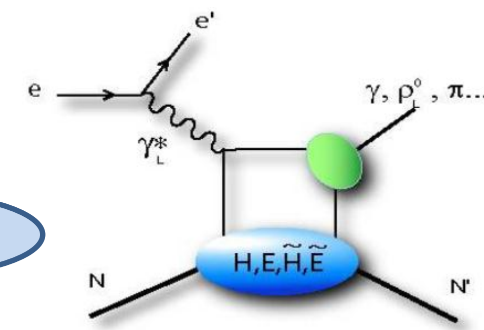


Exclusive processes (DVCS, DVMP)

		Chiral-even: conserve quark spin		Chiral-odd: quark spin flip	
nucleon helicity	non-flip	H	$\tilde{H}$	H_T	$\tilde{H}_T$
	flip	E	$\tilde{E}$	E_T	$\tilde{E}_T$
		Unpol.	Spin dependent		

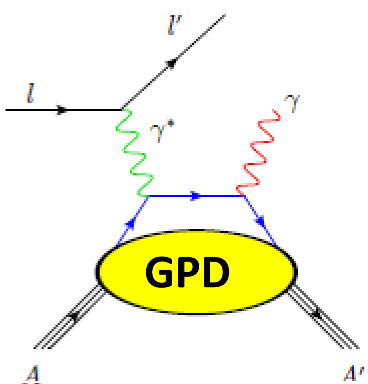
Ji relation

$$\lim_{t\to 0} \int_0^1 \mathrm{d}x \; x \left(H_q(x,\xi,t) + E_q(x,\xi,t)\right) = J_q$$

- **DVCS**
  - at leading twist: H E $\tilde{H}$ $\tilde{E}$
- **vector mesons:**
  - at leading twist: H E
  - higher twist: $\tilde{H}$ $\tilde{E}$
- **pseudoscalar mesons**
  - at leading twist: $\tilde{H}$ $\tilde{E}$
  - higher twist: H_T

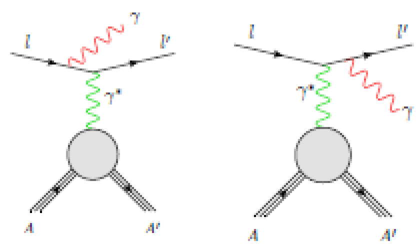
Deeply Virtual Compton Scattering (DVCS)

- Cleanest probe of GPDs
- Theoretical accuracy at NNLO
- GPDs are accessed through convolution integrals with hard scattering amplitudes (CFFs)
- Experimental observables are: azimuthal asymmetries, cross-secrion



+

Bethe - Heitler



$$
\begin{aligned}
d\sigma \sim d\sigma_{UU}^{BH} &+ e_\ell d\sigma_{UU}^{I} + d\sigma_{UU}^{DVCS} \\
&+ e_\ell P_\ell d\sigma_{LU}^{I} + P_\ell d\sigma_{LU}^{DVCS} \\
&+ e_\ell S_L d\sigma_{UL}^{I} + S_L d\sigma_{UL}^{DVCS} \\
&+ e_\ell S_T d\sigma_{UT}^{I} + S_T d\sigma_{UT}^{DVCS} \\
+P_\ell S_L d\sigma_{LL}^{BH} &+ e_\ell P_\ell S_L d\sigma_{LL}^{I} + P_\ell S_L d\sigma_{LL}^{DVCS} \\
+P_\ell S_T d\sigma_{LT}^{BH} &+ e_\ell P_\ell S_T d\sigma_{LT}^{I} + P_\ell S_T d\sigma_{LT}^{DVCS}
\end{aligned}
$$

$$
\frac{d\sigma}{dx_B dQ^2 d|t| d\phi} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{DVCS}\mathcal{T}_{BH}^* + \mathcal{T}_{BH}\mathcal{T}_{DVCS}^*}_{I}
$$

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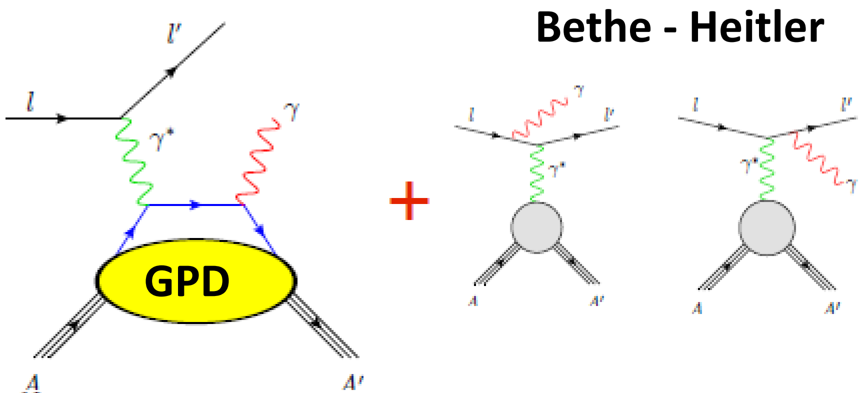
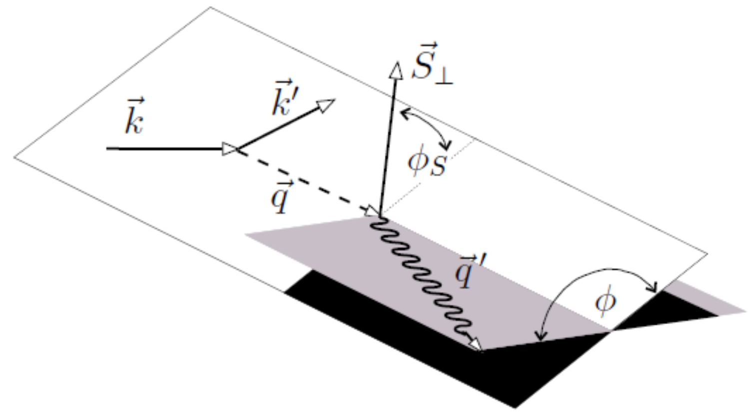




$$\frac{d\sigma}{dx_B dQ^2 d|t| d\phi} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{DVCS}\mathcal{T}^*_{BH} + \mathcal{T}_{BH}\mathcal{T}^*_{DVCS}}_{I}$$

At Hermes $|T_{DVCS}|^2 \ll |T_{BH}|^2 \Rightarrow$ DVCS amplitudes mainly accessed through Interference terms

- Beam-Charge asymmetry
  $\sigma(e^+,\phi) - \sigma(e^-,\phi) \propto Re[F_1\mathcal{H}]$
- Beam-Spin Asymmetry
  $\sigma(\overrightarrow{e},\phi) - \sigma(\overleftarrow{e},\phi) \propto Im[F_1\mathcal{H}]$
- Longitudinal Target-Spin Asymmetry
  $\sigma(\overrightarrow{P},\phi) - \sigma(\overleftarrow{P},\phi) \propto Im[F_1\widetilde{\mathcal{H}}]$
- Longitudinal Double-Spin Asymmetry
  $\sigma(\overrightarrow{P},\overrightarrow{e},\phi) - \sigma(\overrightarrow{P},\overleftarrow{e},\phi) \propto Re[F_1\widetilde{\mathcal{H}}]$
- Transverse Target-Spin Asymmetry
  $\sigma(\phi,\phi_S) - \sigma(\phi,\phi_S+\pi) \propto Im[F_2\mathcal{H} - F_1\mathcal{E}]$
- Transverse Double-Spin Asymmetry
  $\sigma(\overrightarrow{e},\phi,\phi_S) - \sigma(\overleftarrow{e},\phi,\phi_S+\pi) \propto Re[F_2\mathcal{H} - F_1\mathcal{E}]$

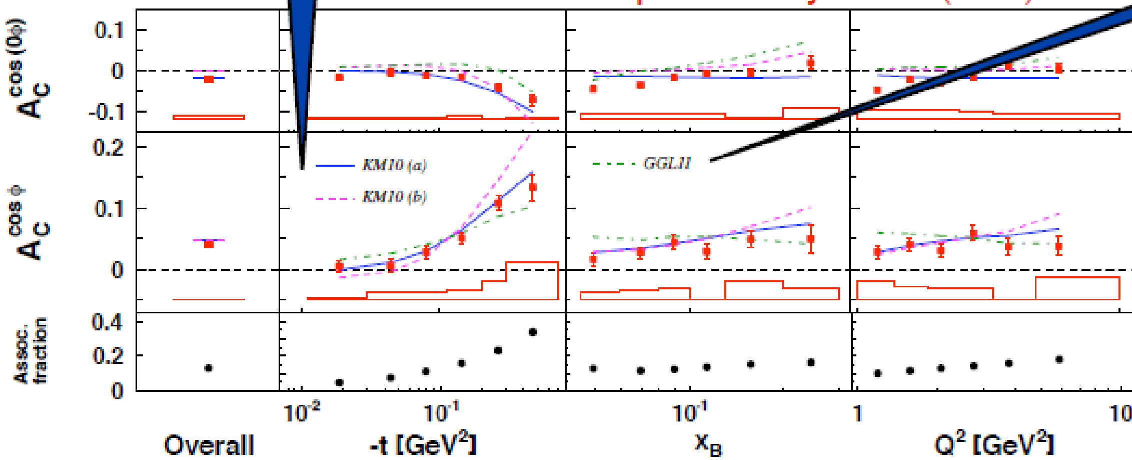
Beam-Charge & Beam-Helicity Asymmetries → H

KM10: Global fit
K. Kumericki, D. Muller
Nucl.Phys.B 841(2010) 1

$$A_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}$$

GGL11: Model calculation
G. Goldstein, S. Liuti,
J. Hernandez
Phys.Rev.D 84 034007 (2011)

Airapetian el al. JHEP 07 (2012) 032



Fractions of associated process from MC

Beam-charge asymmetry:

- Non-zero leading amplitude
- Strong $-t$ dependence
- Mild dependence on x_B, Q^2

Beam-Charge & Beam-Helicity Asymmetries $\rightarrow$ H

KM10: Global fit
K. Kumericki, D. Muller
Nucl.Phys.B 841(2010) 1

$$A_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}$$

Airapetian el al. JHEP 07 (2012) 032

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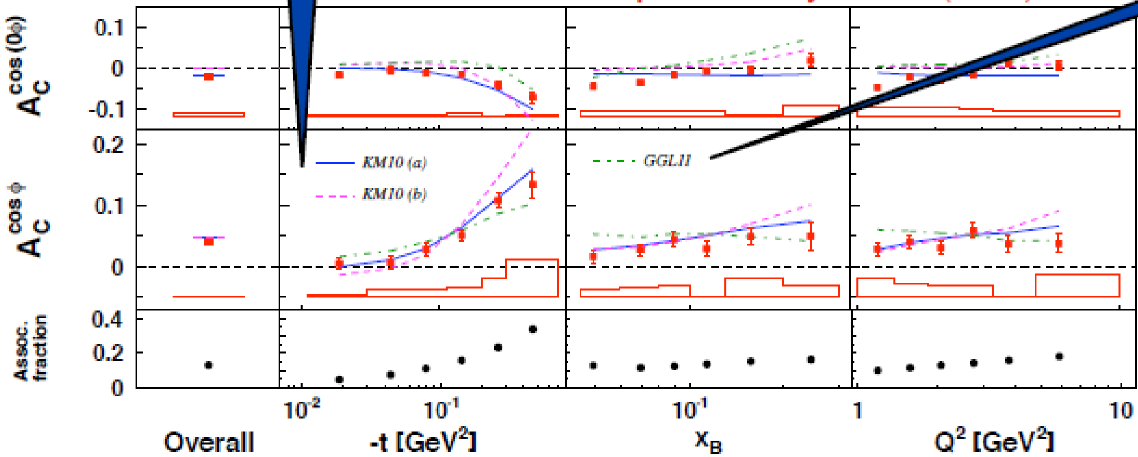
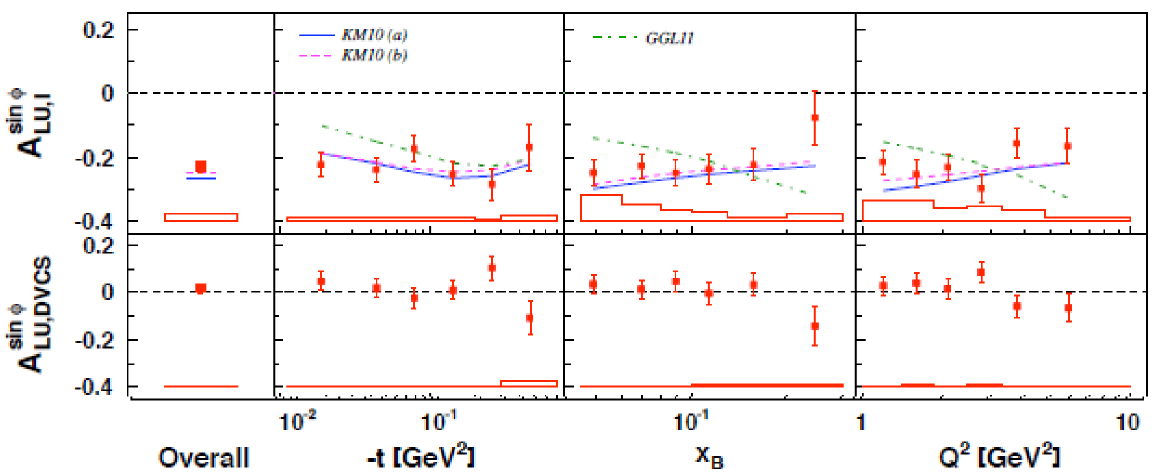


Beam-charge asymmetry:

- Non-zero leading amplitude
- Strong $-t$ dependence
- Mild dependence on x_B, Q^2

Fractions of associated process from MC

$$A_{LU}^{I,DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) \pm (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})}$$



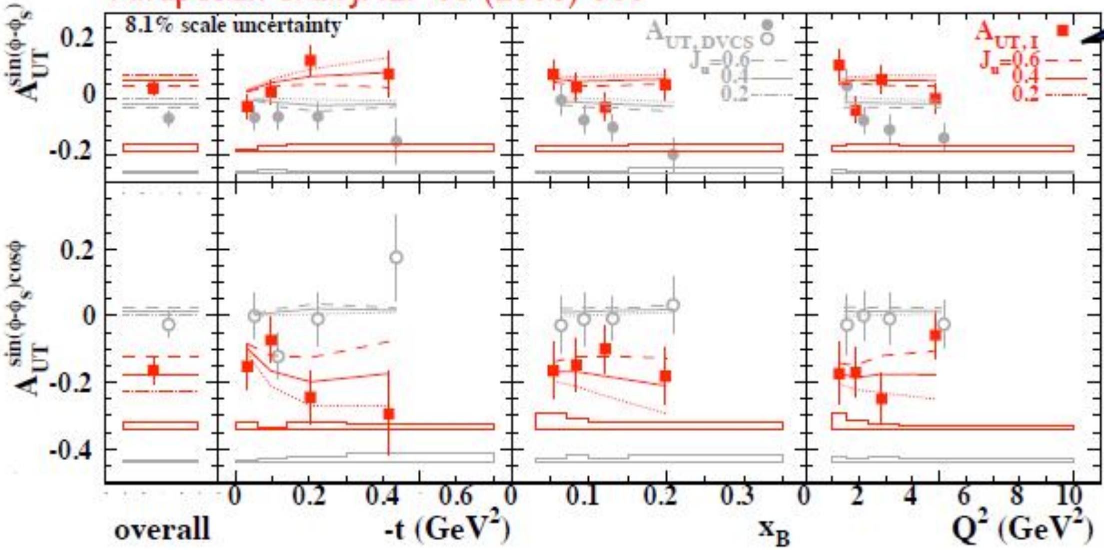
Combined beam-charge and beam-helicity asymmetry

- Leading amplitude large & negative
- Mild dependence of kinematic var.

Transverse Target-Spin Asymmetries $\to$ E $\tilde{H}$ $\tilde{E}$

$$A_{UT}^{I,DVCS}(\phi,\phi_S) = \frac{(\sigma^{+\Uparrow} - \sigma^{+\Downarrow}) \pm (\sigma^{-\Uparrow} - \sigma^{-\Downarrow})}{(\sigma^{+\Uparrow} + \sigma^{+\Downarrow}) + (\sigma^{-\Uparrow} + \sigma^{-\Downarrow})}$$

Airapetian el al. JHEP 06 (2008) 066



VGG: Model calculation
M.Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

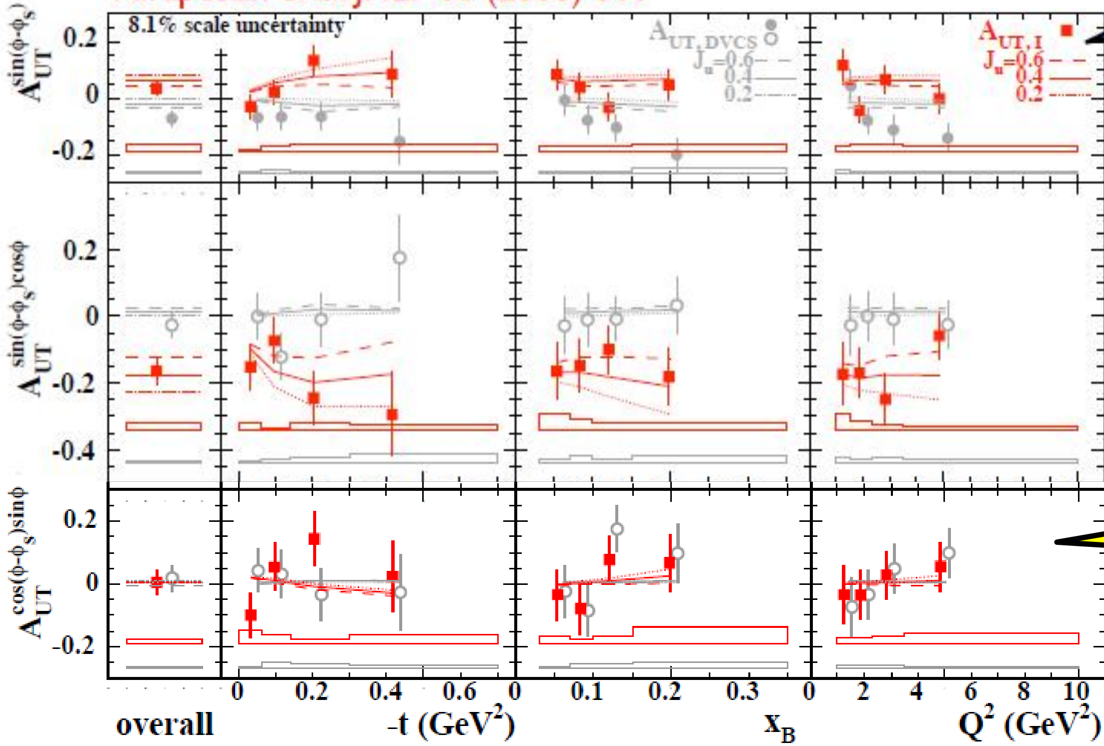
Combined beam-charge & transverse target spin asymmetry

- Leading amplitude large & negative

Transverse Target-Spin Asymmetries → E $\widetilde{H}$ $\widetilde{E}$

$$A_{UT}^{I,DVCS}(\phi,\phi_S) = \frac{(\sigma^{+\Uparrow} - \sigma^{+\Downarrow}) \pm (\sigma^{-\Uparrow} - \sigma^{-\Downarrow})}{(\sigma^{+\Uparrow} + \sigma^{+\Downarrow}) + (\sigma^{-\Uparrow} + \sigma^{-\Downarrow})}$$

Airapetian el al. JHEP 06 (2008) 066



VGG: Model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

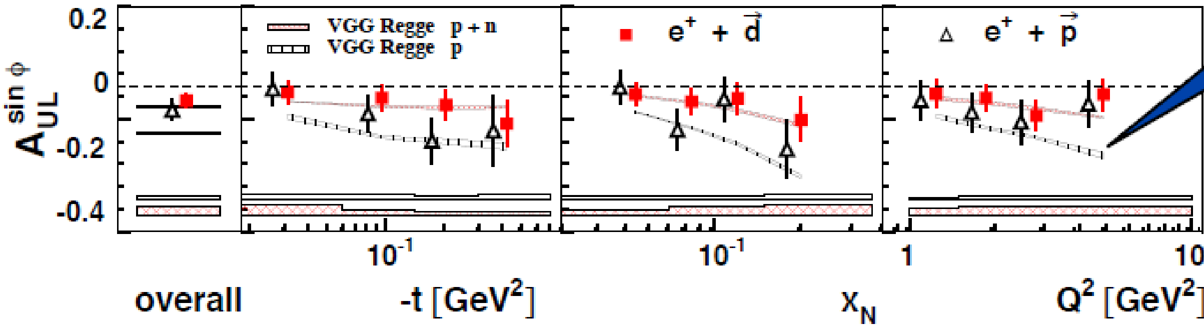
Combined beam-charge & transverse target spin asymmetry
- Leading amplitude large & negative

Sensitive to $\widetilde{H}$ and $\widetilde{E}$ but consistent with zero

Longitudinal Target-Spin Asymmetries $\rightarrow \widetilde{H}$

Airapetian et. al..Nucl. Phys. B 842 (2011)

$$A_{UL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}$$



VGG: Model calculation
M.Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

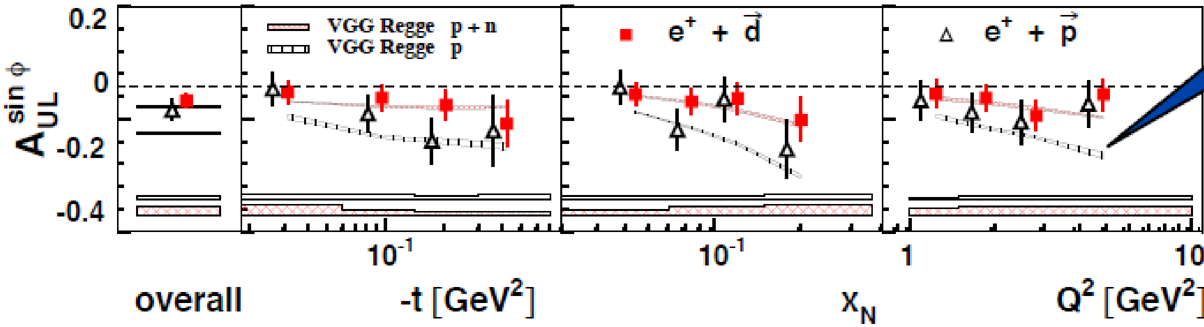
Longitud. target spin asymmetry

- Non-zero sin ϕ amplitude on both H and D targets
- Results on H and D targets compatible within uncertainties
- **Results on deuteron neither support nor disfavor large contribution from the neutron**

Longitudinal Target-Spin Asymmetries → $\tilde{H}$

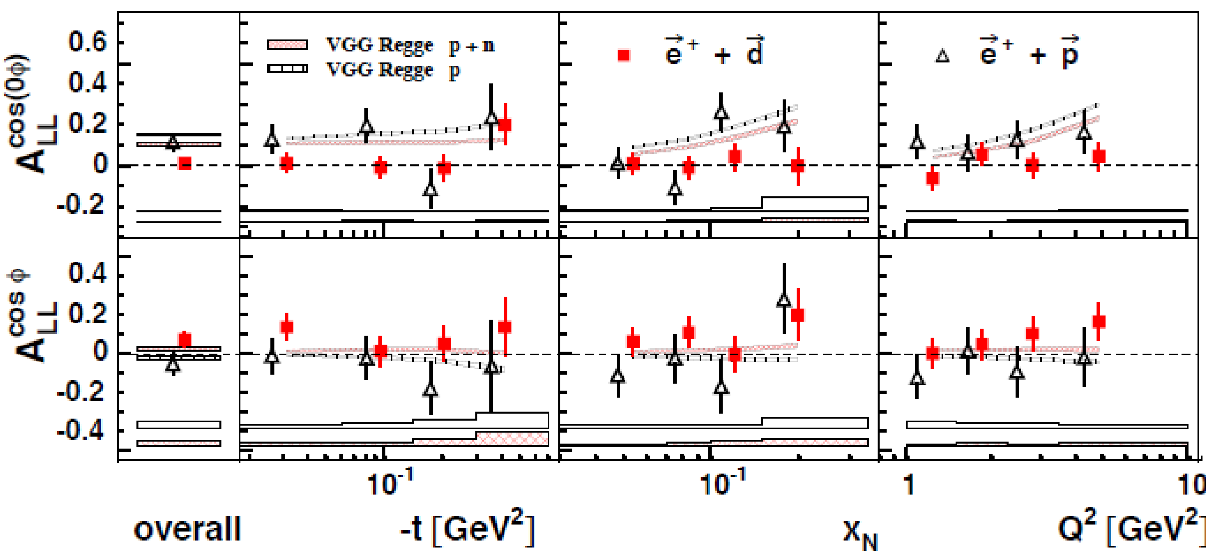
Airapetian et. al..Nucl. Phys. B 842 (2011)

$$\mathcal{A}_{UL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}$$



VGG: Model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

$$\mathcal{A}_{LL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}$$



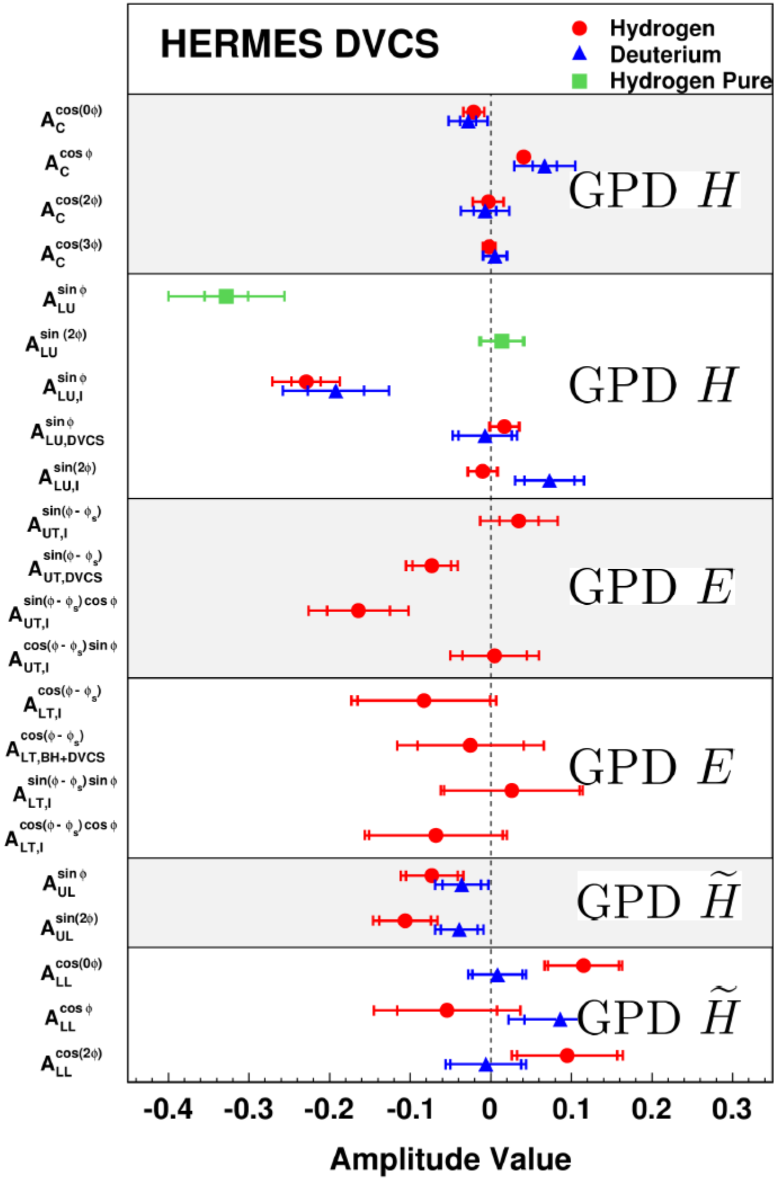
Longitud. target spin asymmetry

- Non-zero sin ϕ amplitude on both H and D targets
- Results on H and D targets compatible within uncertainties
- **Results on deuteron neither support nor disfavor large contribution from the neutron**

Longitud. double spin asymmetry

- $\sim 2\sigma$ discrepancy for $\cos(0\phi)$ where D results are ~ 0
- D results slightly positive for $\cos(\phi)$
- **In general no significant evidence of coherent scattering on d**
- **Process dominated by scattering on p**

Deeply Virtual Compton Scattering (DVCS)



> Beam-charge and beam-spin asymmetry

PRL 87 (2001) 182001

PRD 75 (2007) 011103

JHEP 11 (2009) 083

JHEP 07 (2012) 032, *JHEP 10 (2012) 042*

Nucl. Phys. B 829 (2010) 1

> Transverse target-spin asymmetry

JHEP 06 (2008) 066

> Transverse double-spin asymmetry

Phys. Lett. B 704 (2011) 15

> Longitudinal target spin asymmetry

JHEP 06 (2010) 019

> Longitudinal target & double spin asymmetry

Nucl. Phys. B 842 (2011) 265

Conclusions

A **rich phenomenology** and surprising effects arise when intrinsic transverse degrees of freedom (spin, momentum) are not integrated out!

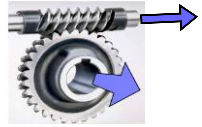
Flavor sensitivity ensured by the excellent hadron ID of present experiments reveals interesting and unexpected facets of data

Global analyses of data from different experiments allow to extract the underlying parton distributions (**TMDs, GPDs**) opening the way for a high precision and multi-dimensional study of the nucleon structure

The **3D imaging of the nucleon (nucleon tomography)** is a joung, fashinating and fast evolving research field. HERMES, as a pioneer experiment, has played a key role in these studies.

Back-up

Worm-gear $g^{\perp}_{1T}$



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

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

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

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

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

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

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

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

Describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon!

- requires interference between wave funct. components that differ by 1 unit of **OAM**
- Can be accessed in **LT DSAs**

Distribution Functions

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

Fragmentation Functions

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

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

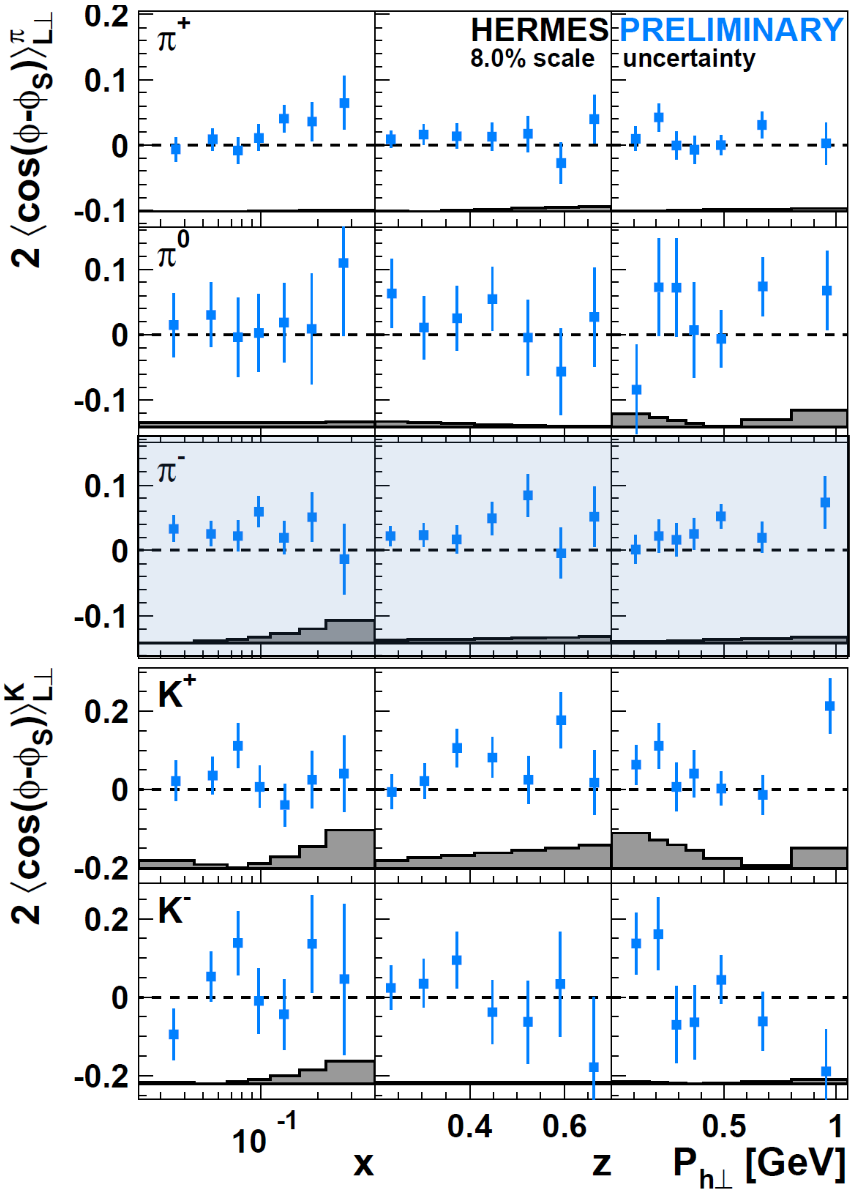
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\, g_{1T} D_1\right]$$

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

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

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

The cos(ϕ-ϕ$_S$) amplitudes $\propto g_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$

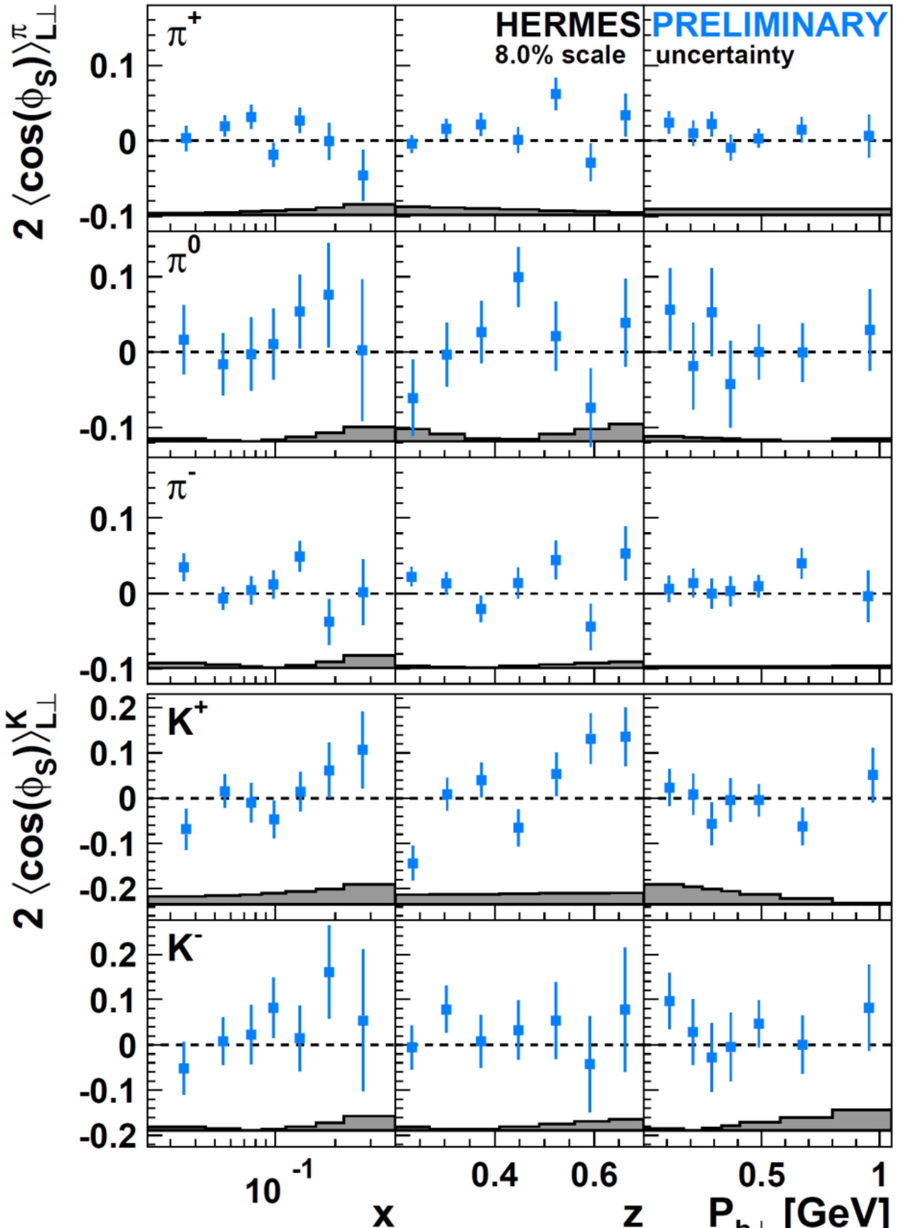


- slightly positive ?
- consistent with zero
- positive!!

similar observations from Hall-A and COMPASS

- slightly positive ?
- consistent with zero

The cos(ϕ_S) Fourier component



≈ 0

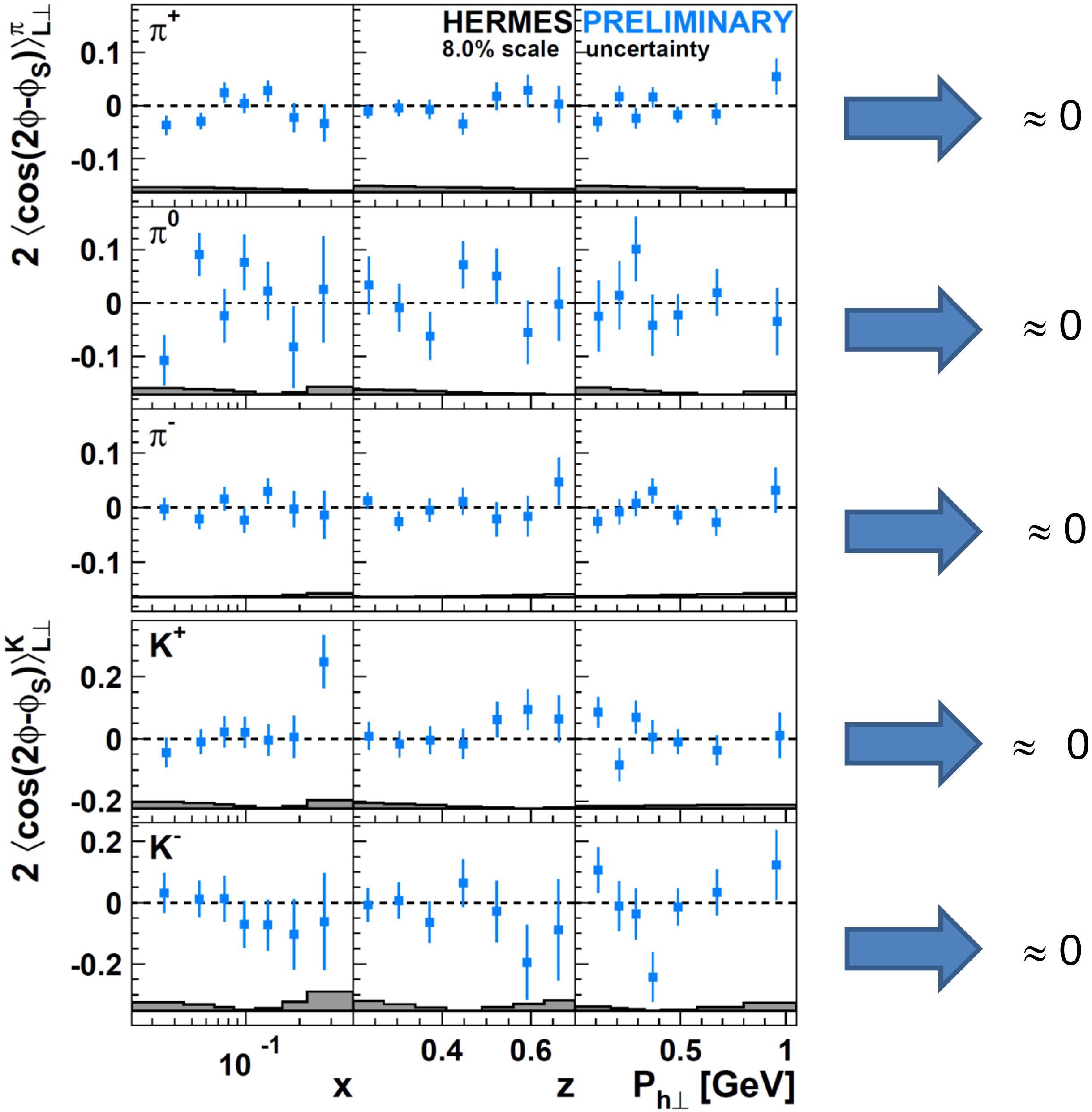
≈ 0

≈ 0

$\approx$ 0
sign change?

≈ 0

The cos(2ϕ-ϕ$_S$) Fourier component



Pretzelosity

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

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

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

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

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

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

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

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

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

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

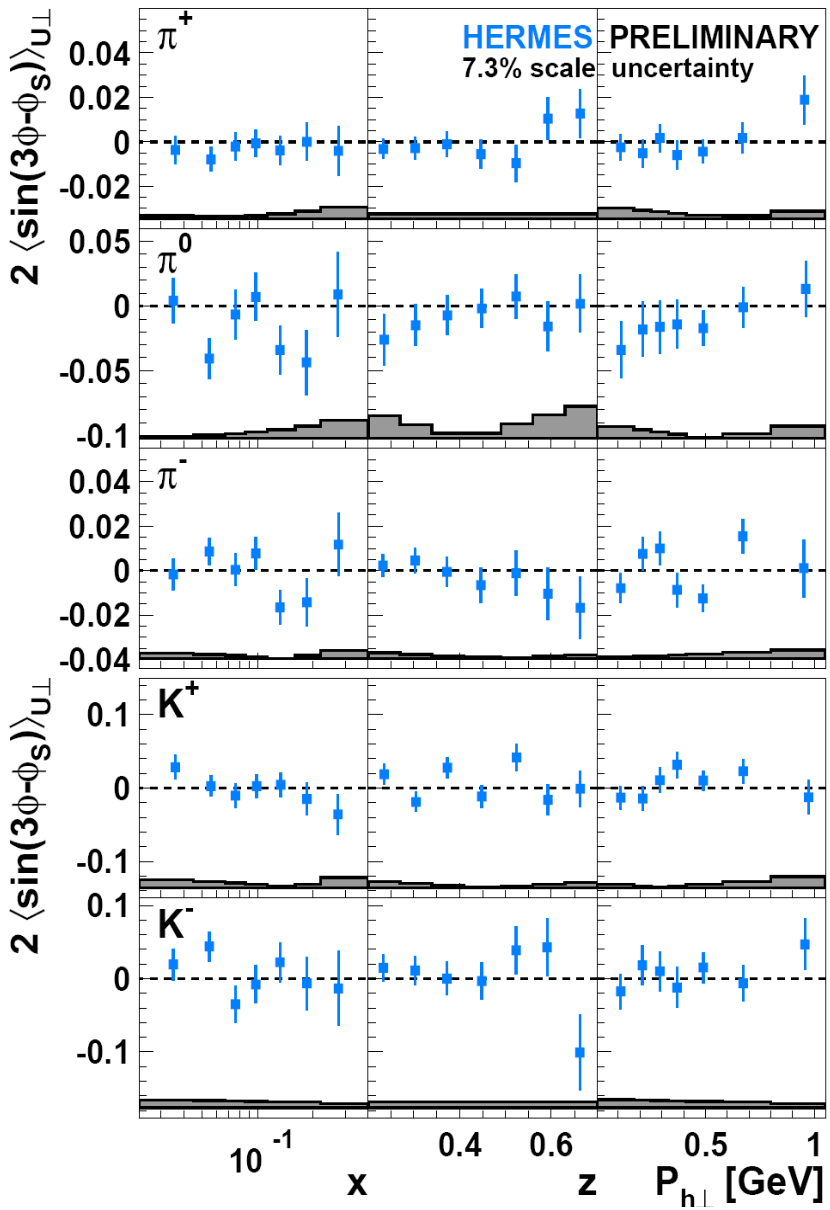
Distribution Functions

		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

Subleading twist

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

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

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

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

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

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

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

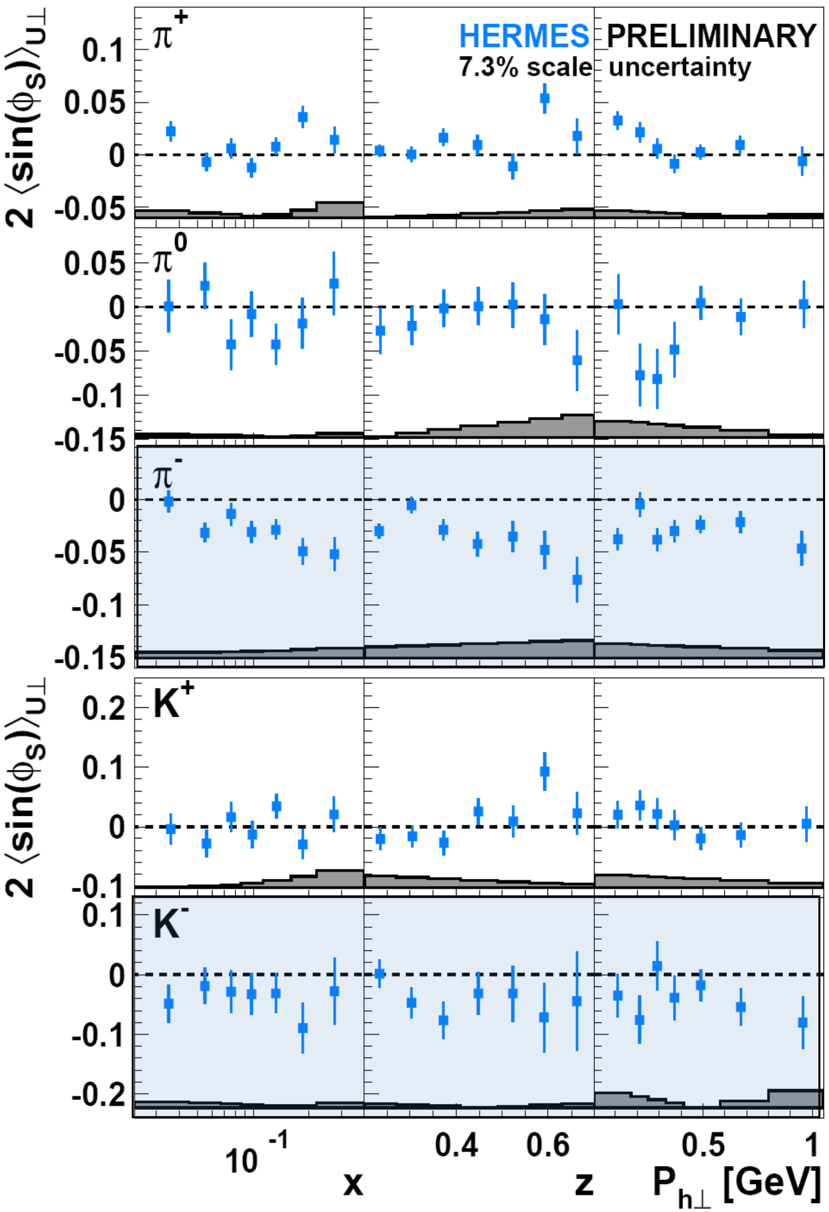
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}\,\mathcal{C}\Big\{\Big(x f_T D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z}\Big) - \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\Big[\Big(x h_T H_1^\perp + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^\perp}{z}\Big) - \Big(x h_T^\perp H_1^\perp - \frac{M_h}{M} f_{1T}^\perp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

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

Distribution Functions

		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 - ; $h_{1T}^\perp$ -

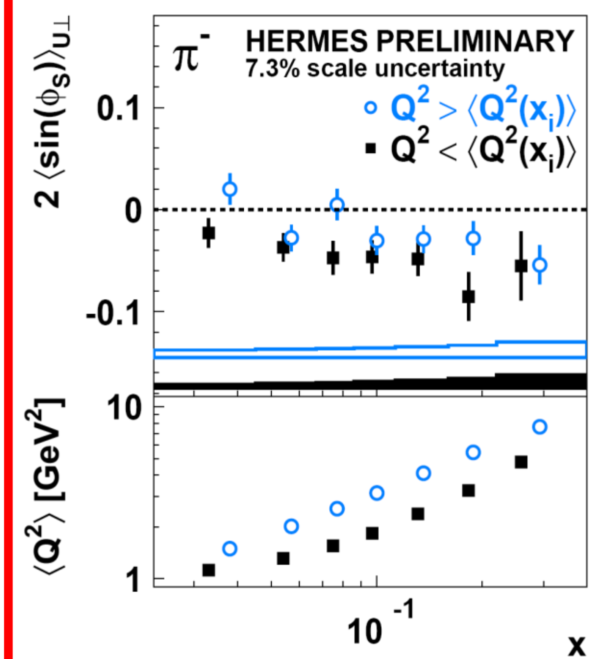
Subleading-twist sin(ϕ_S) Fourier component



- 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^-

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

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

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

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

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

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

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

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

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

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

Distribution Functions

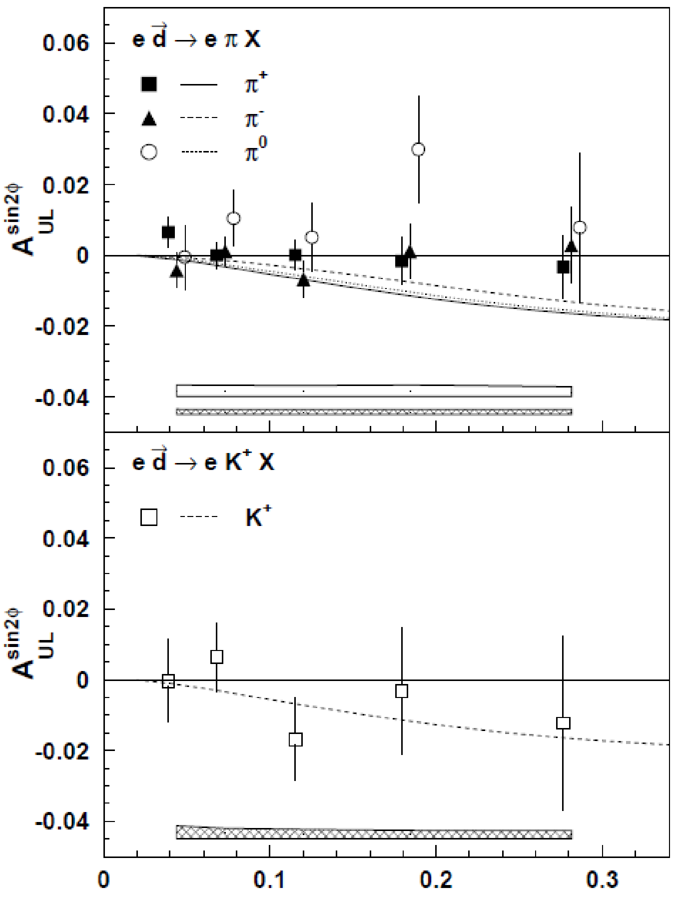
		quark U	quark L	quark T
nucleon	U	f_1		$h_1^{\perp}$ -
nucleon	L		g_1 -	$h_{1L}^{\perp}$ -
nucleon	T	$f_{1T}^{\perp}$ -	$g_{1T}^{\perp}$ -	h_1 - ; $h_{1T}^{\perp}$ -

Fragmentation Functions

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

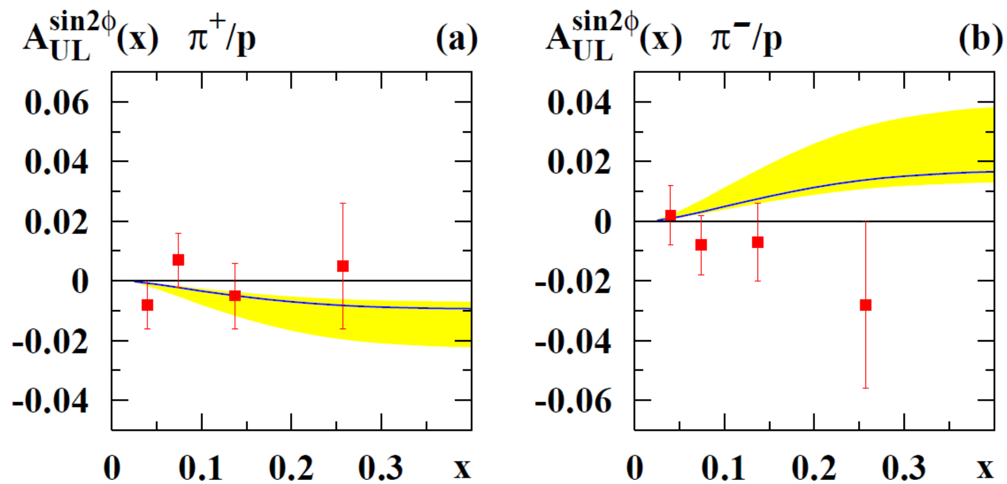
The sin(2ϕ) amplitude $\propto h_{1L}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

Deuterium target



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

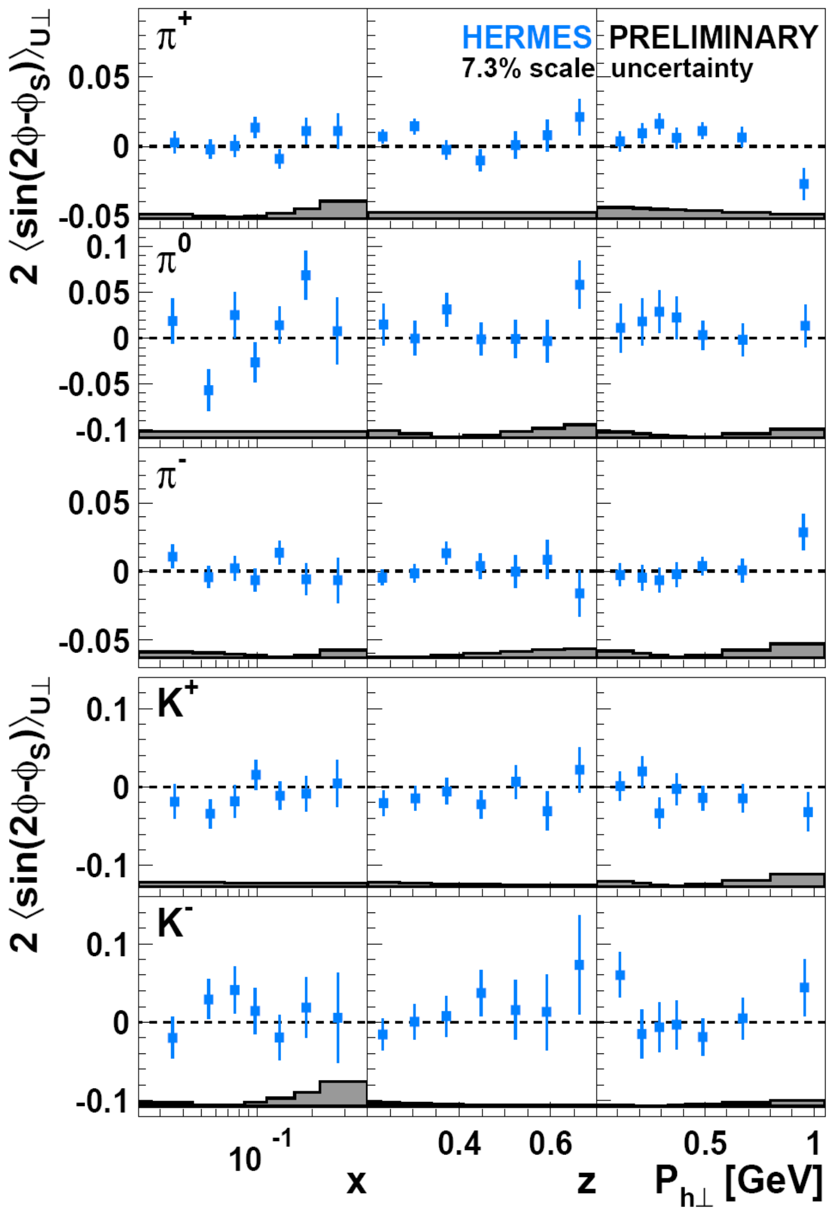
Hydrogen target



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

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

The subleading-twist sin(2ϕ-ϕ_S) Fourier component



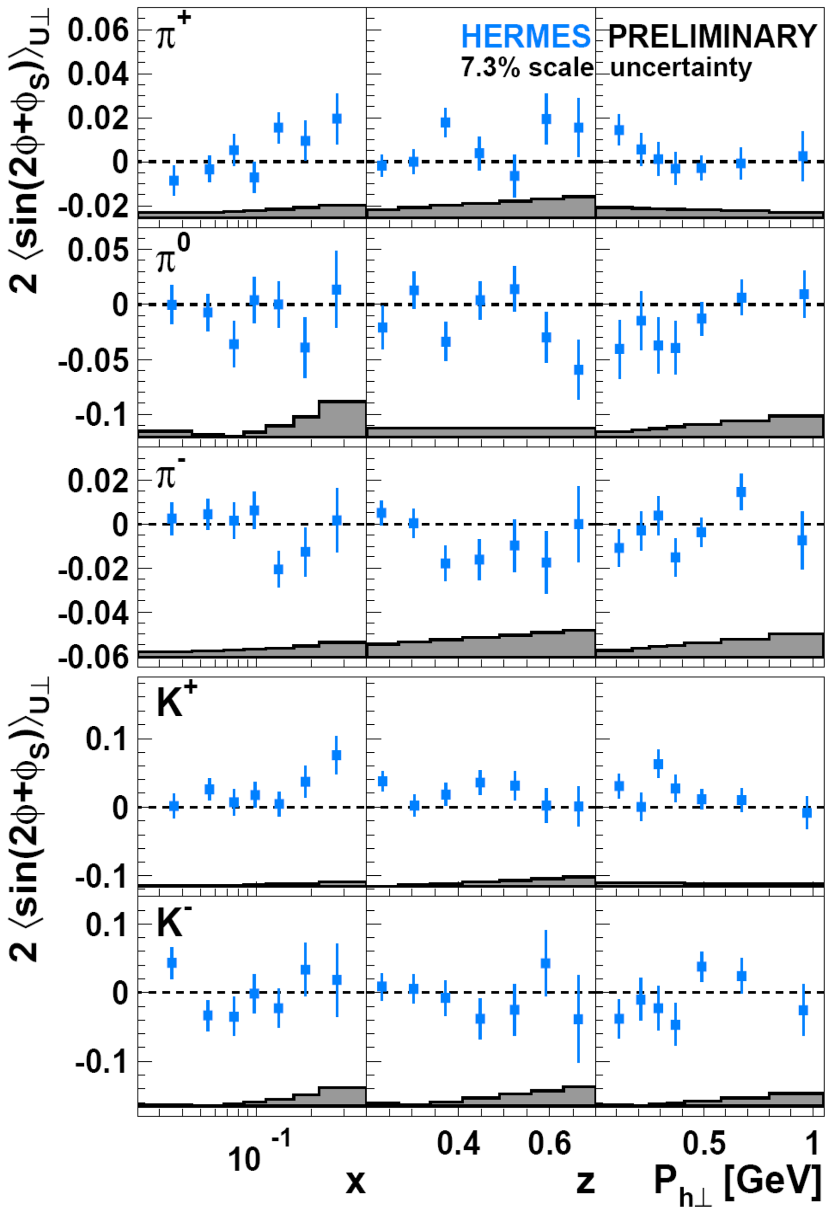
- sensitive to **worm-gear** $g_{1T}^{\perp}$, **Pretzelosity** and **Sivers function**:

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

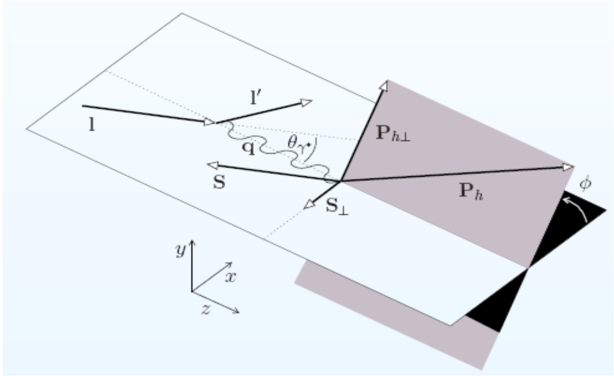
- suppressed by one power of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

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

The sin(2ϕ+ϕ_S) Fourier component



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



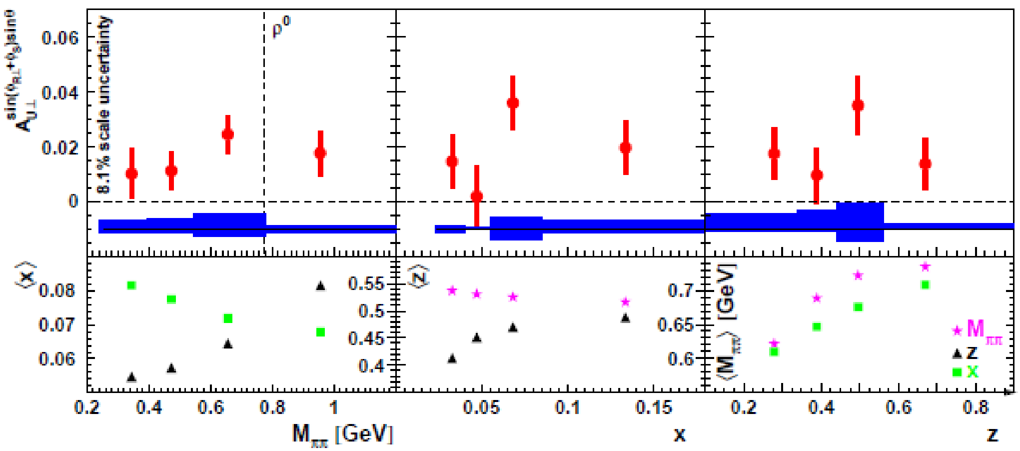
- related to <sin(2ϕ)>$_{UL}$ Fourier comp:

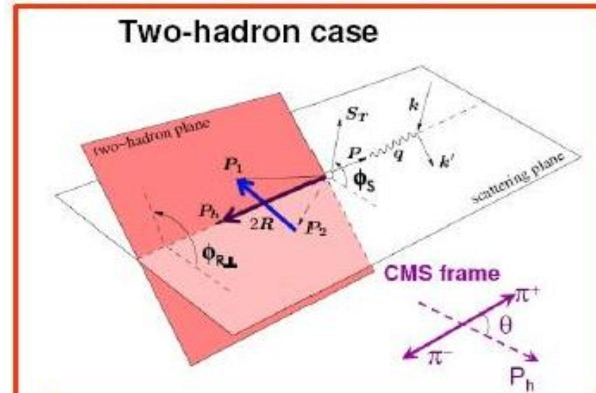
$$2\left\langle \sin(2\phi+\phi_S)\right\rangle_{UT}^{h} \propto \frac{1}{2}\sin(\vartheta_{l\gamma^*})2\left\langle \sin(2\phi)\right\rangle_{UL}^{h}$$

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

The di-hadron SIDIS cross-section

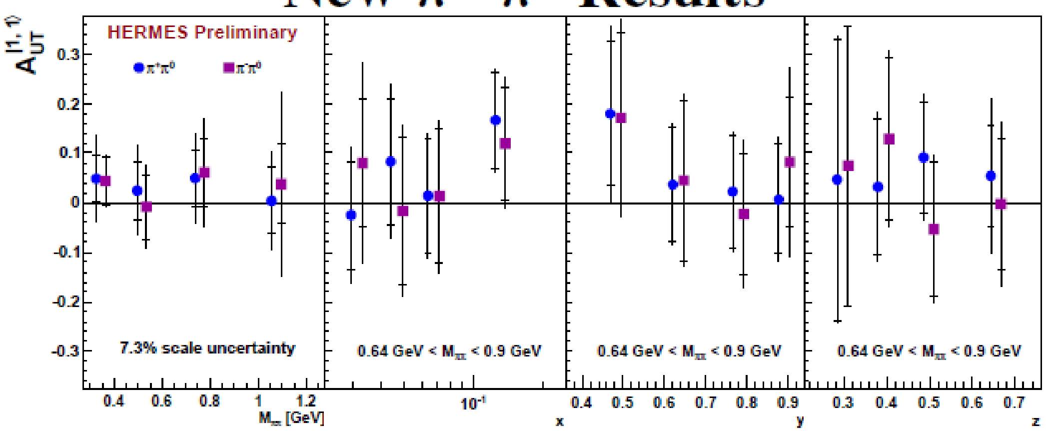
Published $\pi^+\pi^-$ Results





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

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

- independent way to access transversity
- significantly positive amplitudes
- 1^{st} evidence of non zero dihadron FF
- no convolution integral involved
- 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