TMDs studies at HERMES

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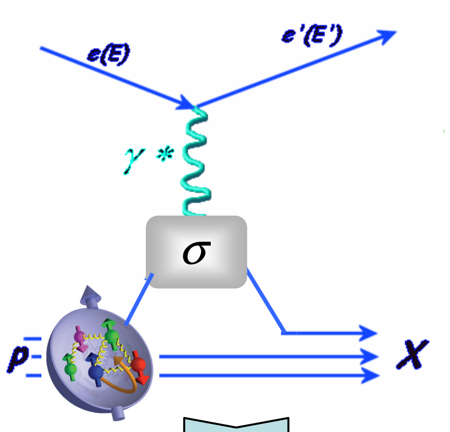
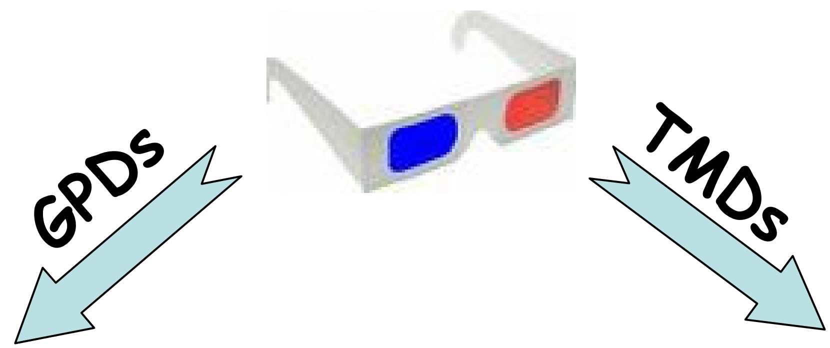
(for the HERMES Collaboration)

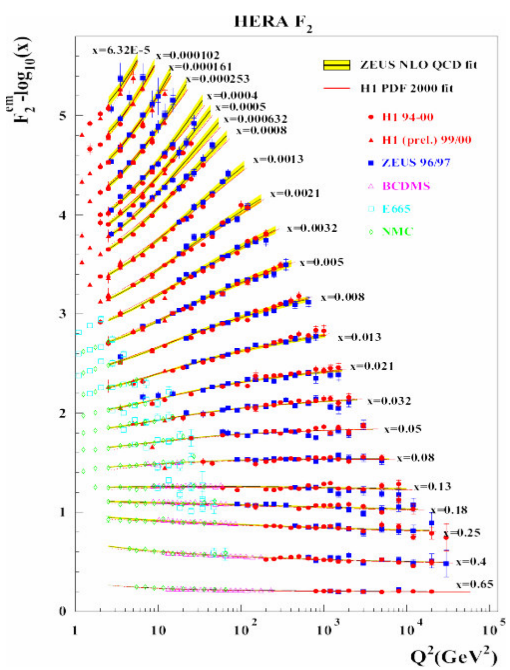
ECT - Trento, October 11-15 2010

Quantum phase-space tomography of the nucleon

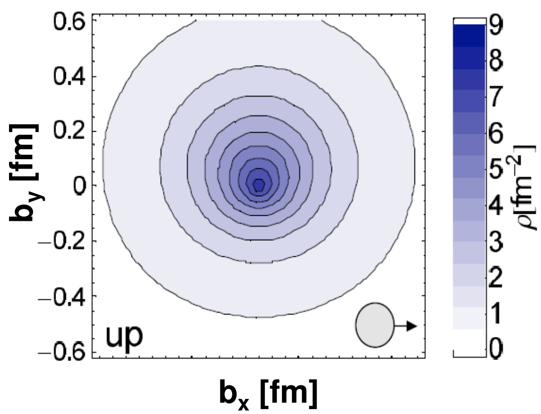


Join the real 3D experience!!



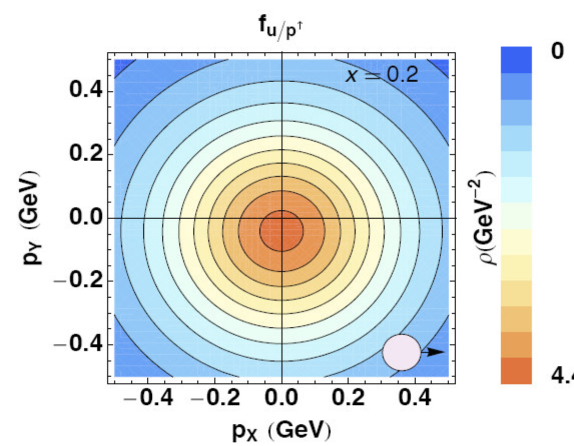


Longitudinal momentum structure of the nucleon



QCDSF/UKQCD, PRL 98 (07)

3D picture in coordinate space



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

3D picture in momentum space

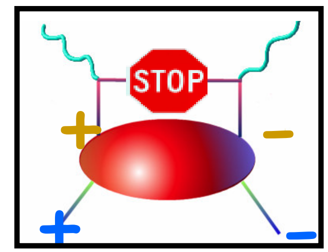
The nucleon spin structure at leading twist

momentum

helicity

transversity

		quark		
		U	L	T
nucleon	U	f_1		
	L		g_1 -	
	T			h_1 -



Legenda **(courtesy of A. Bachetta):**

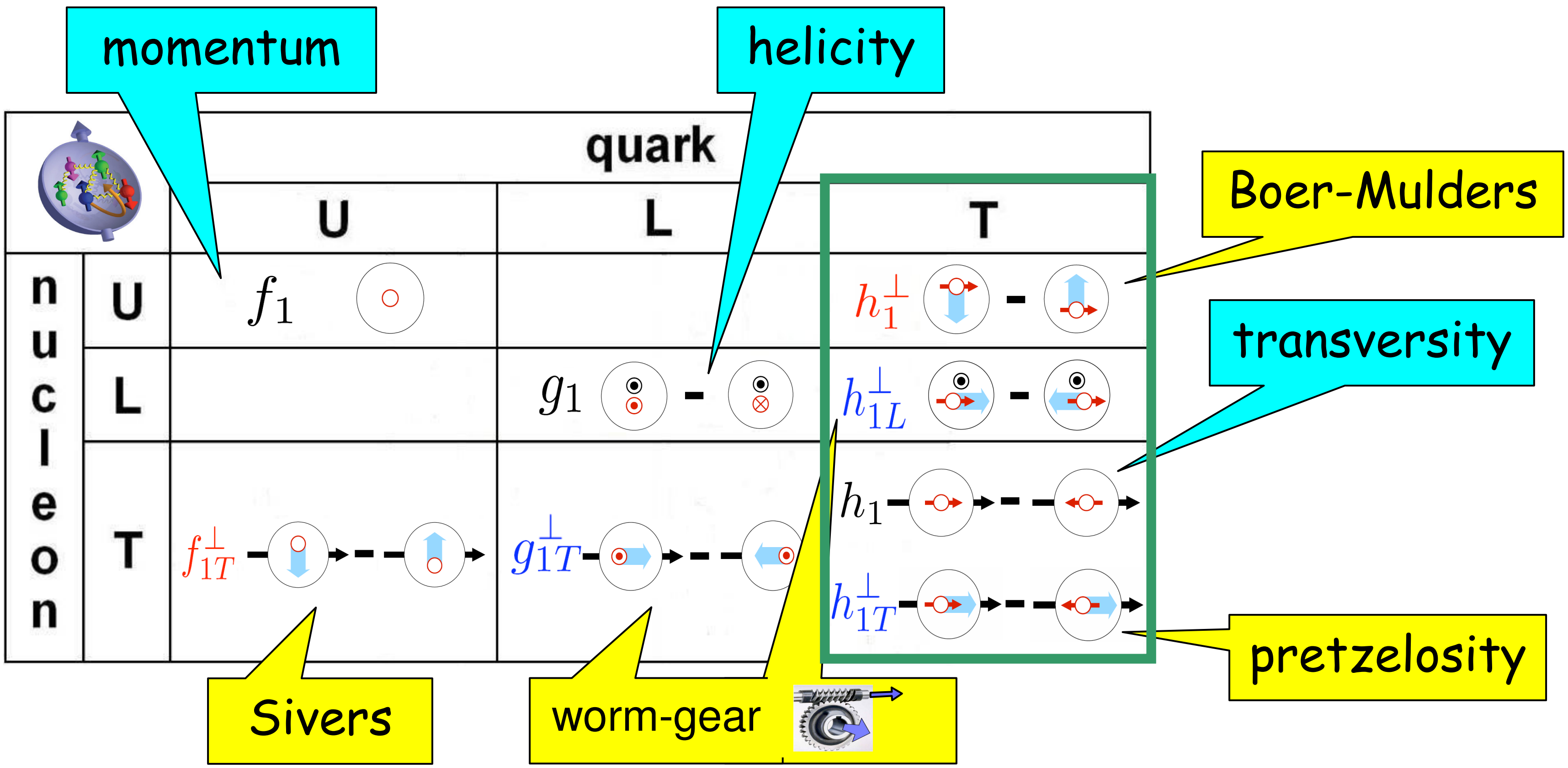
Proton comes out of the screen photon goes into the screen

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

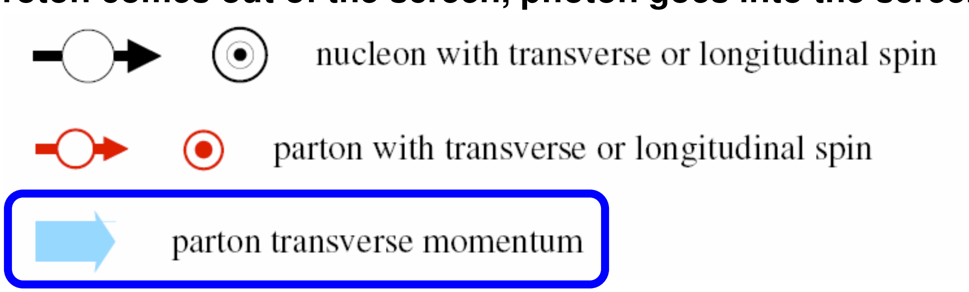
- **functions in black survive integration over transverse momentum**

The nucleon spin structure at leading twist



Legenda **(courtesy of A. Bacchetta):**

Proton comes out of the screen, photon goes into the screen

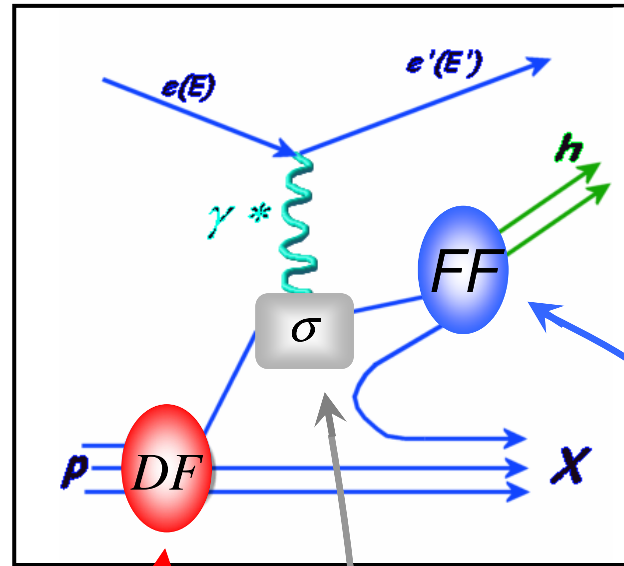


- **functions in black survive integration over transverse momentum**
- functions in red are naive T-odd
- functions in green box are chirally odd

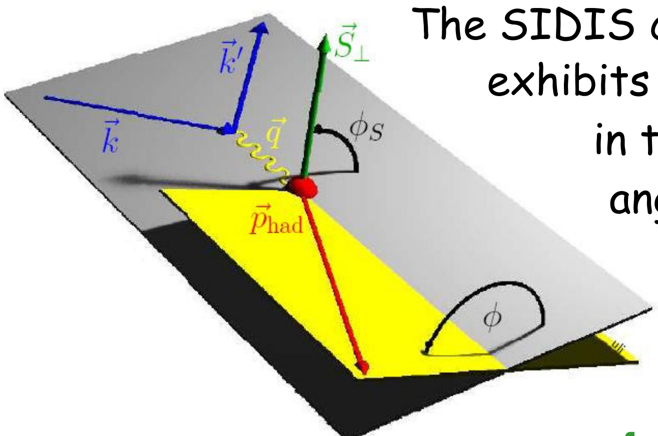
TMDs can be studied by measuring azimuthal asymmetries in SIDIS

Distribution Functions (DF)

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



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



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

Fragmentation Functions (FF)

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

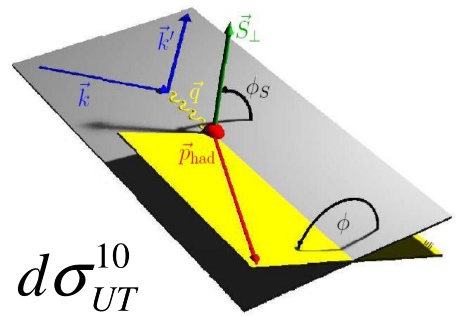
functions in green box are chirally odd

The SIDIS cross section up to twist-3

$d\sigma_{XY}$ — X: Beam, Y: Target — Polarization

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

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



$$+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right.$$

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

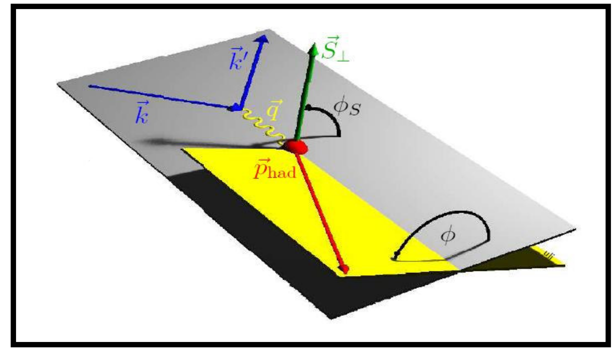
$$\left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\cos\phi_S \, d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi - \phi_S) d\sigma^{15}_{LT} \right] \right\}$$

How can we disentangle all these contributions ?

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

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

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



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

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

Boer-Mulders effect

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

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

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

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

The Boer-Mulders effect

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

Boer-Mulders effect

Cahn effect

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

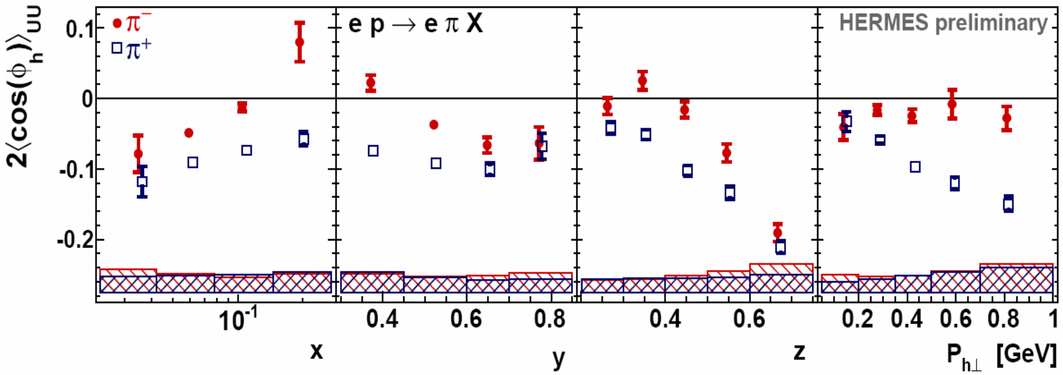
Accessed through azimuthal modulations in SIDIS with unpol. H and D targets

Sophisticated analysis based on a **multidimensional unfolding** to correct data for acceptance, detector smearing and higher order QED effects

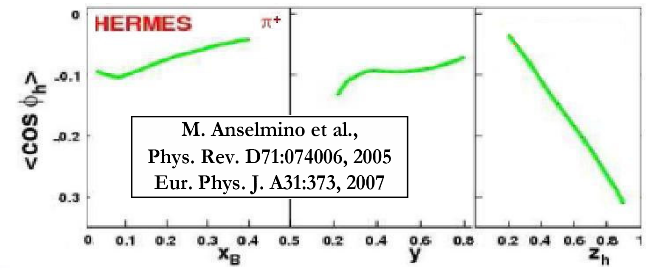
BINNING
900 kinematical bins x 12 ϕ_η-bins

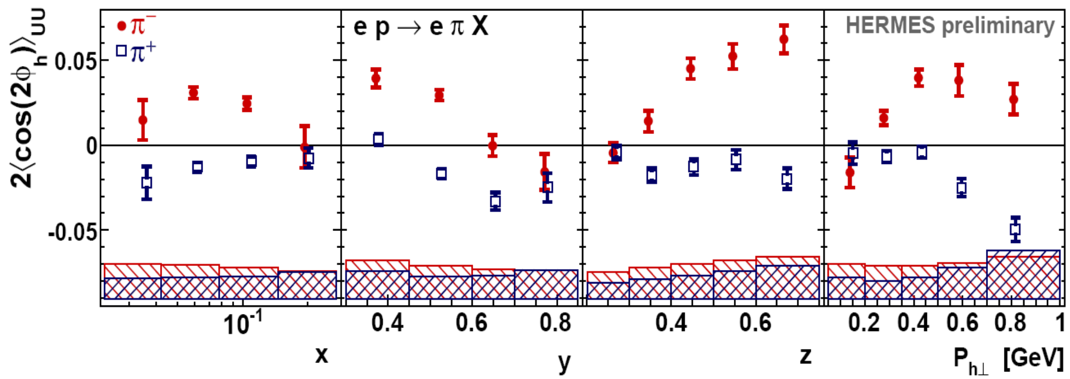
Variable	Bin limits							#
x	0.023	0.042	0.078	0.145	0.27	0.6		**5**
y	0.2	0.3	0.45	0.6	0.7	0.85		**5**
z	0.2	0.3	0.4	0.5	0.6	0.75	1	**6**
Pt	0.05	0.2	0.35	0.5	0.7	1	1.3	**6**

The Boer-Mulders effect (Hydrogen target)



- negative cos(ϕ) amplitudes for both π^+ and π^-

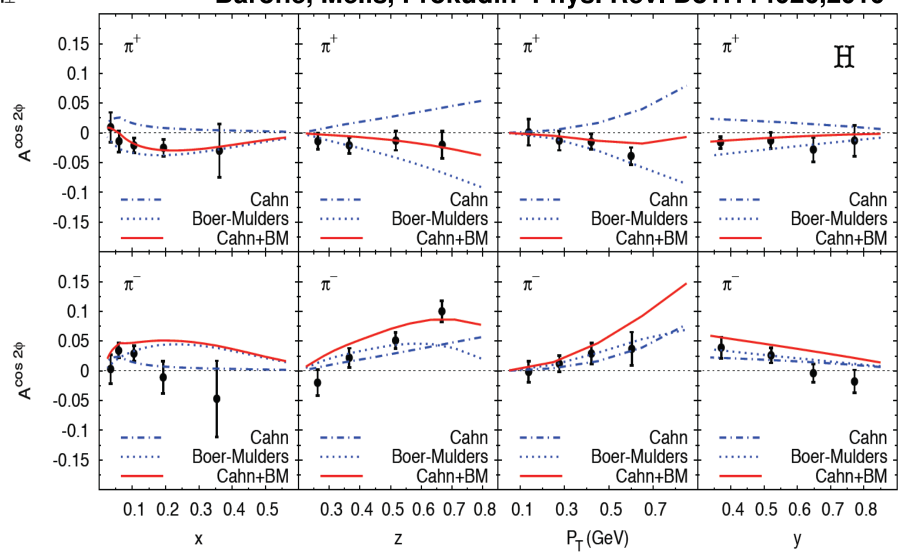




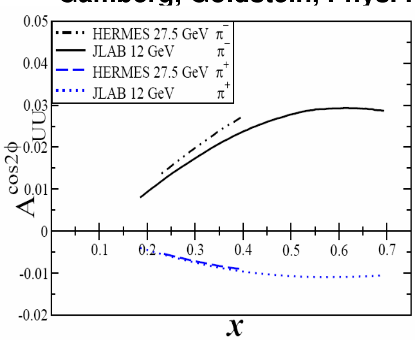
- • cos(2ϕ) ampl. of opposite sign for π^+ and π^-
- • results compatible with B-M function negative for u and d quarks assuming $H_1^{\perp,unfav} \approx -H_1^{\perp,fav}$

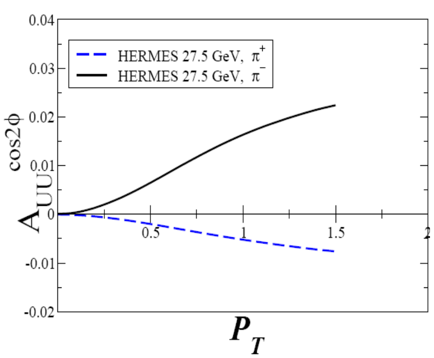
Similar results for D target

Barone, Melis, Prokudin Phys. Rev. D81:114026,2010

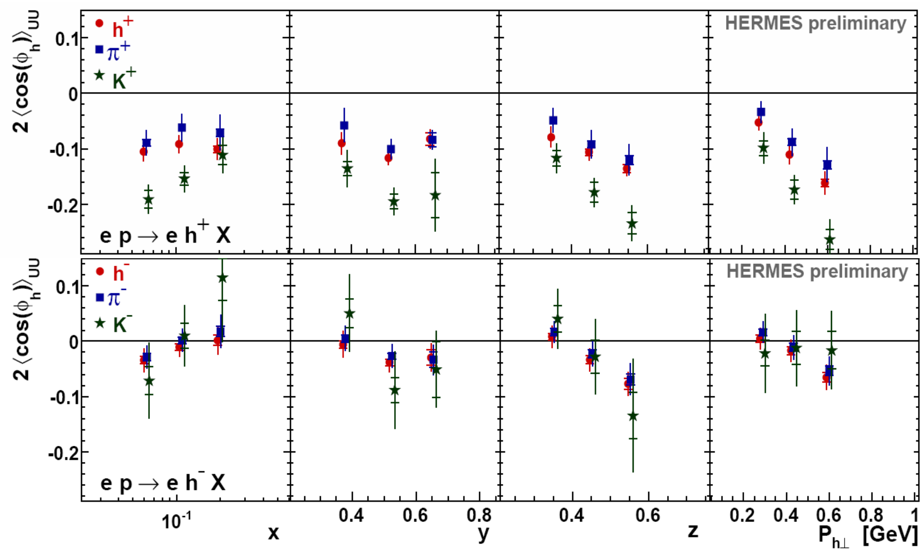


Gamberg, Goldstein, Phys. Rev. D77:094016,2008



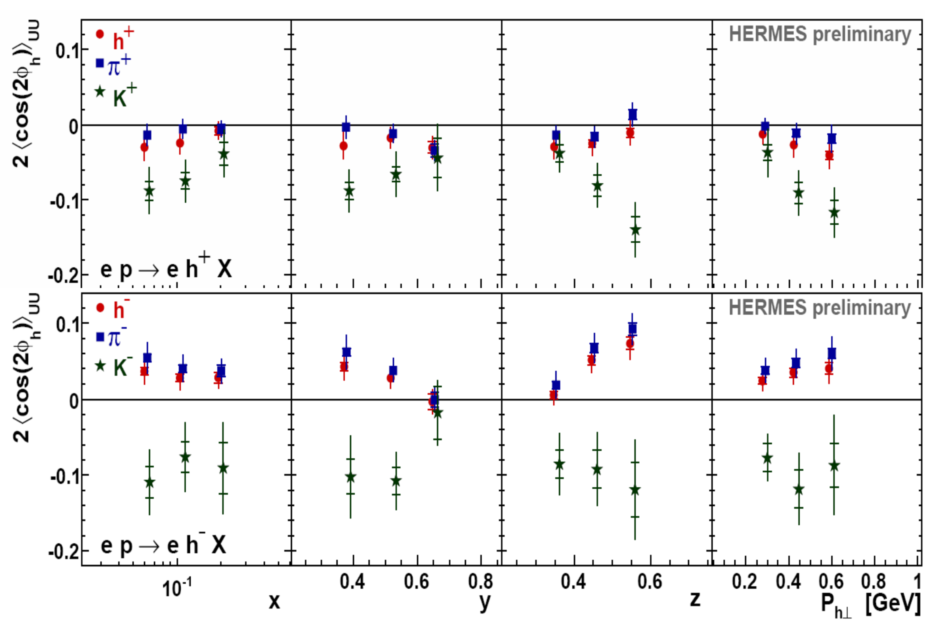


The kaons cos(nϕ) amplitudes (Hydrogen target)



- cos(ϕ): K^+ larger than π^+

  K^- compatible with π^-



- cos(2ϕ): K+ larger than π^+

  K^- and π^- of opposite sign

Similar results for D target

Accessing the polarized cross section through SSAs

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

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

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

probability of i_{th} SIDIS event — free parameter

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

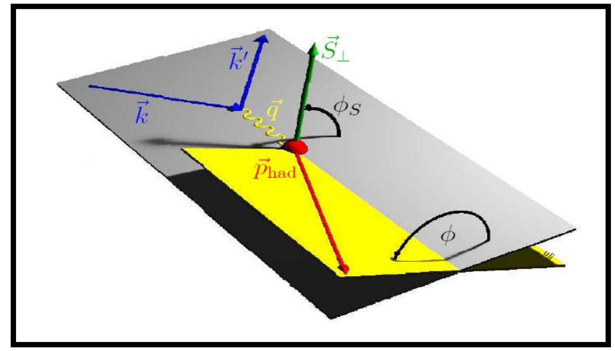
$$A_{UT}^h(\phi,\phi_S) = \frac{1}{|P_T|}\frac{d\sigma^h(\phi,\phi_S) - d\sigma^h(\phi,\phi_S+\pi)}{d\sigma^h(\phi,\phi_S) + d\sigma^h(\phi,\phi_S+\pi)}$$

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

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

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

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



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

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

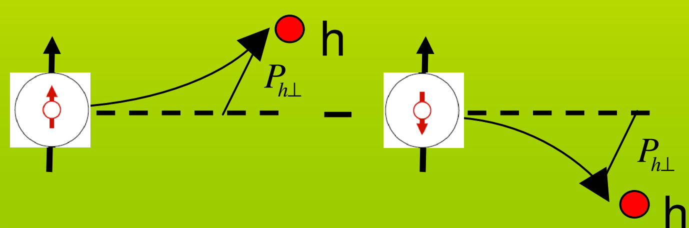
$$\ldots + \sin(\phi+\phi_S)\ d\sigma^9_{UT} + \sin(3\phi-\phi_S)\ d\sigma^{10}_{UT}$$

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

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

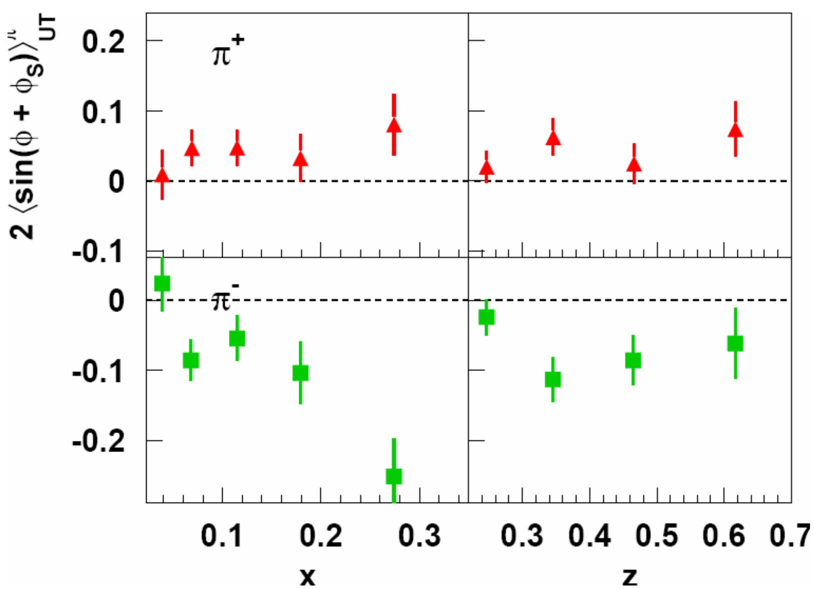
Collins effect

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

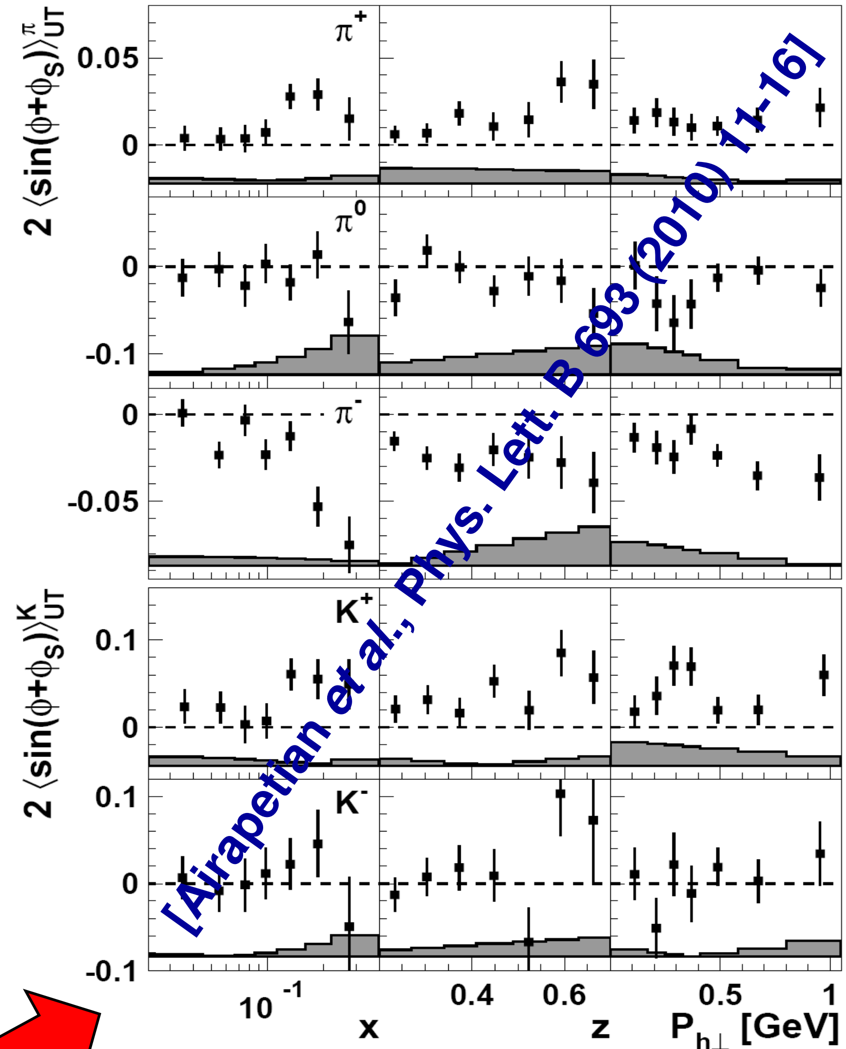


Collins amplitudes

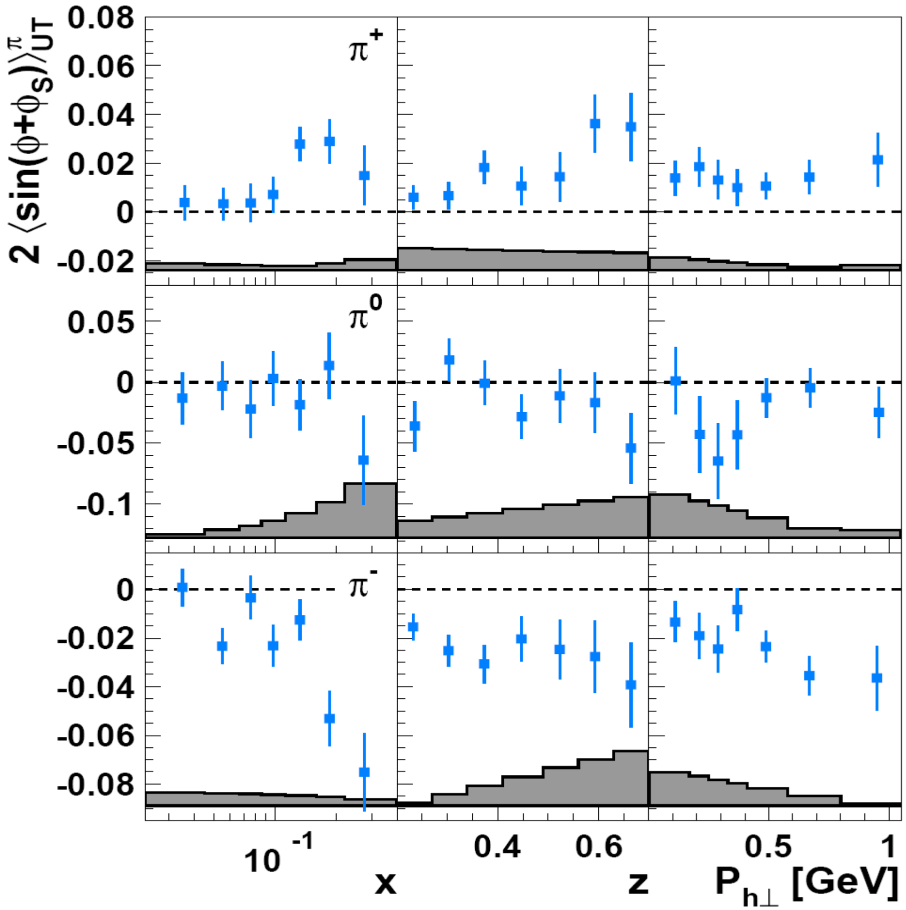
[*A. Airapetian et al.*, Phys. Rev.Lett. 94 (2005) 012002]



- First observation of non-zero Collins amplitudes
- π^+/π^- amplit. of opposite sign
- Main features confirmed by new high-statistics results



Collins pions amplitudes



- Non-zero Collins effect observed
- Both transversity and Collins function sizeable!
- Ampl. increase with x, i.e. towards the valence region
- Isospin symmetry fulfilled

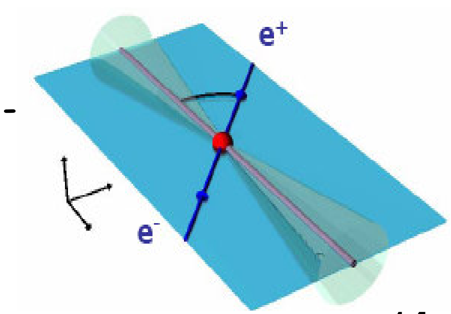
the large negative π^- amplitude suggests disfavored Collins FF with opposite sign:

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

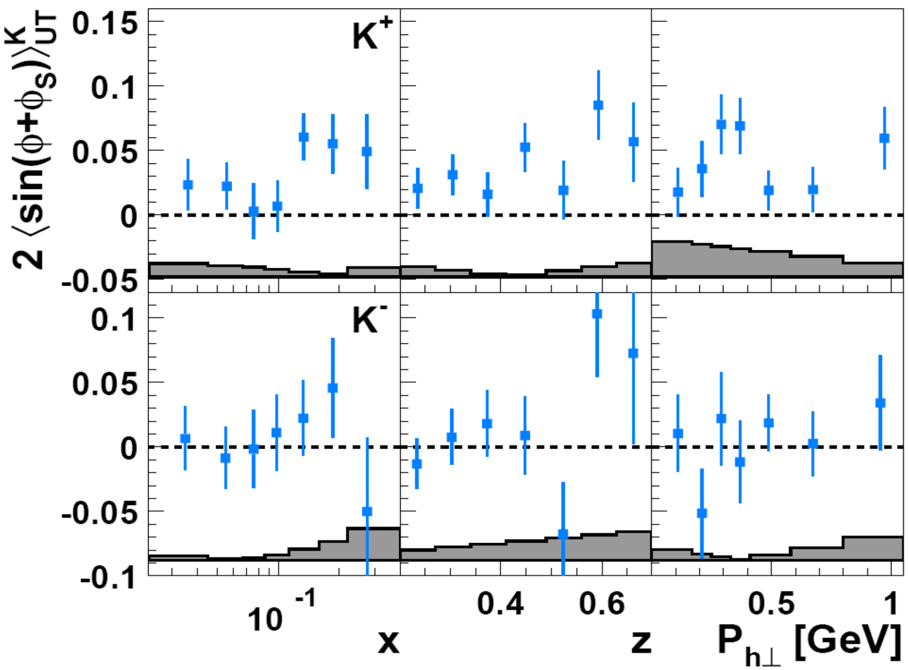
- positive for π^+
- consistent with zero for π^0
- negative for π^-

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

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



Collins kaons amplitudes



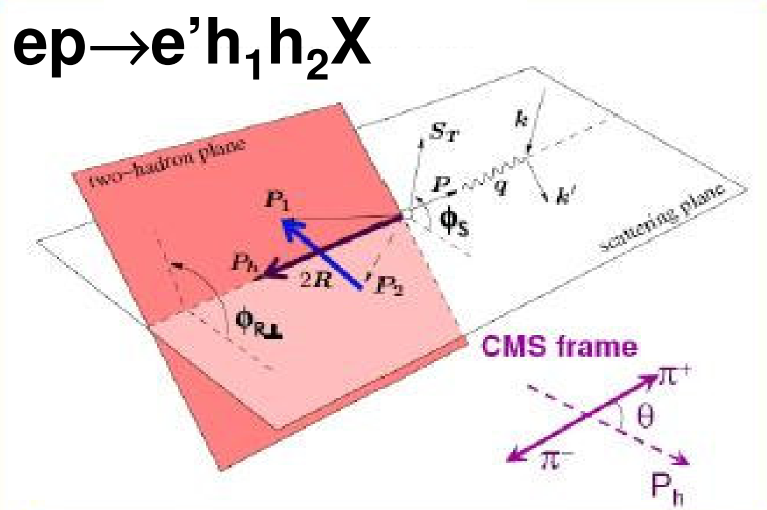
- Non-zero Collins effect observed
- Both transversity and Collins function sizeable!
- Ampl. increase with x, i.e. towards the valence region

☛ positive for K^+

☛ consistent with zero for K^-

An alternative access to transversity: the di-hadron SSA

$ep \rightarrow e' h_1 h_2 X$



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

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

Di-hadron FF

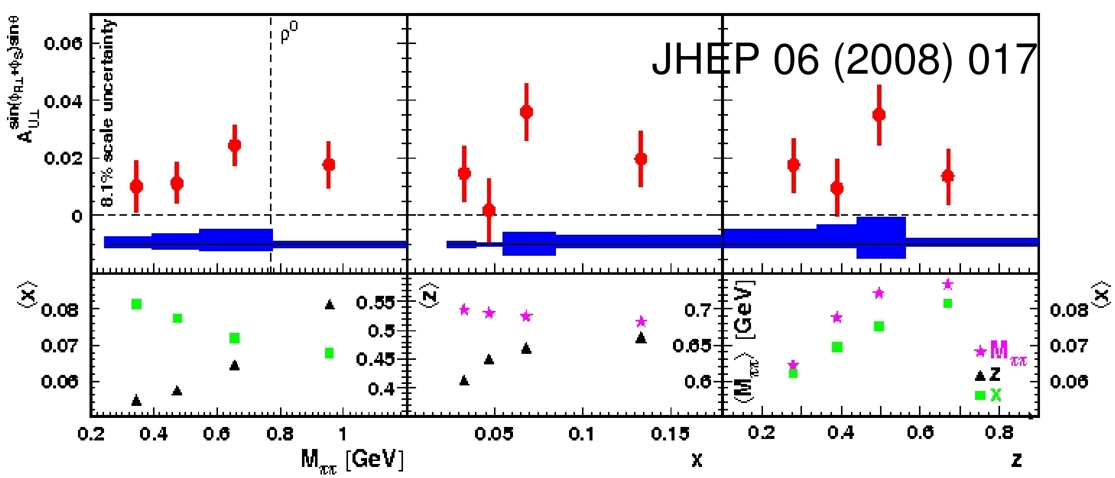
(does not depend on quark transv. momentum)

Chiral-odd T- odd

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

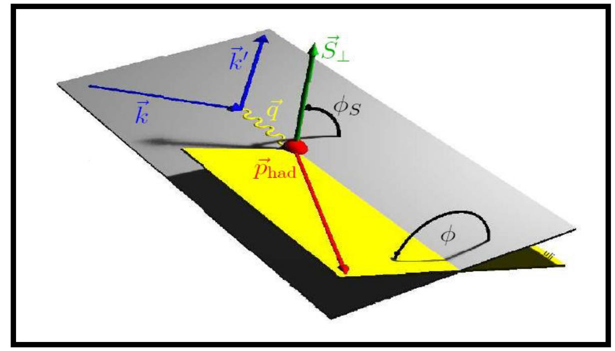
Describes Spin-orbit correlation in fragmentation

azimuthal asymmetries in the direction of the outgoing hadron pairs.



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

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, $h_{1T}^\perp$



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

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

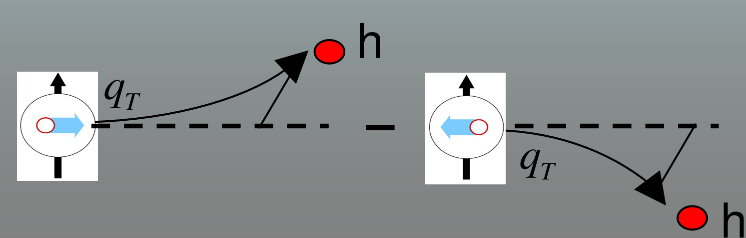
$$+ S_T \left\{ \sin(\phi - \phi_S) \; d\sigma^8_{UT} + \sin(\ldots \right.$$

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

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

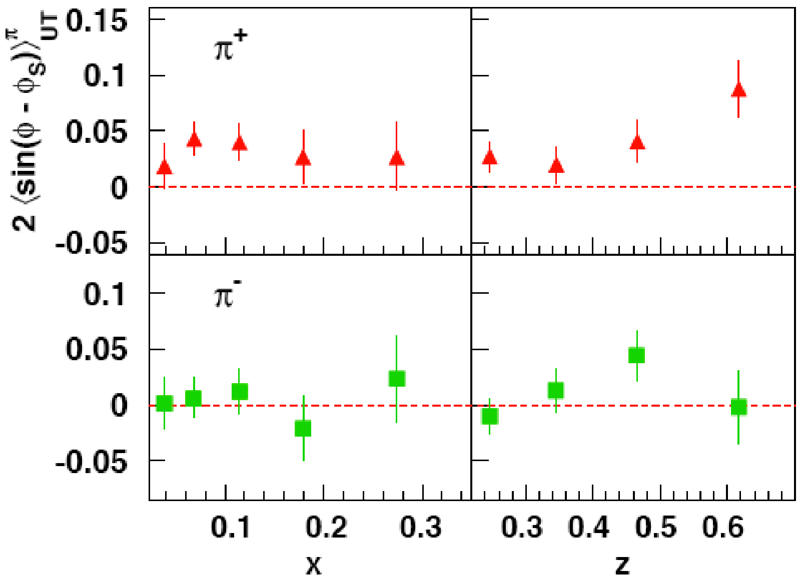
Sivers effect

- $\propto f_{1T}^\perp(x, p_T^2) \otimes D_1(z, k_T^2)$
- correlation between parton transverse momentum and nucleon transverse polarization
- requires orbital angular momentum

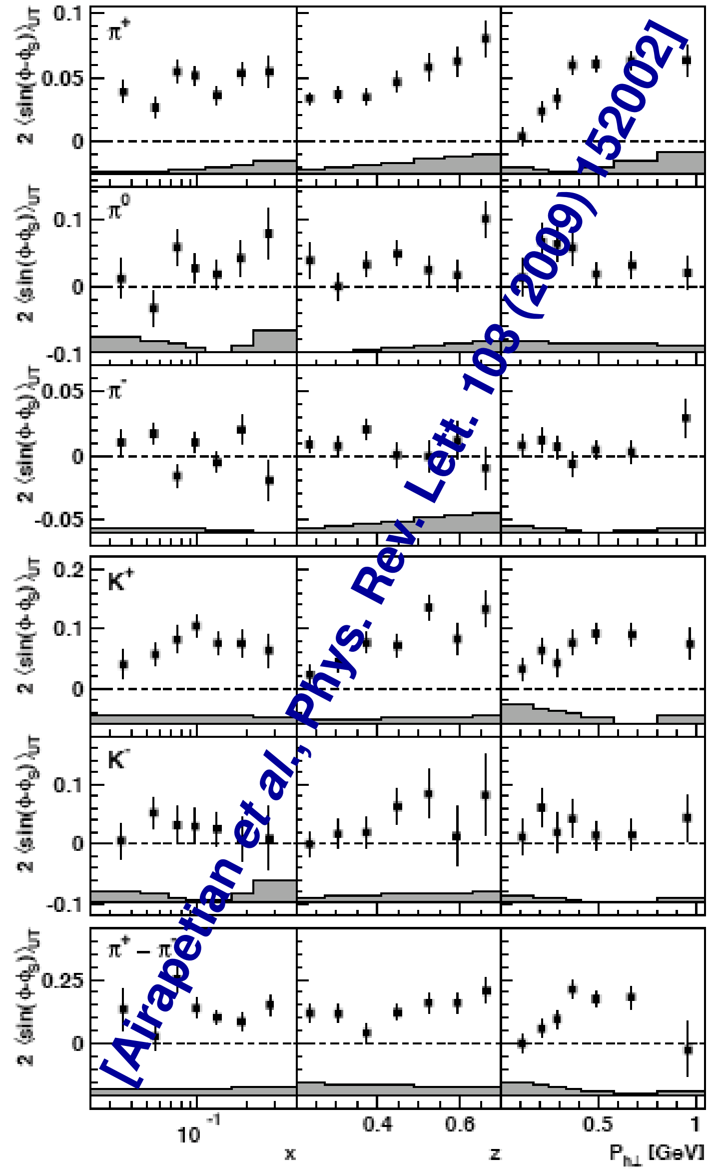


Sivers amplitudes

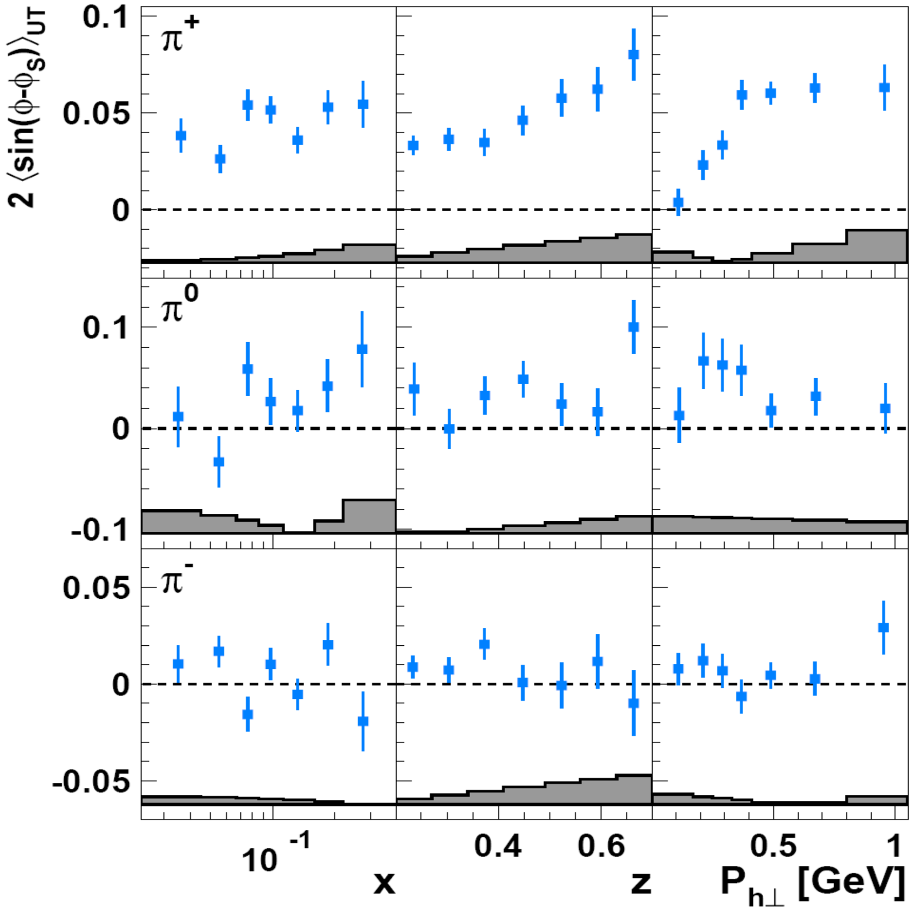
[*A. Airapetian et al.*, Phys. Rev.Lett. 94 (2005) 012002]



- ☑ **First observation of T-odd Sivers effects in SIDIS!**
- ☑ **Main features confirmed by new high-statistics results**



Sivers pions amplitudes



- Slignificantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- Sligthly positive
- Consistent with zero

☑ **Isospin symmetry fulfilled**

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

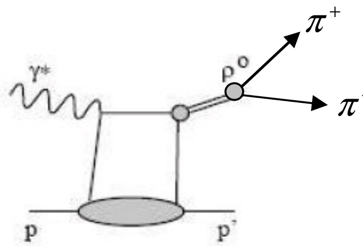
$$2\langle\sin(\phi-\phi_S)\rangle_{UT}^{\pi^+} \propto -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_W D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$ → u-quark Sivers DF < 0

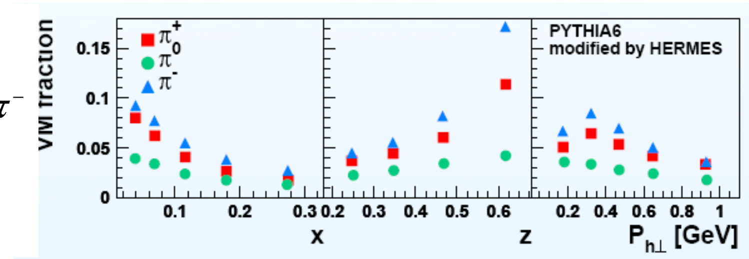
null signal for π⁻ indicates that d-quark Sivers DF > 0 (cancellation)

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

The pion-difference asymmetry

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

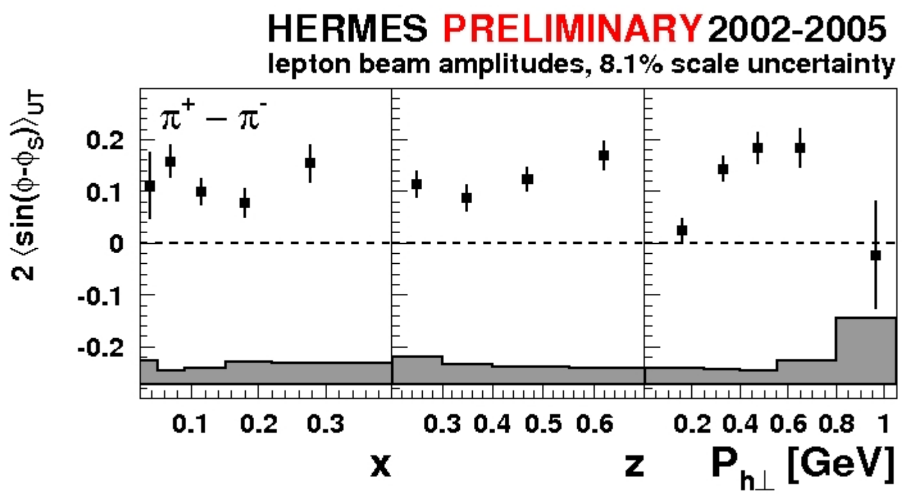


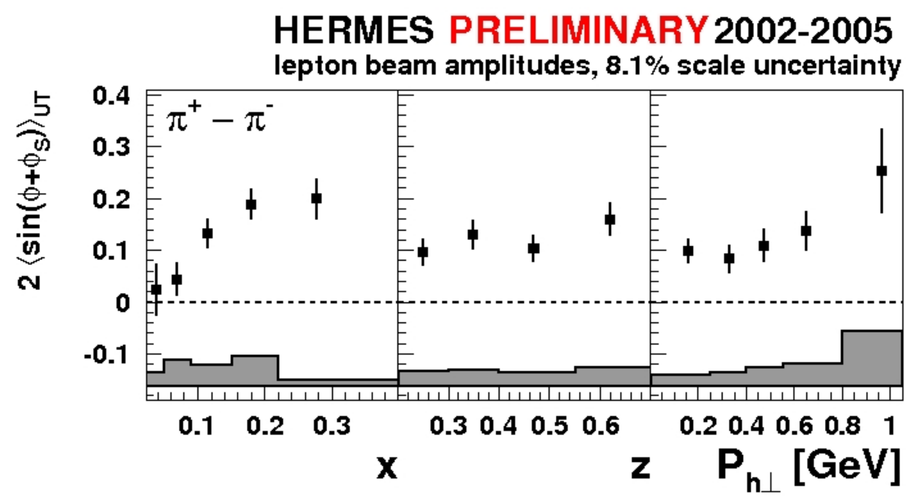


a new observable

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

Contribution from exclusive ρ^0 largely cancels out!

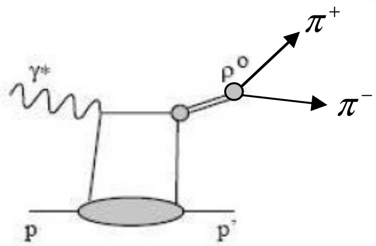


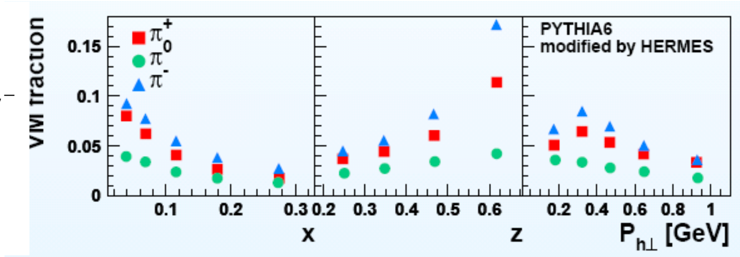


- significantly positive Sivers and Collins amplitudes are obtained
- measured amplitudes are not generated by exclusive VM contribution

The pion-difference asymmetry

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

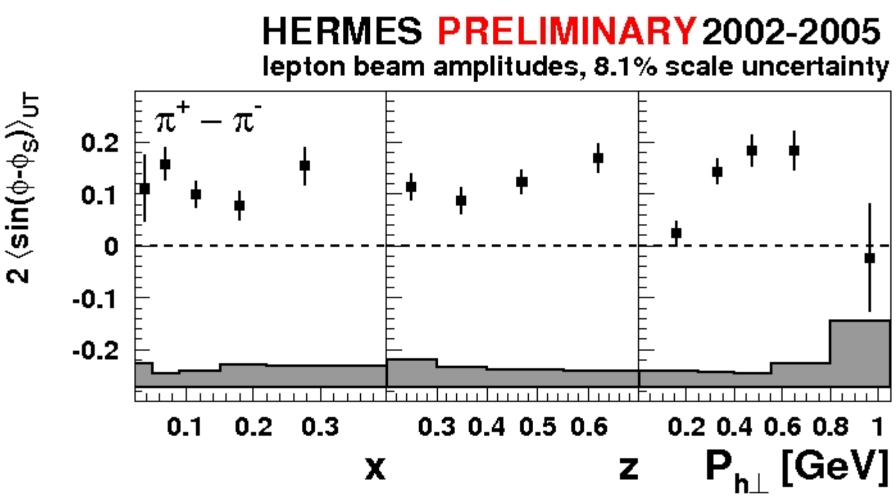




a new observable

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

Contribution from exclusive ρ^0 largely cancels out!

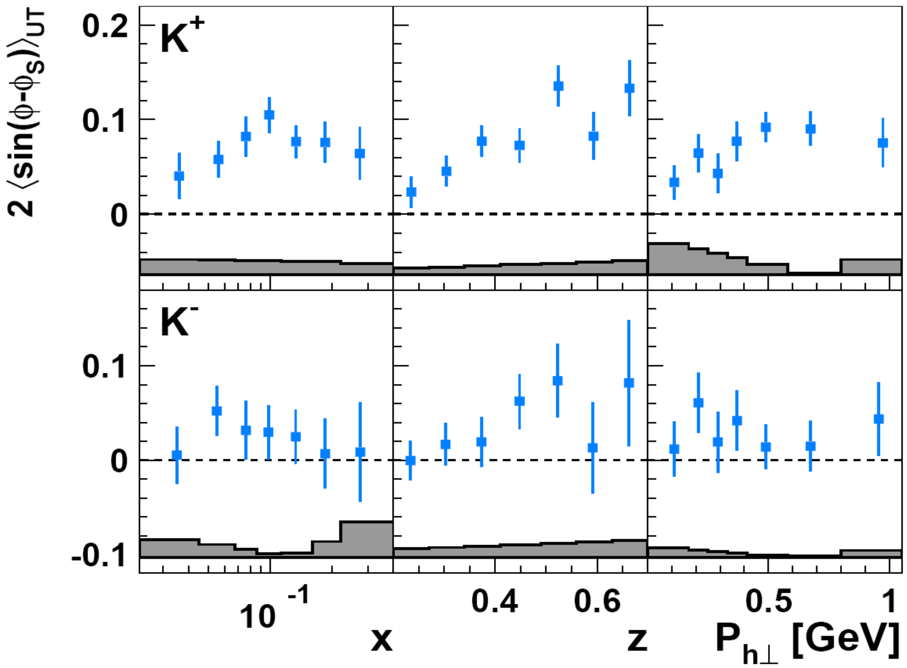


$$A_{UT}^{\pi^+-\pi^-} = -\frac{4f_{1T}^{\perp,u_v}-f_{1T}^{\perp,d_v}}{4f_1^{u_v}-f_1^{d_v}}$$

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

provides access to Sivers valence quarks distribution!

Sivers kaons amplitudes



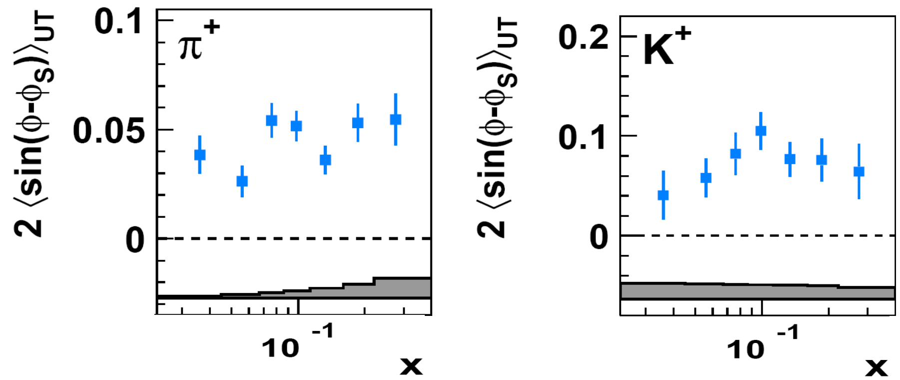
- Slignificantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$

- Sligthly positive

The Sivers π^+/K^+ riddle

π^+/K^+ production dominated by scattering off u-quarks:

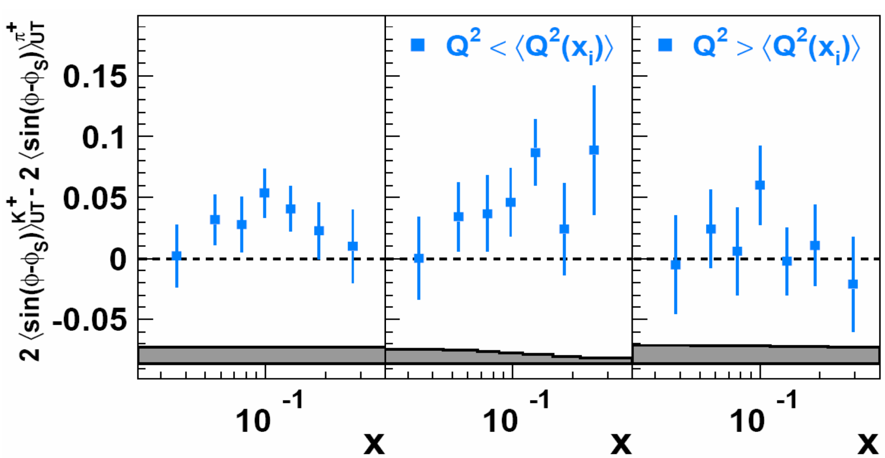
$$A_{UT}^{Sivers} \propto -\frac{f_{1T}^{\perp,u}(x,p_T^2) \otimes_W D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2)}$$



Dedicated studies ruled out possible influences from hadron misidentification (impact of high multiplicity events) or target remnant contributions (W^2 cut rised from 10 to 25 GeV^2)

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

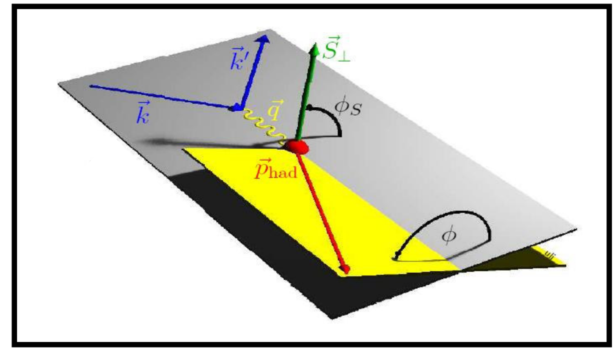
? impact of different k_T dependence of FFs in the convolution int. $\otimes_W$



- Difference of π^+ and K^+ amplitudes
- each x-bin divided into two Q^2 bins
- only in low-Q^2 region significant (90% C.L.) deviation is observed

? Higher-twist contrib. for Kaons

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 $h_{1T}^\perp$



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

$$+\lambda_e\left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL}\right]\Bigg\}$$

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

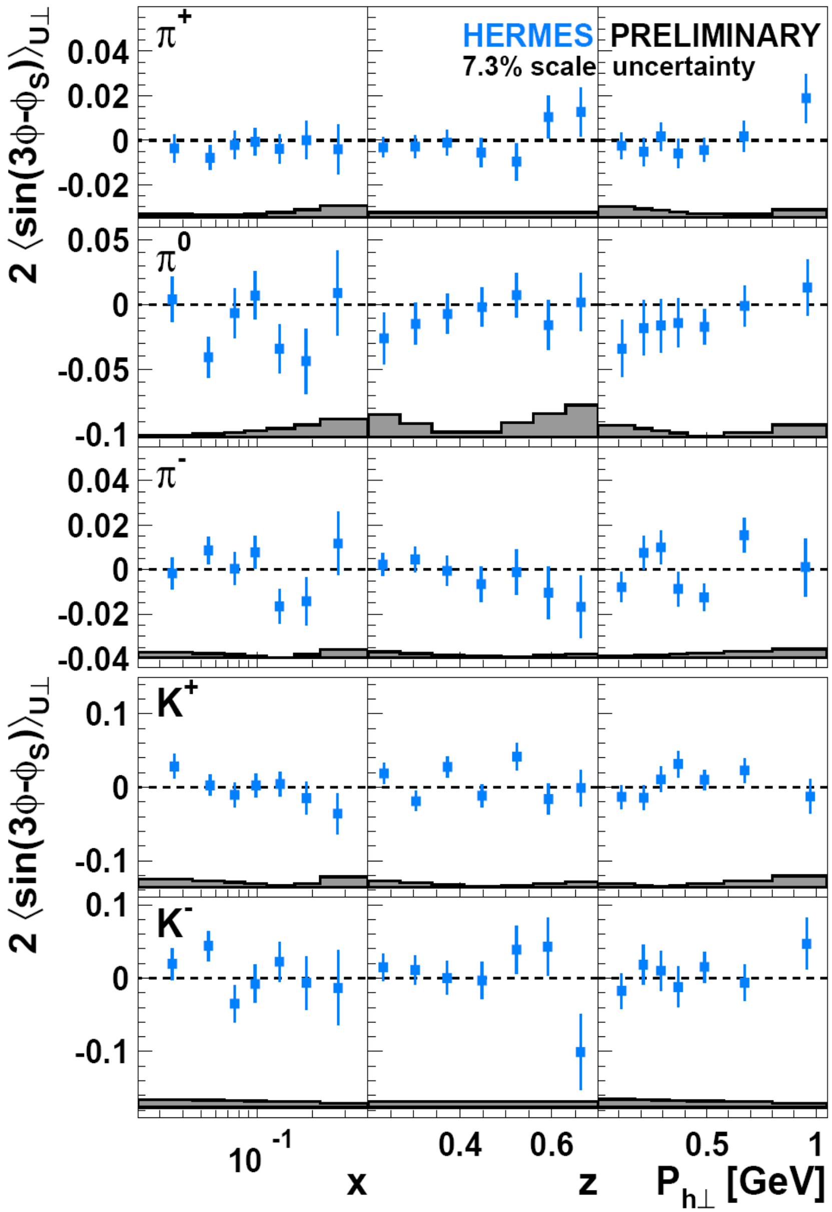
$$\ldots d\sigma^{11}_{UT} + \frac{1}{Q}\sin\phi_S d\sigma^{12}_{UT}$$

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

pretzelosity

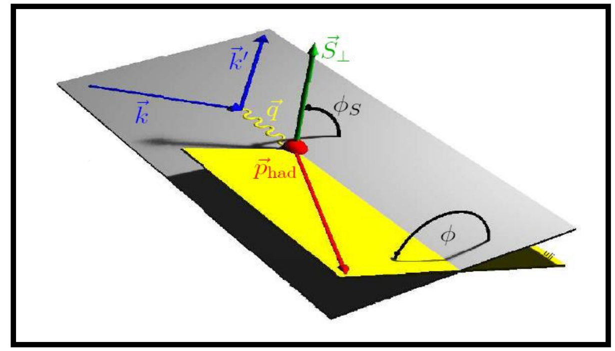
- $\propto h_{1T}^\perp(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$
- characterizes the p_T dependence of the transverse quark polarization in a transversely polarized nucleon.
- can be linked to the non-spherical shape of the nucleon resulting from substantial quark orbital angular momentum

The sin(3ϕ-ϕ_S) Fourier component



- Sensitive to **pretzelosity**
- suppressed by two powers of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes
- **no significant non-zero signals oberseved**

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



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

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

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

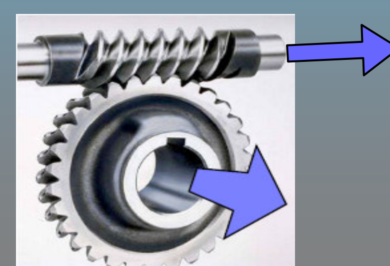
$$+ \frac{1}{Q} \ldots$$

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

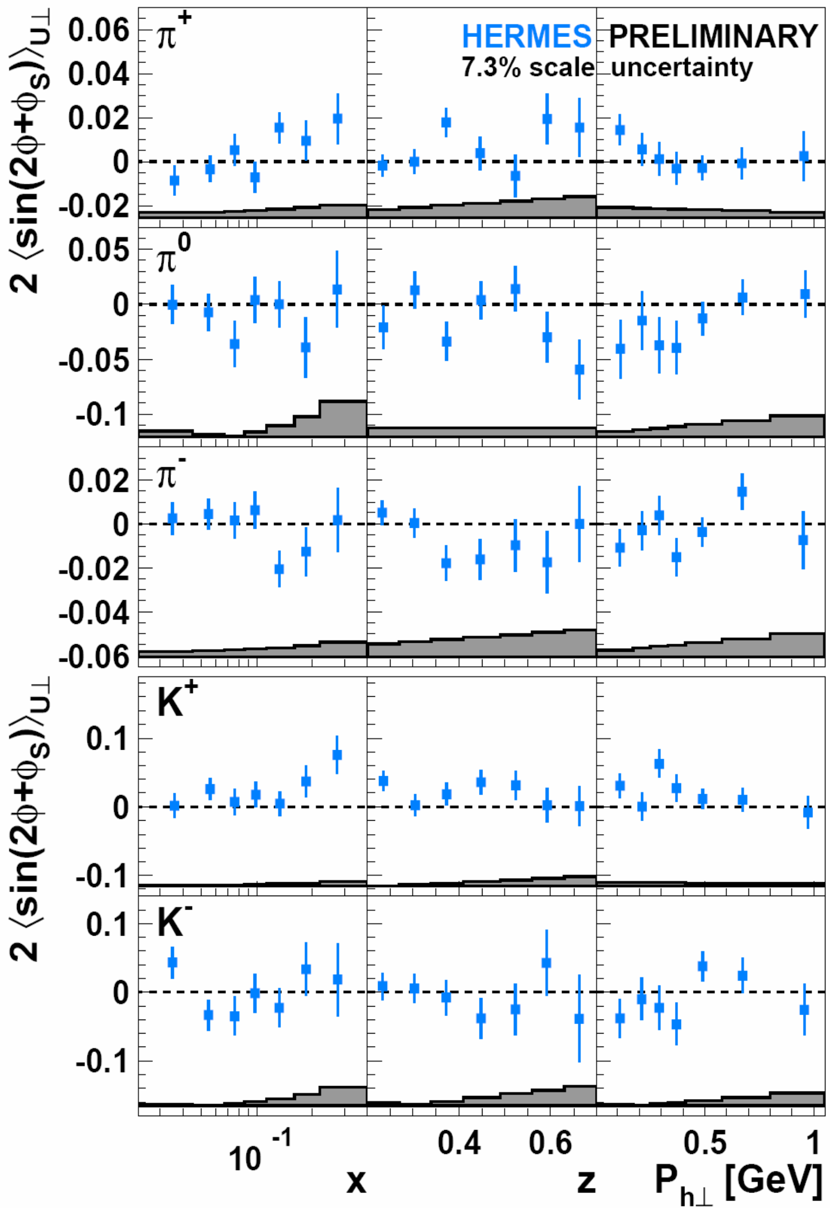
Worm-gear (UL)

(Kotzinian-Mulders)

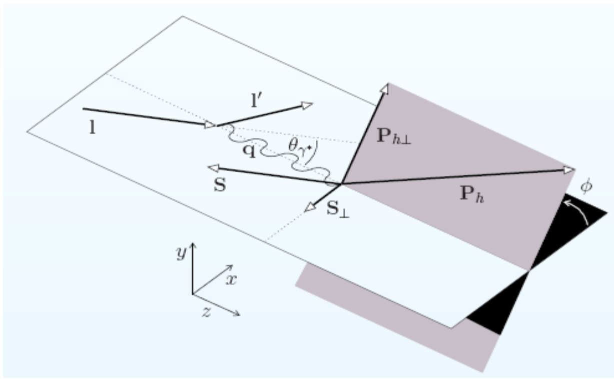
- $\propto h_{1L}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$
- describes the probability to find transversely polarized quarks in a longitudinally polarized nucleon
- accessible in UT measurements through $\sin(2\phi+\phi_S)$ Fourier component



The sin(2ϕ+ϕ$_S$) Fourier component



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

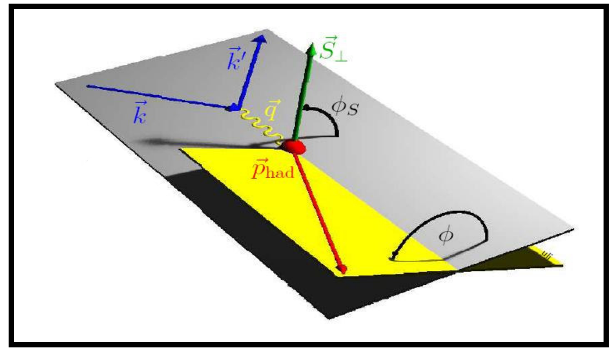


- related to <sin(2ϕ)>$_{UL}$ Fourier comp:

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

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

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



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

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

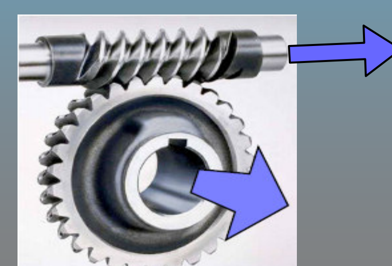
$$+ \mathbf{S_T} \left\{ \sin(\phi - \phi_S) \;\; d\sigma_{UT}^{8} + \sin(\phi \ldots \right.$$

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

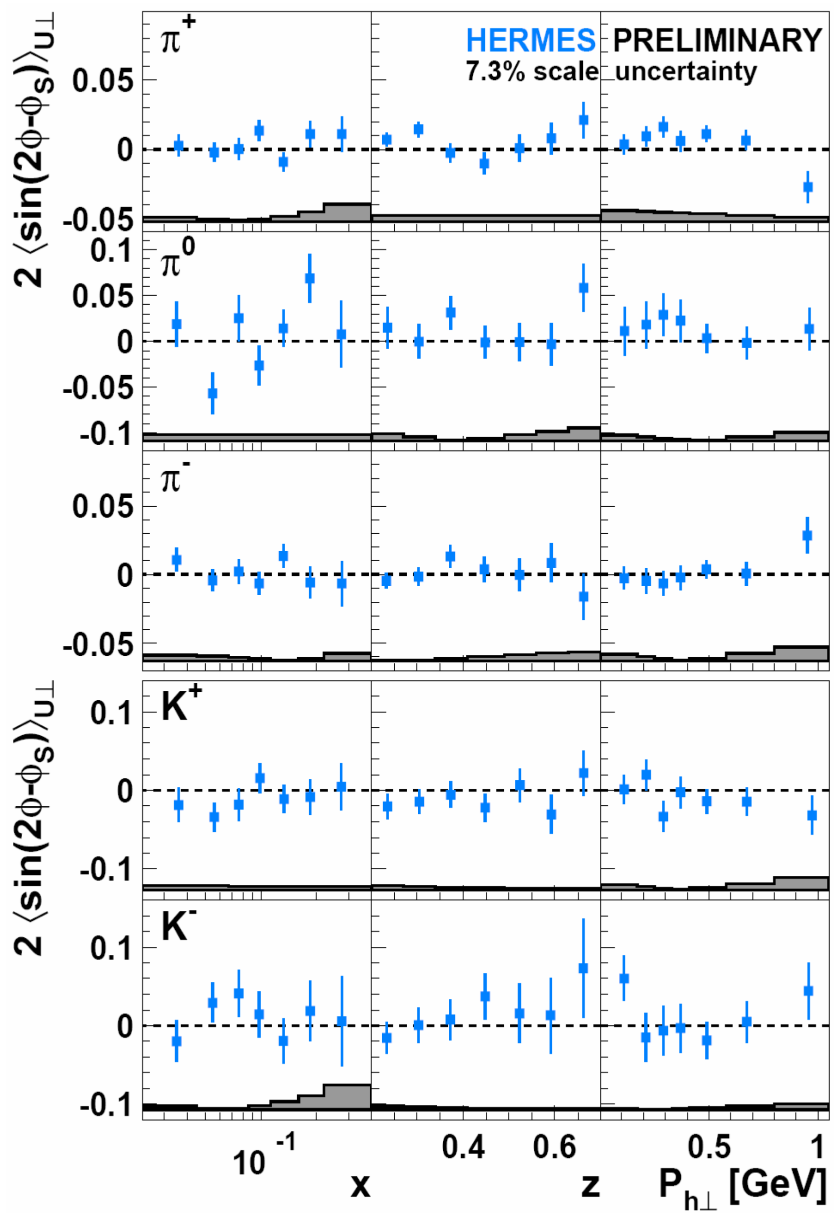
$$+ \lambda_e \left[\cos(\phi - \phi_S) \;\; d\sigma_{LT}^{13} + \frac{1}{Q} \ldots \right.$$

Worm-gear (LT)

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



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



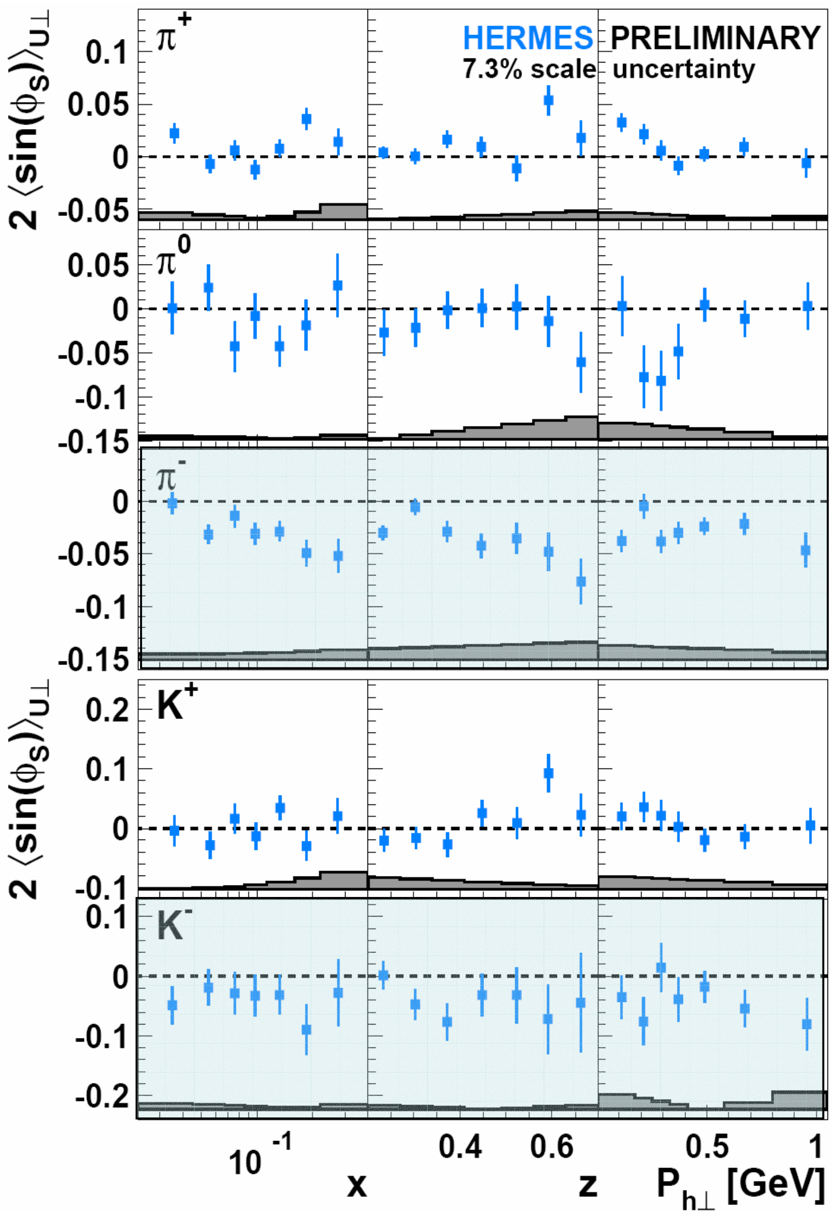
• sensitive to **worm-gear** $g_{1T}^{\perp}$, **Pretzelosity** and **Sivers function**:

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

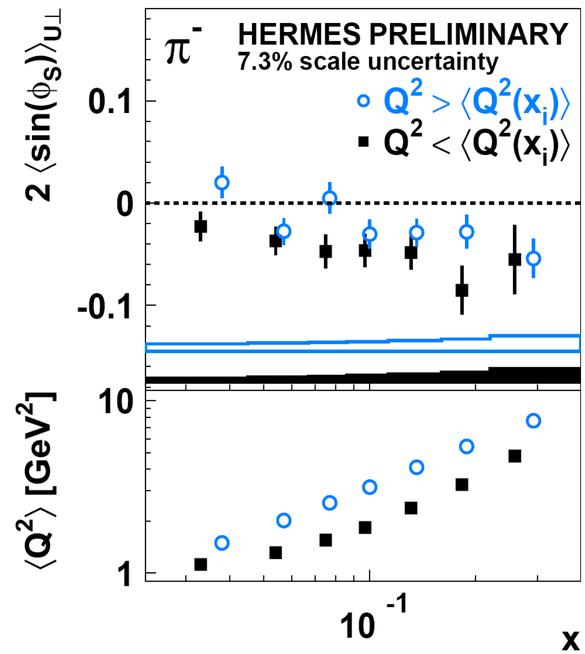
• suppressed by one power of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

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

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



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



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

Conclusions

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

• **Non-zero Boer-Mulders effect observed for identified charged pions and kaons** → clear evidence of non-zero Boer-Mulders function and Collins FF

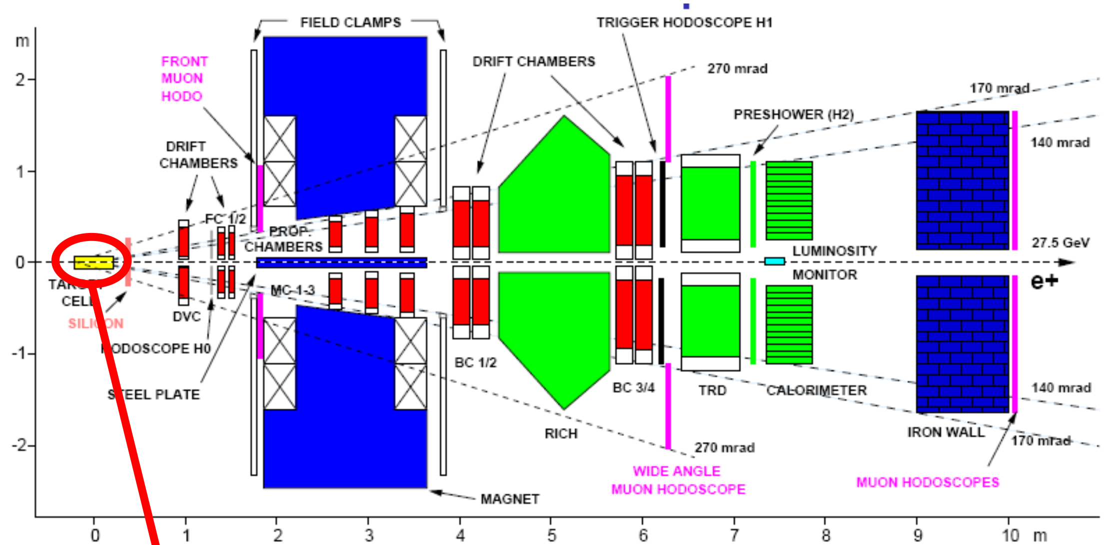
• **significant Collins amplitudes observed for charged pions and K^+**
→ preliminary results enabled first extraction of transversity and Collins FF (by Torino group)

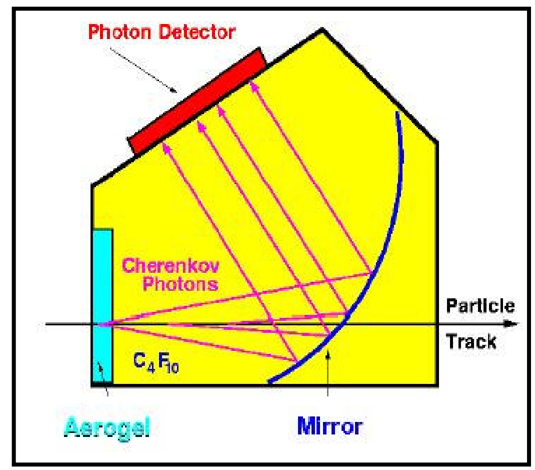
• **significant Sivers amplitudes observed for π^+ and K^+**
→ clear evidence of non-zero T-odd Sivers function
→ (indirect) evidence for non-zero quark orbital angular momentum
→ hint of non-trivial role of sea quarks and of higher-twist contrib. for positive kaons

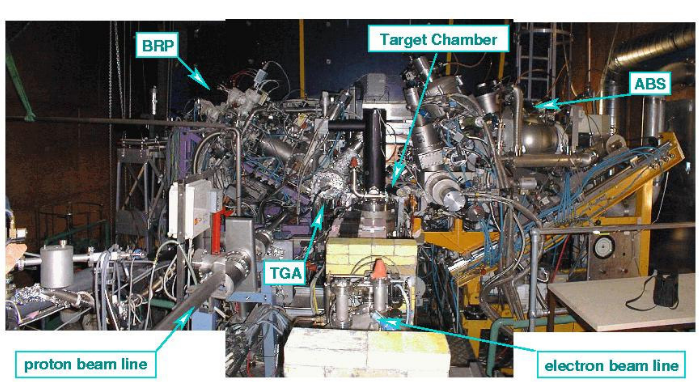
• **additional Fourier components recently extracted**
→ no evidence of non-zero pretzelosity (though amplitude kinematically suppressed)
→ first glimpse on worm-gears $h_{1L}^{\perp}$ and $g_{1T}^{\perp}$ related observables
→ significant non-zero $\langle \sin(\phi_S) \rangle_{UT}^{h}$ amplitude for negatively charged mesons

Back-up slides

The HERMES experiment at HERA

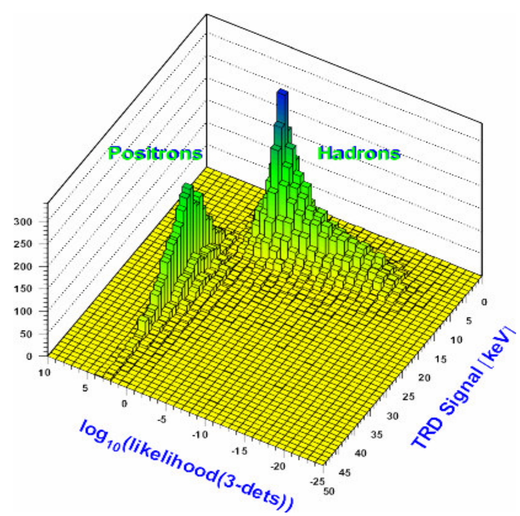




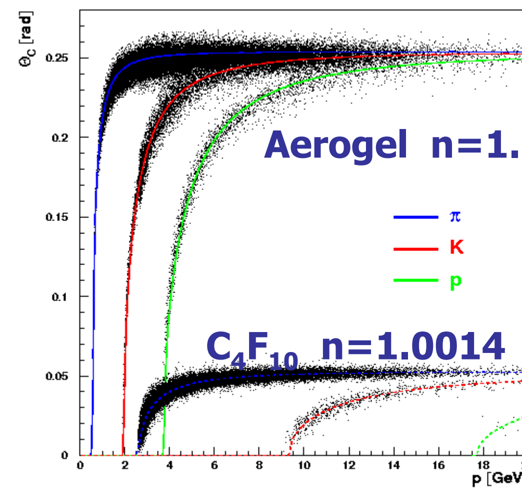


TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%



hadron separation



π ~ 98%, K ~ 88% , P ~ 85%

The Boer-Mulders effect

analysis based on a **multidimensional unfolding** of data to correct for acceptance, detector smearing and higher order QED effects

$$n_{BORN} = S^{-1}\left[n_{EXP} - n_{Bg}\right]$$

S^{-1}: Probability that an event generated with kinematics w is measured with kinematics w'

n_{Bg}: Includes the events smeared into the acceptance

▢ = Kinematic range of integration

BINNING

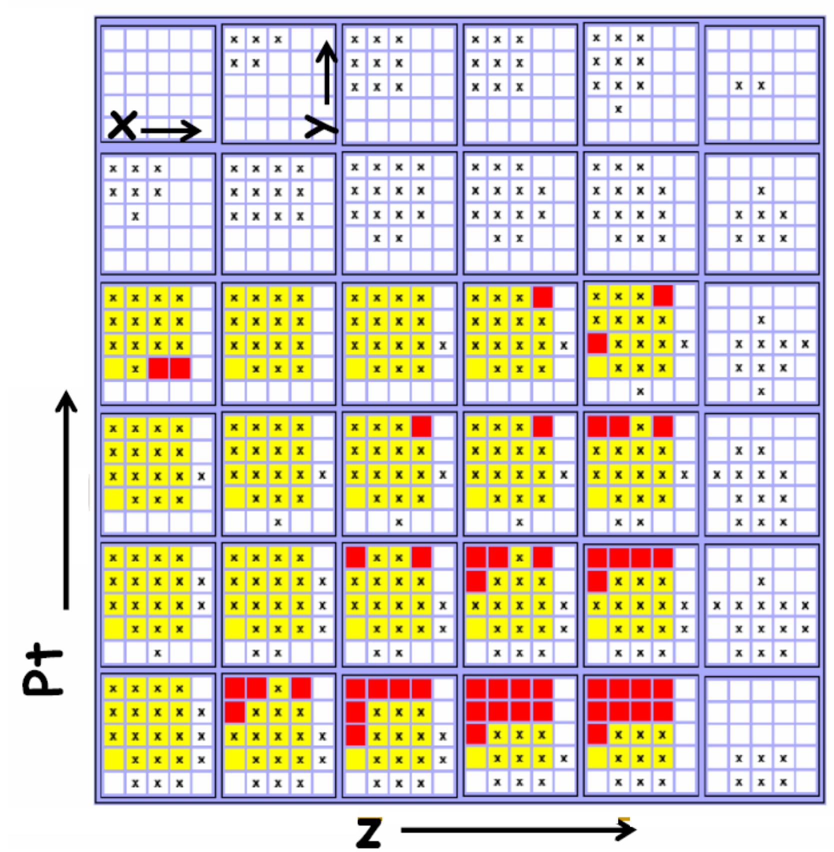
900 kinematical bins x 12 ϕ_η-bins

Variable	Bin limits							#
x	0.023	0.042	0.078	0.145	0.27	0.6		5
y	0.2	0.3	0.45	0.6	0.7	0.85		5
z	0.2	0.3	0.4	0.5	0.6	0.75	1	6
Pt	0.05	0.2	0.35	0.5	0.7	1	1.3	6

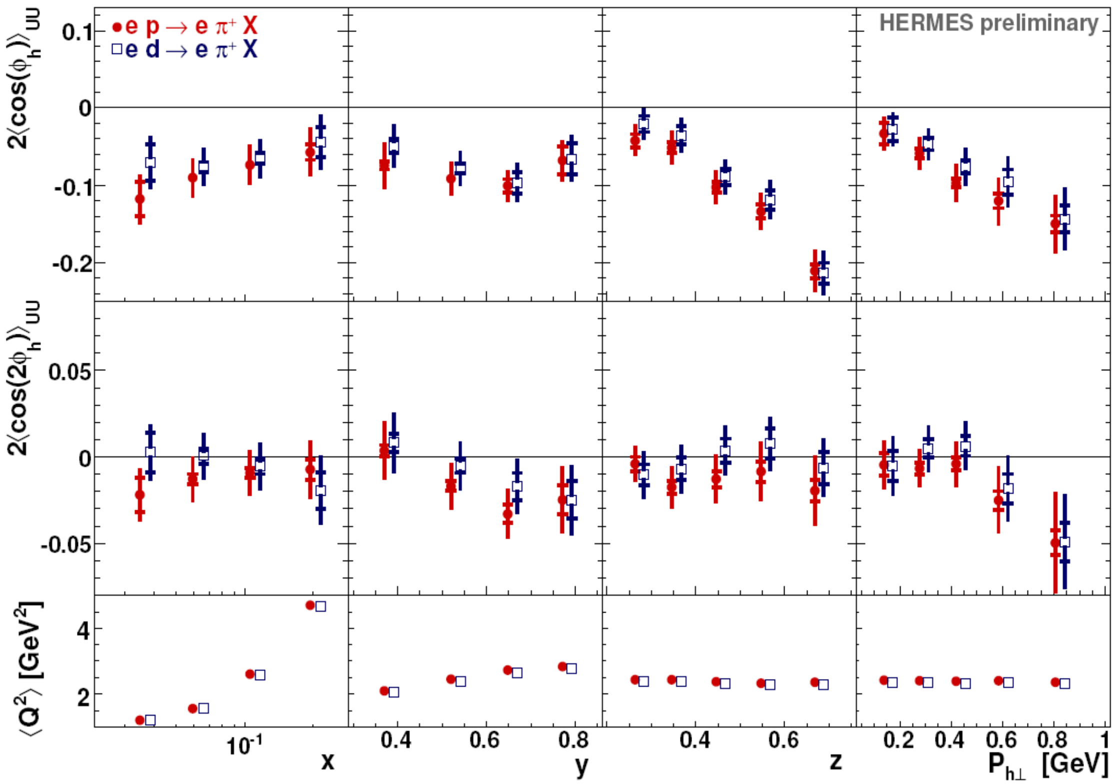
▢ = signal not expected and not observed

▢x = signal expected and observed

▢ = signal expected but not observed

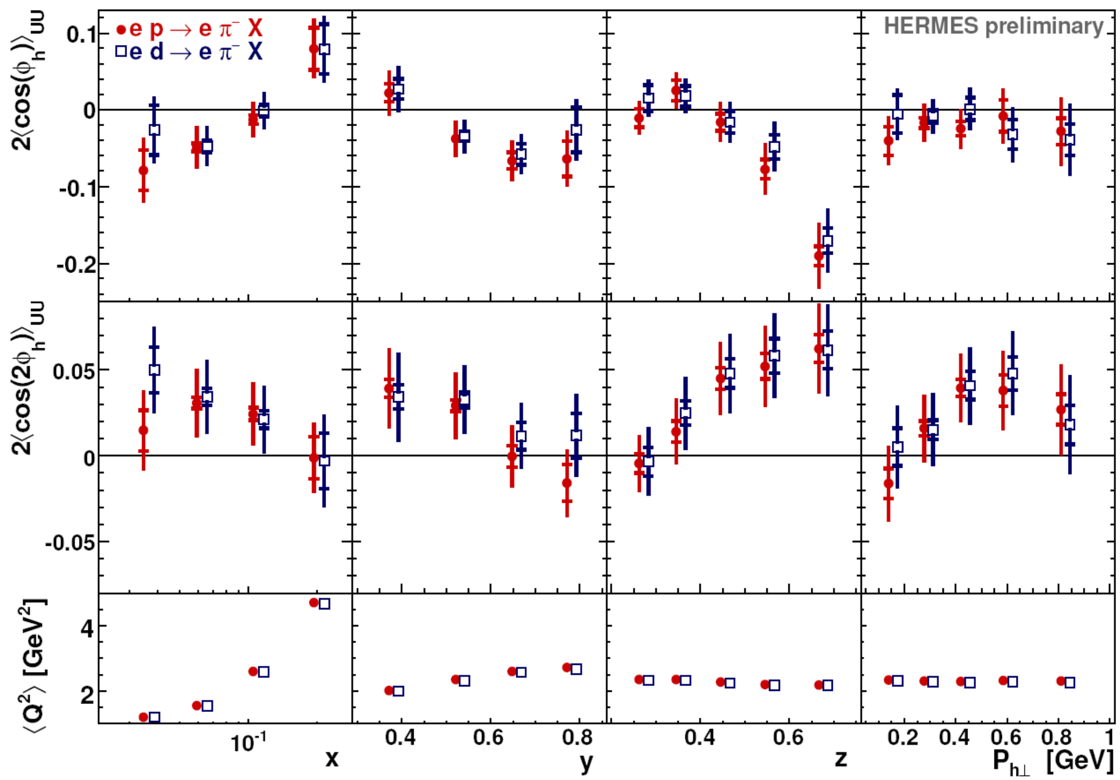


The Boer-Mulders effect for π^+: H vs D target



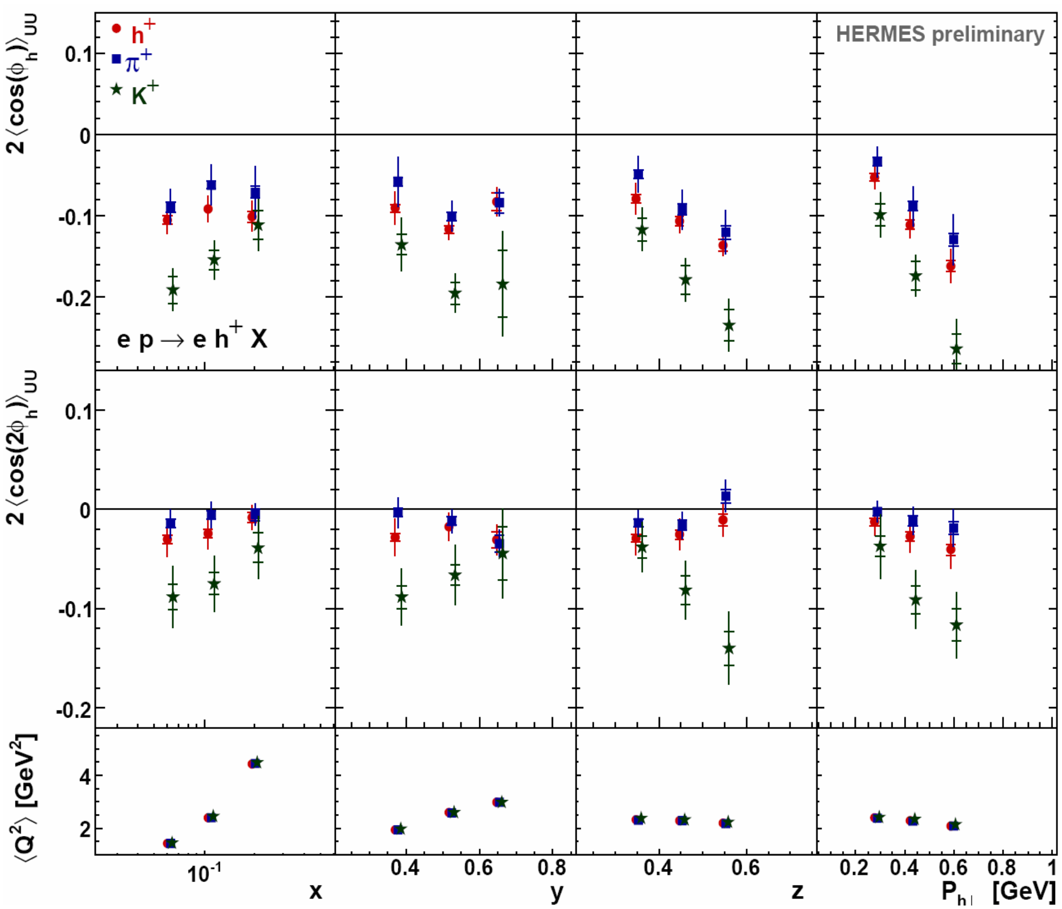
- Hydrogen vs. Deuteron target data
- The two samples are compatible

The Boer-Mulders effect for π⁻: H vs. D target



- Hydrogen vs. Deuteron target data
- The two samples are compatible

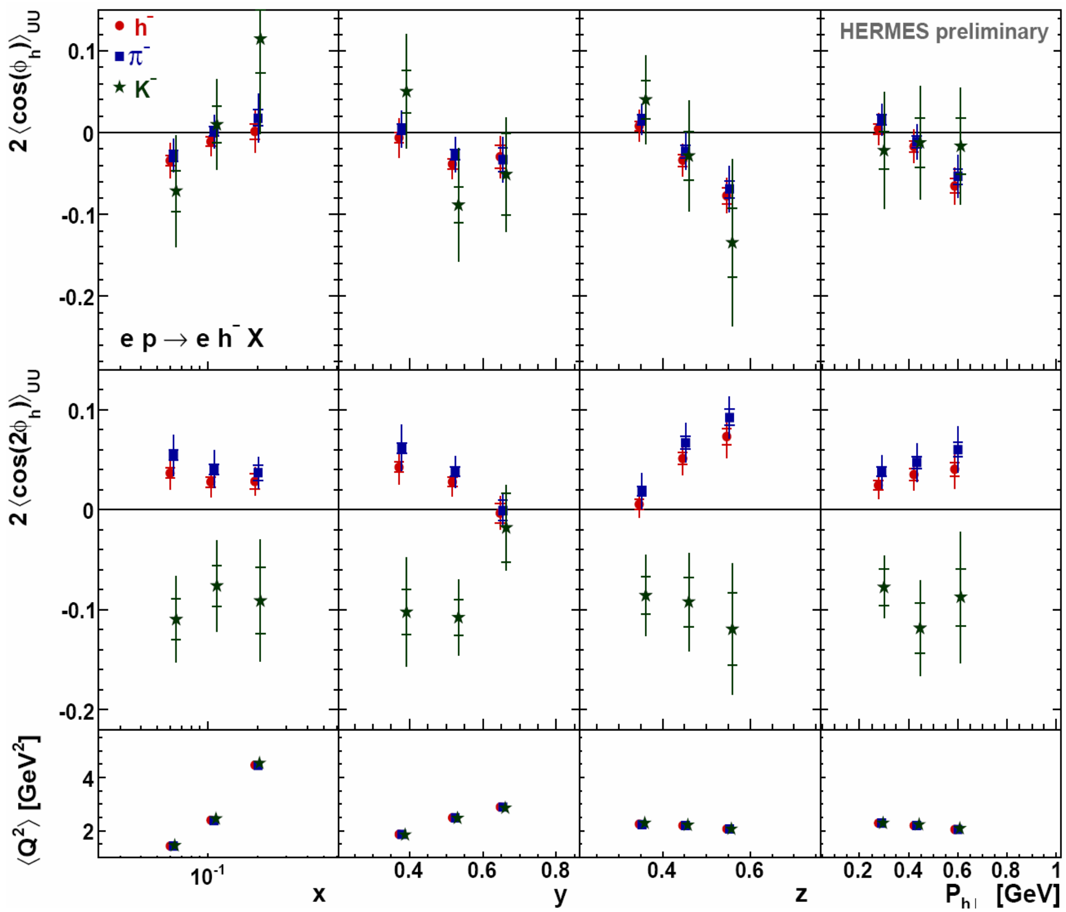
The Boer-Mulders effect (Hydrogen target)



- K^+ $\cos(\phi)$ and $\cos(2\phi)$ amplitudes larger than π^+

Similar results for D target

The Boer-Mulders effect (Hydrogen target)



- cos(ϕ) amplitudes compatible for π^- and K^-
- cos(2ϕ) amplitudes of opposite sign for π^- and K^-

Similar results for D target

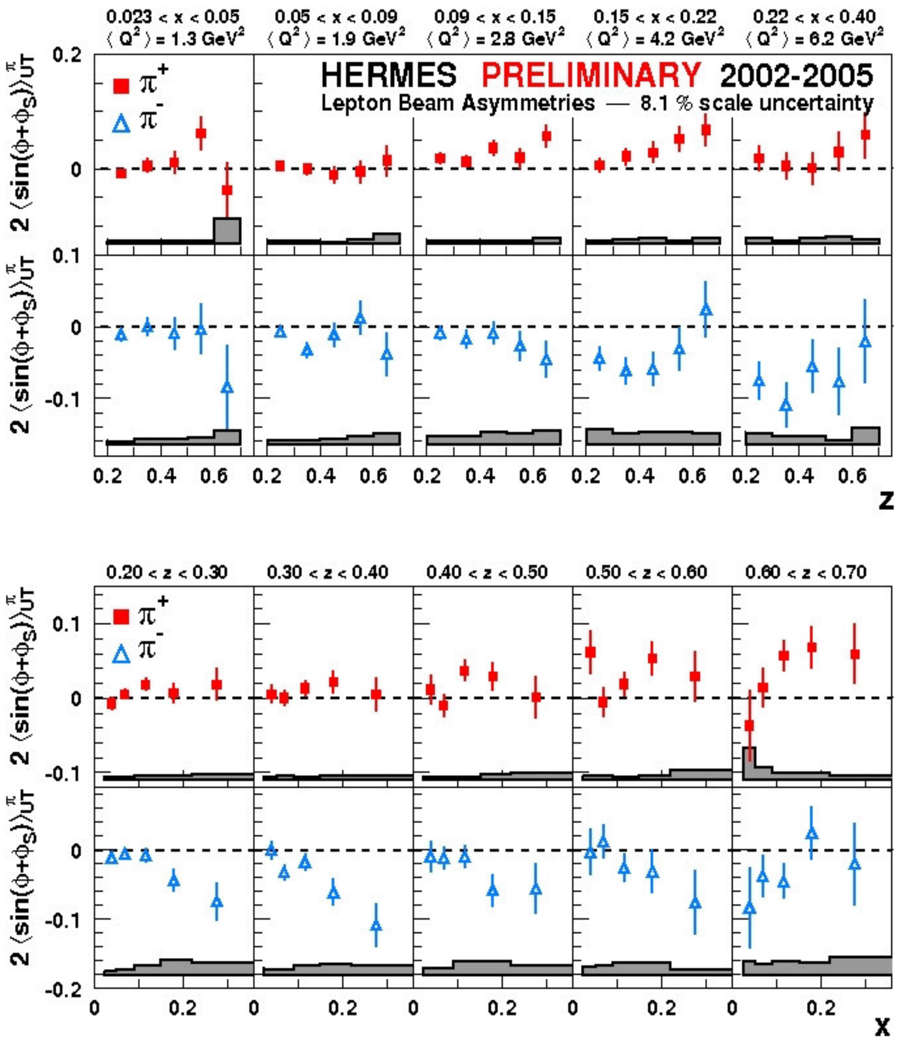
Standard cuts
$Q^2 > 1\,\mathrm{GeV}^2$
$W^2 > 10\,\mathrm{GeV}^2$
$0.023 < x < 0.4$
$y < 0.95$
$0.2 < z < 0.7$
$2\,\mathrm{GeV} < P_h < 15\,\mathrm{GeV}$

2-D Collins pions amplitudes

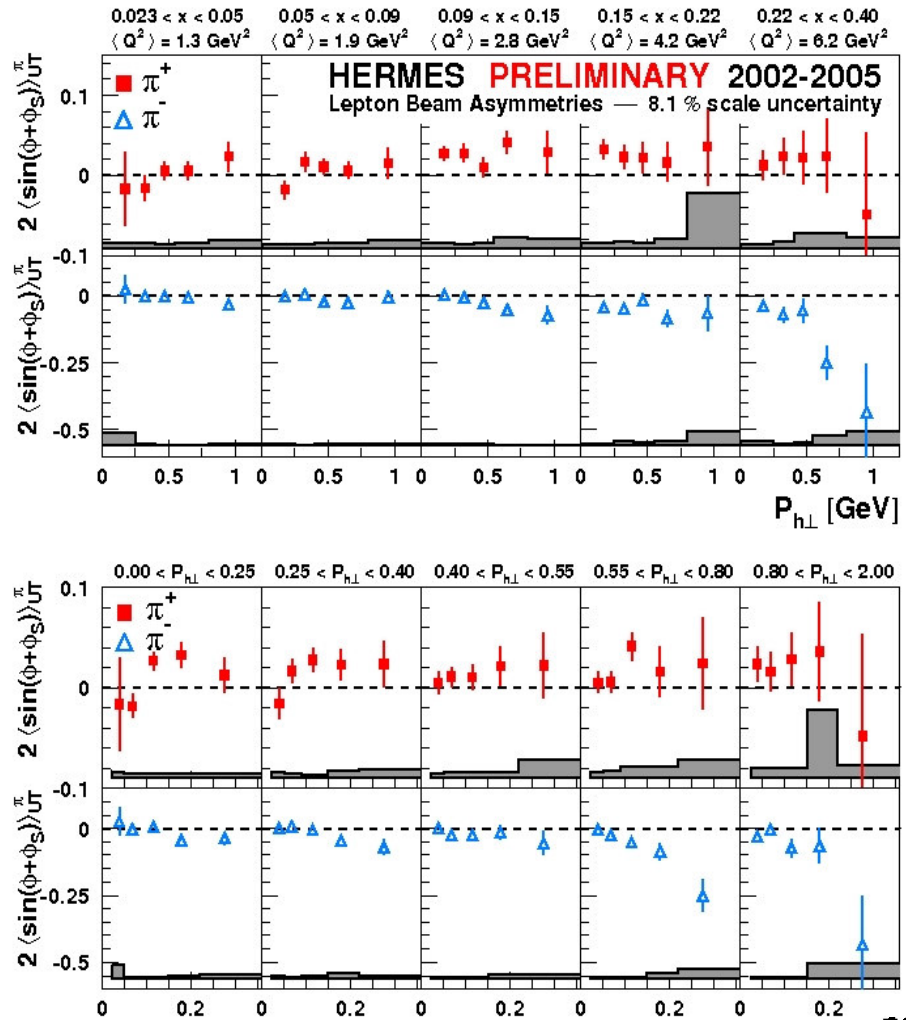
Kinematic dependencies often don't factorize → correlations among variables

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

X vs. Z



X vs. $P_{h\perp}$

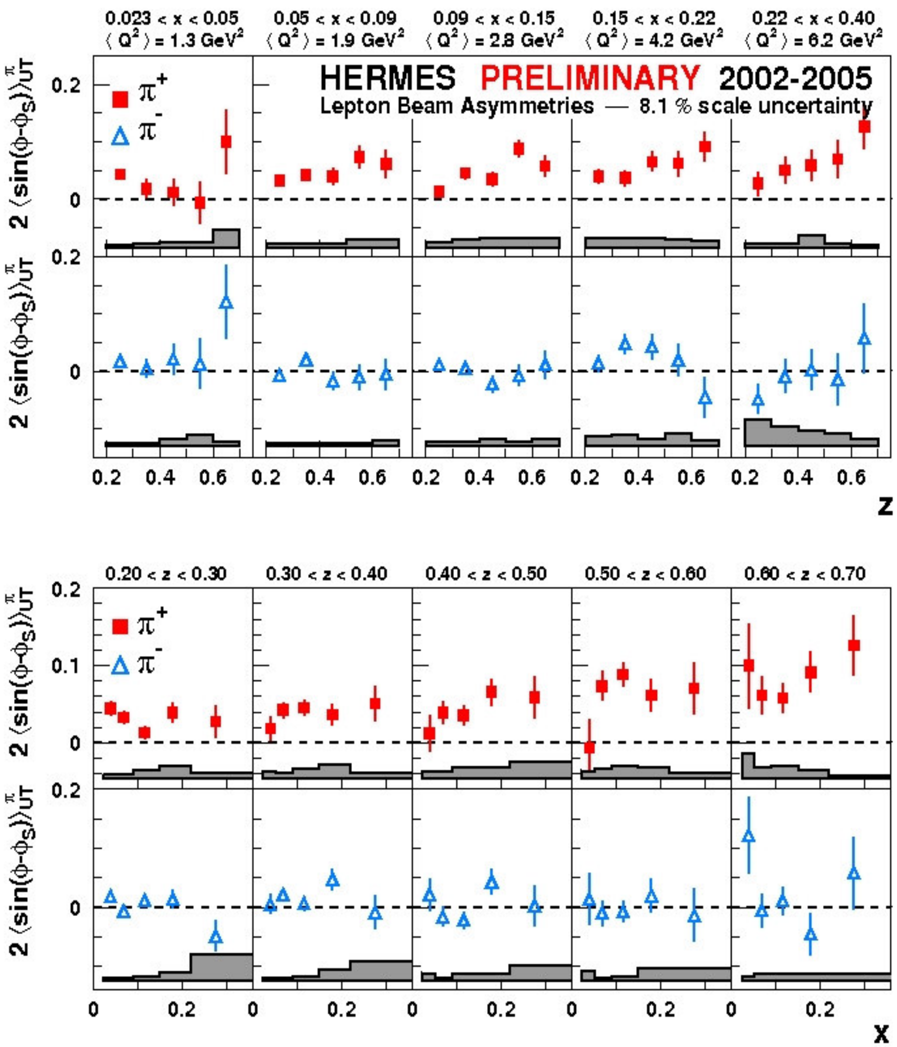


2-D Sivers pions amplitudes

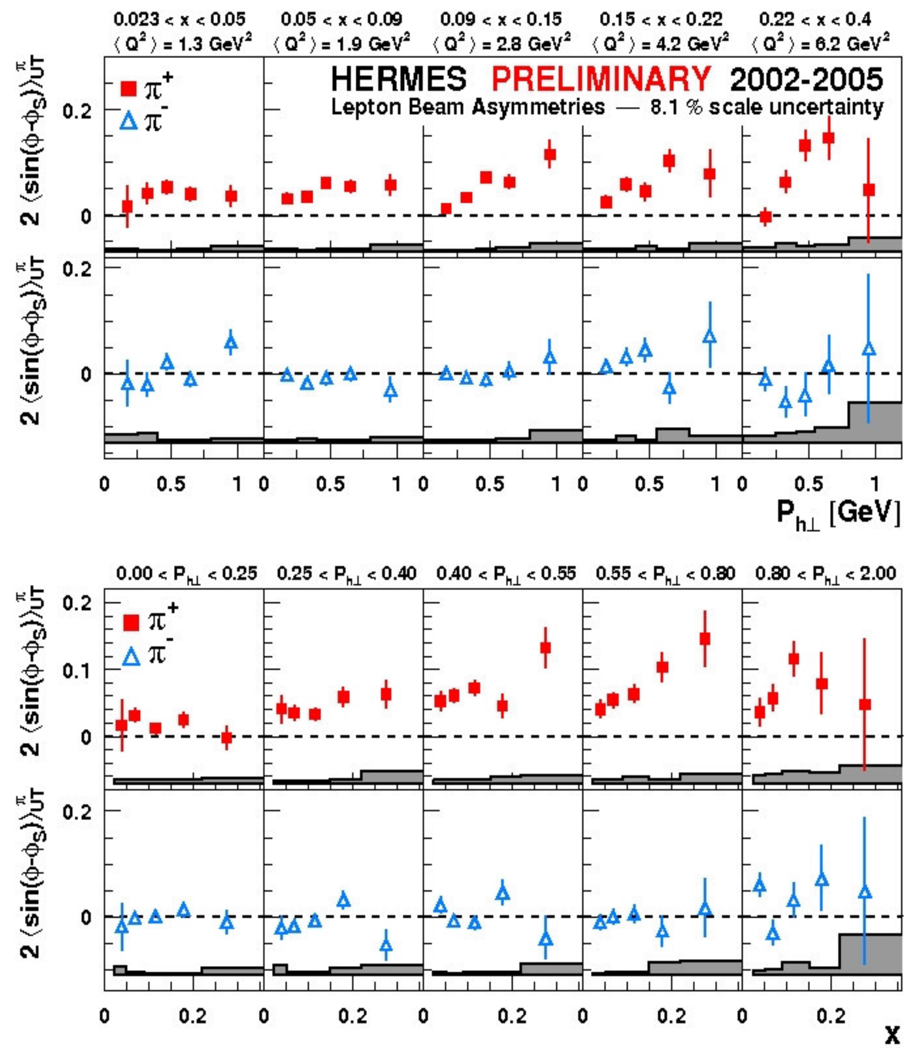
Kinematic dependencies often don't factorize → correlations among variables

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

X vs. Z

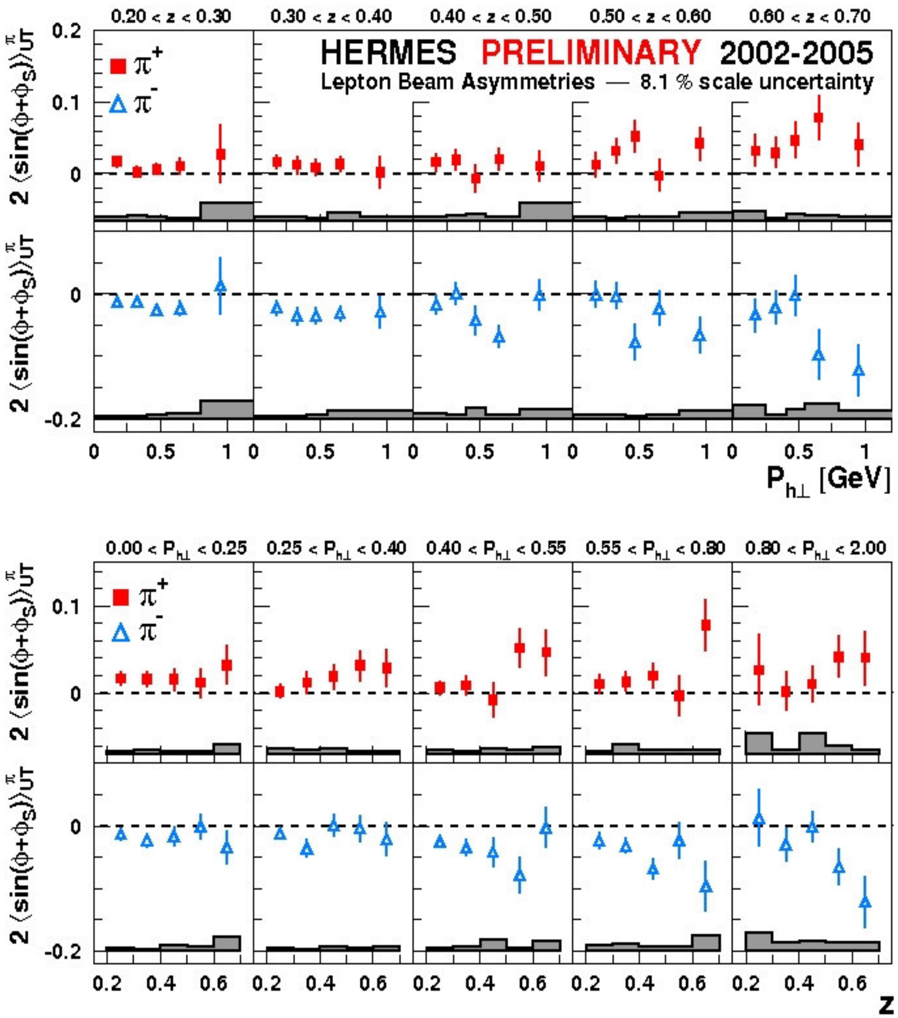


X vs. $P_{h\perp}$

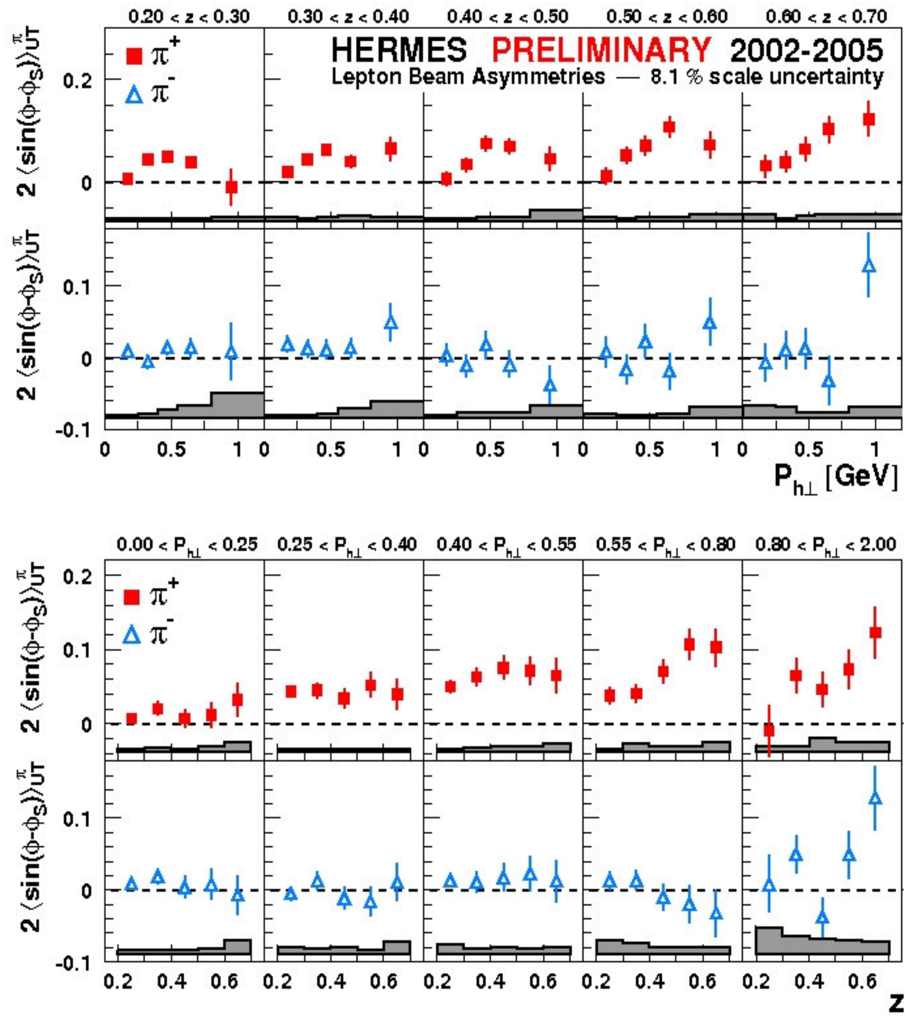


2-D moments for $\pi^{\pm}$: z vs. $P_{h\perp}$

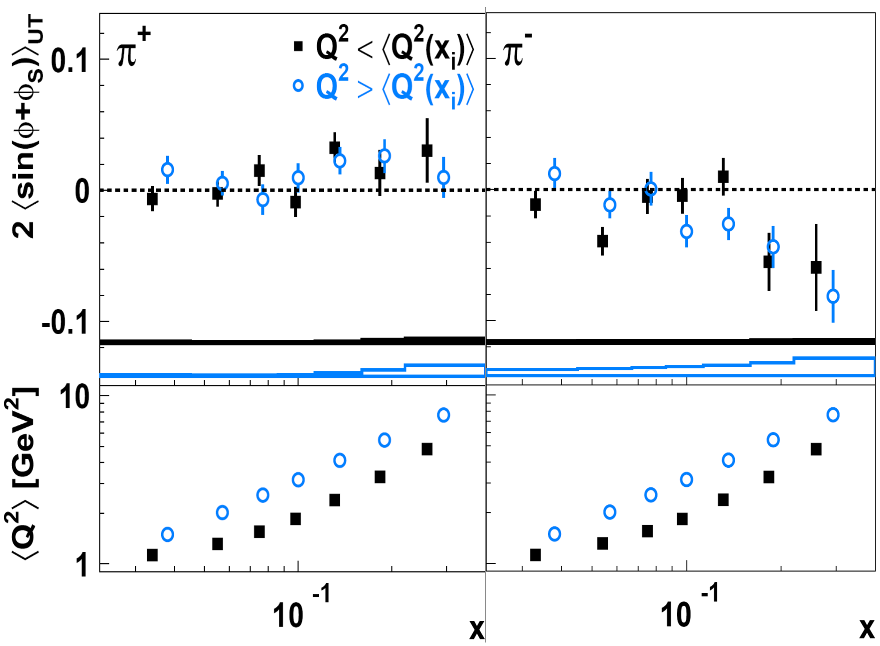
Collins: Z vs. $P_{h\perp}$



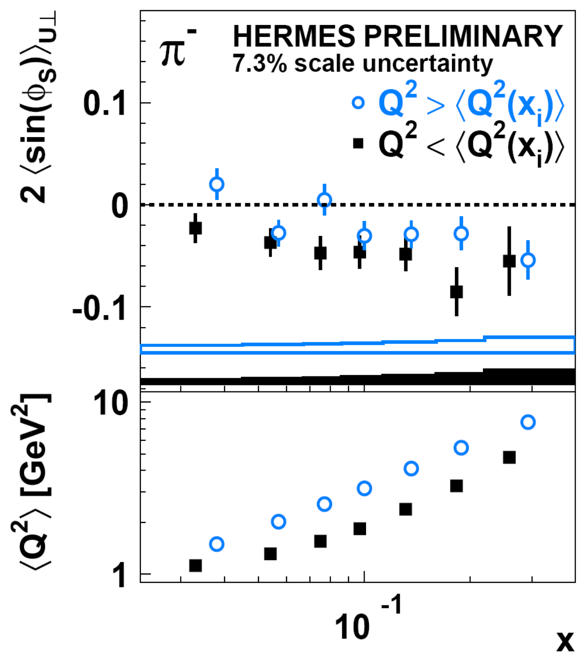
Sivers: Z vs. Ph⊥



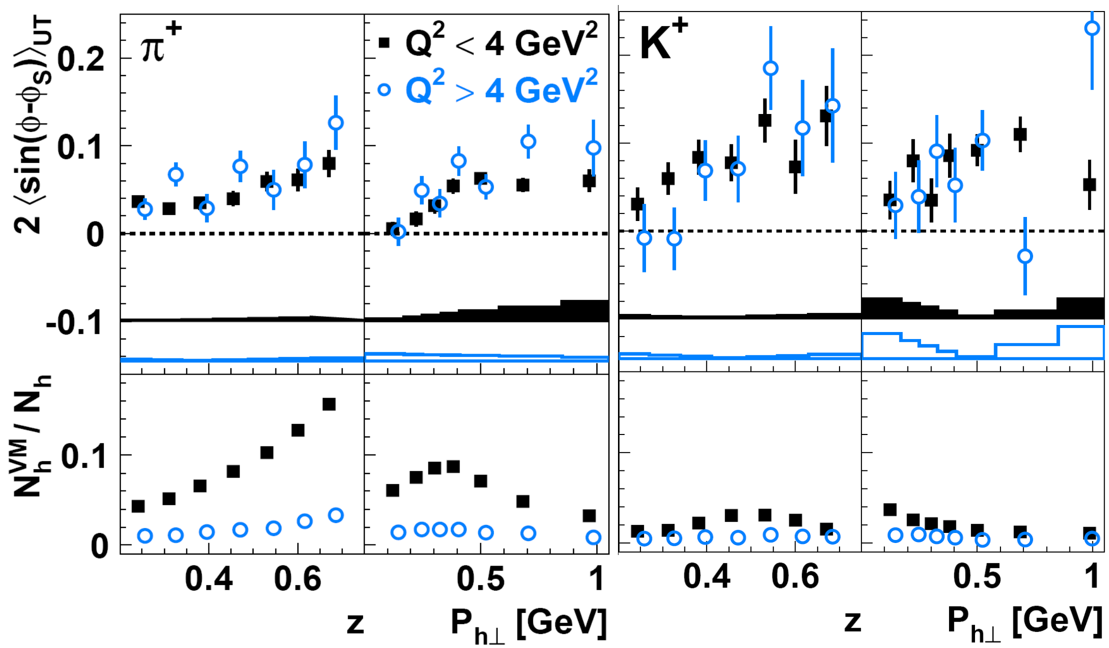
Collins amplitudes:
twist-4 contrib ?



sin(ϕ_S):
Q^2 dependence for π^-

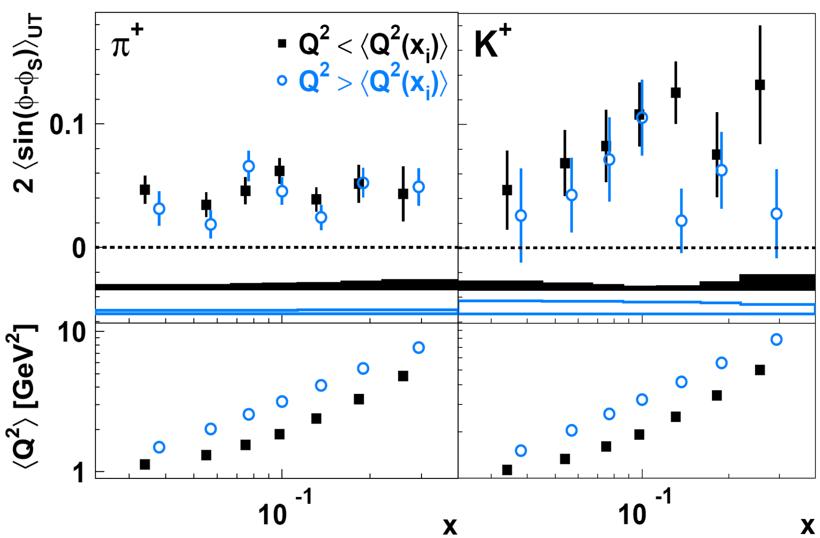


Siver amplitudes: additional studies



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

  No indication of important contributions from exclusive VM



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

  separate each x-bin in two Q^2 bins

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

The extraction of the Distribution Functions

$$\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{h} = \frac{\int d\phi_S d^2\vec{P}_{h\perp} \sin(\phi+\phi_S)\; d\sigma_{UT}}{\int d\phi_S d^2\vec{P}_{h\perp} d\sigma_{UU}} \propto \mathbf{I}\left[\frac{\vec{k}_T\cdot\hat{P}_{h\perp}}{M_h} h_1(x,p_T^2) H_1^{\perp q}(z,k_T^2)\right]$$

Convolution integral on transverse momenta p_T and k_T

$$\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{h} = \frac{\int d\phi_S d^2\vec{P}_{h\perp} \sin(\phi-\phi_S)\; d\sigma_{UT}}{\int d\phi_S d^2\vec{P}_{h\perp} d\sigma_{UU}} \propto \mathbf{I}\left[\frac{\vec{p}_T\cdot\hat{P}_{h\perp}}{M} f_{1T}^{\perp q}(x,p_T^2) D_1^q(z,k_T^2)\right]$$

Experiment: only partial coverage of the full $P_{h\perp}$ range (acceptance effects)

Theory: difficult to solve ⟹ Gaussian ansatz

$$h_1(x,p_T^2) \approx \frac{h_1(x)}{\pi\left\langle p_T^2(x)\right\rangle} e^{-\frac{p_T^2}{\left\langle p_T^2(x)\right\rangle}} \qquad H_1^{\perp q}(z,k_T^2) \approx \frac{H_1^{\perp q}(z)}{\pi\left\langle k_T^2(z)\right\rangle} e^{-\frac{k_T^2}{\left\langle k_T^2(z)\right\rangle}}$$

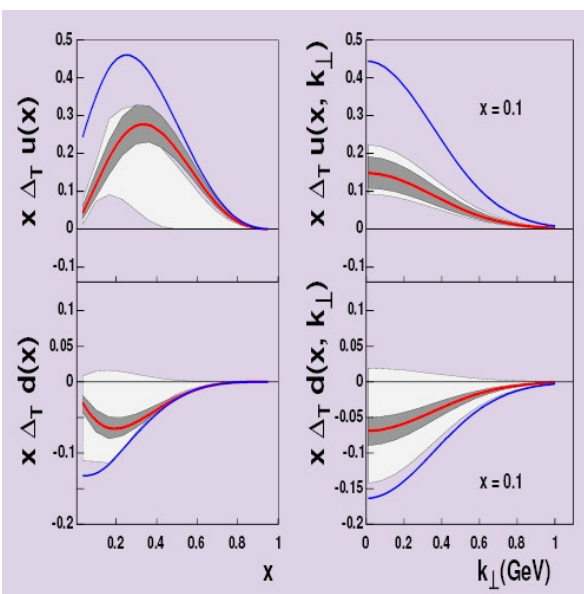
(extraction assumption-dependent)

Extraction of transversity and Sivers function form global analyses

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

$lp \to l'hX$ $\quad ld \to l'hX$ $\quad e^+e^- \to h_1 h_2 X$

First extraction of Transversity!



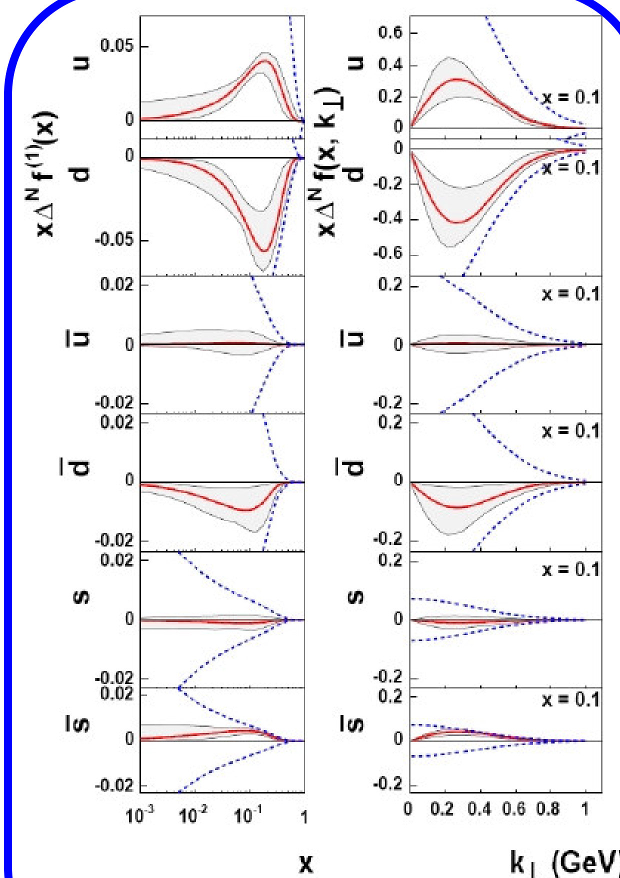
Anselmino et al. Phys. Rev. D 75 (2007)

$$A_{UT}^{\sin(\phi-\phi_S)} \propto f_{1,T}^{\perp}(x) \otimes D_1^q(z)$$

Known

$lp \to l'hX$

$ld \to l'hX$



Anselmino et al. Eur.Phys.J.A39 (2009)