Studies of TMDs at HERMES

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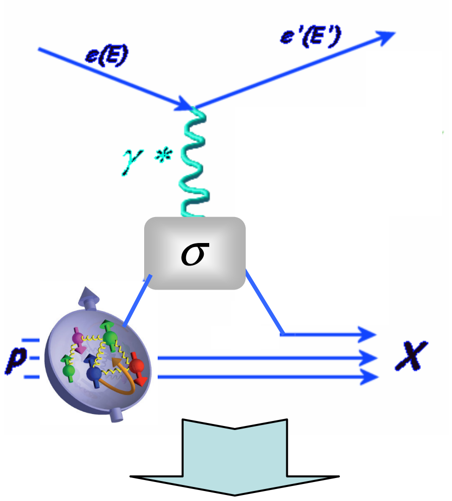
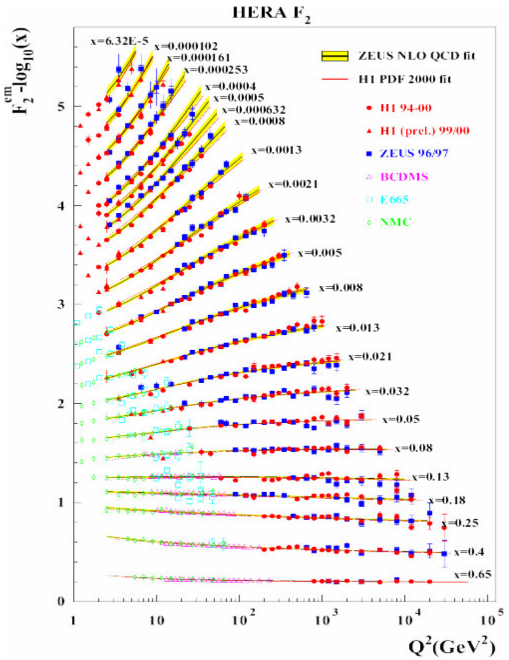
(for the HERMES Collaboration)

JLAB, Newport News, Virginia USA , May 18-21 2010

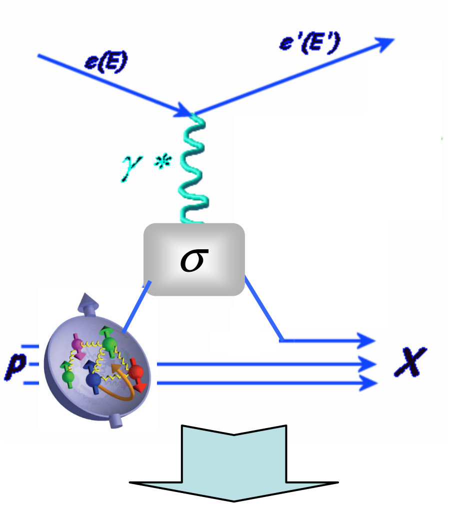
Quantum phase-space tomography of the nucleon

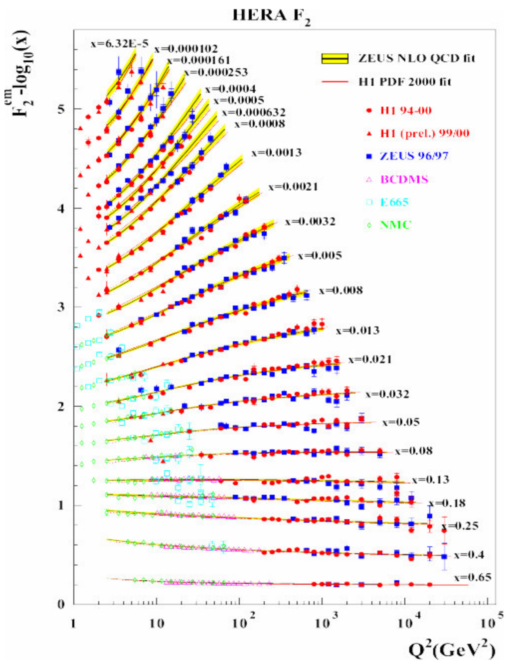




Longitudinal momentum structure of the nucleon

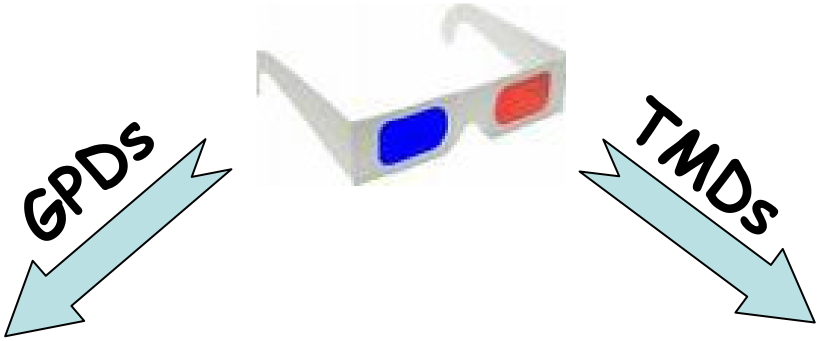
Quantum phase-space tomography of the nucleon

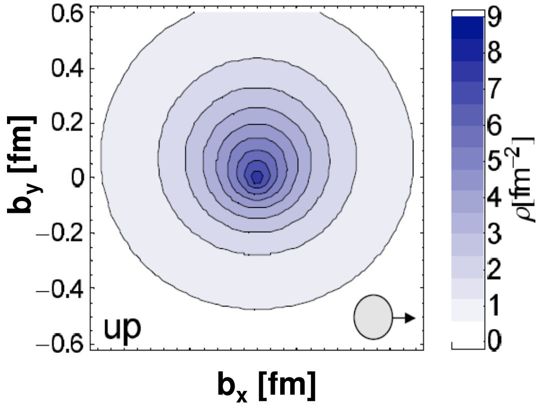




Longitudinal momentum structure of the nucleon

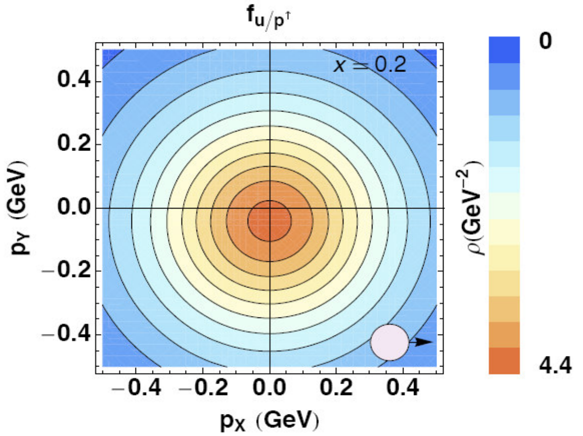
Join the real 3D experience!!





QCDSF/UKQCD, PRL 98 (07)

3D picture in coordinate space



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

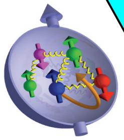
3D picture in momentum space

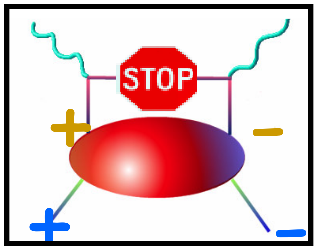
The nucleon spin structure at leading twist

momentum

helicity

transversity

		quark		
		U	L	T
nucleon	U	f_1 ○		
	L		g_1 ⊙⊙ - ⊙⊗	
	T			h_1 −○→ − −○→ − −←○→



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

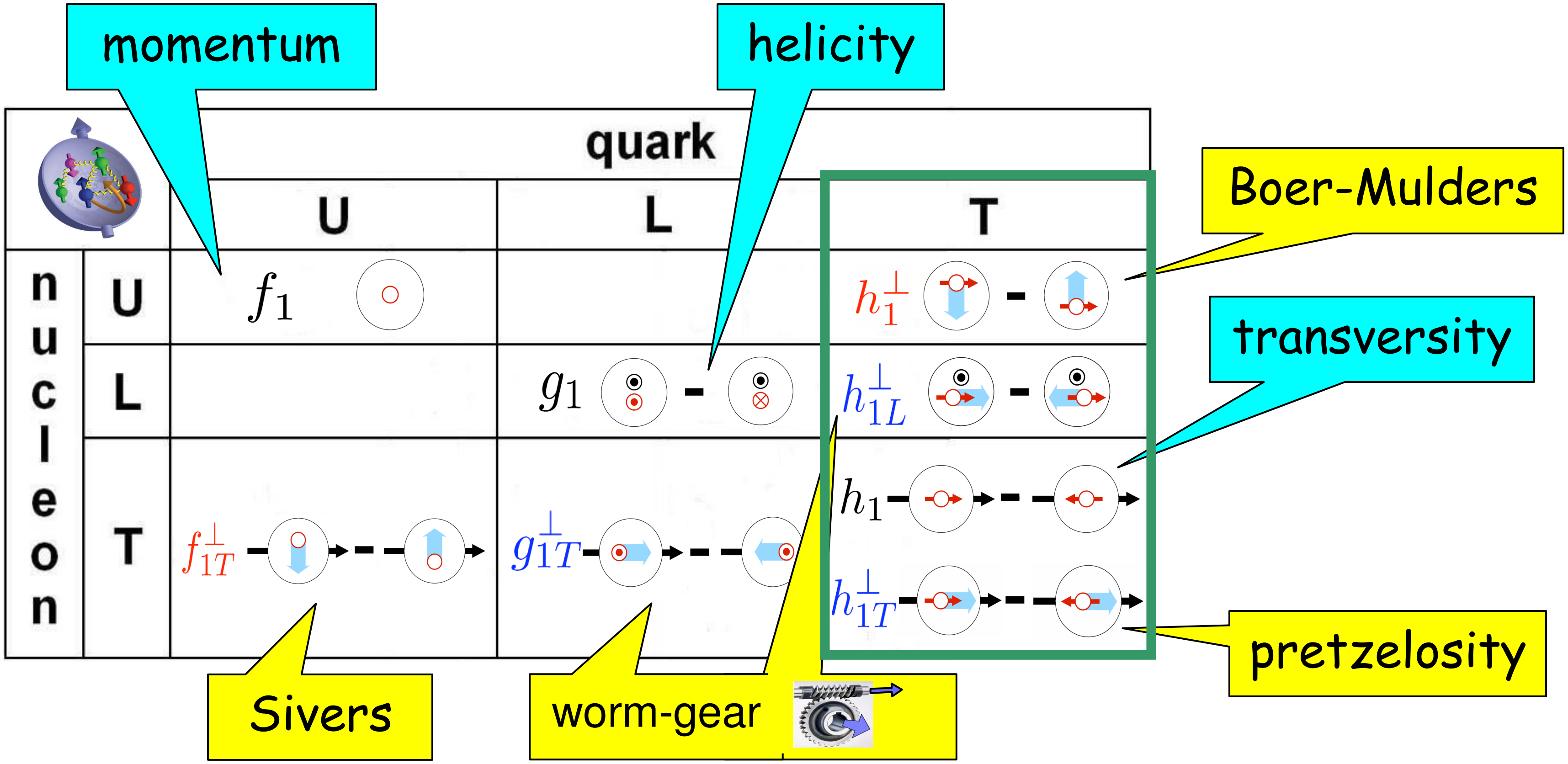
Proton comes out of the screen photon goes into the screen

−○→ ⊙ nucleon with transverse or longitudinal spin

−○→ ⊙ parton with transverse or longitudinal spin

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

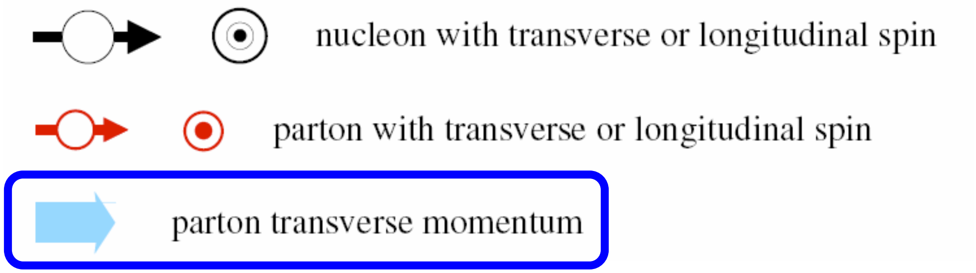
The nucleon spin structure at leading twist



		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 $h_{1T}^\perp$

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

Proton comes out of the screen photon goes into the screen



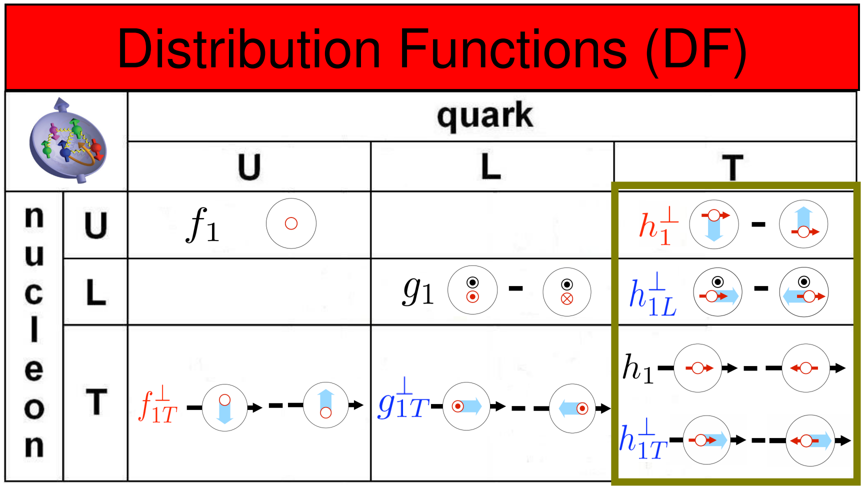
nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

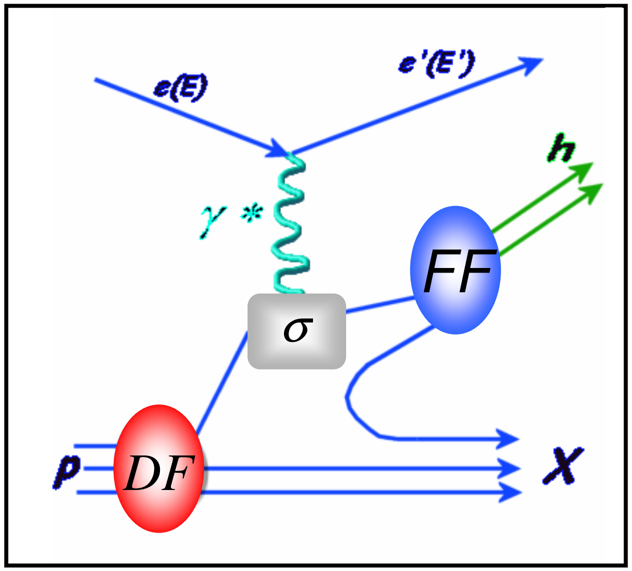
- **functions in black survive integration over transverse momentum**
- functions in red are naive T-odd
- functions in green box are chirally odd

TMDs can be studied by measuring azimuthal asymmetries in SIDIS



Distribution Functions (DF)

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

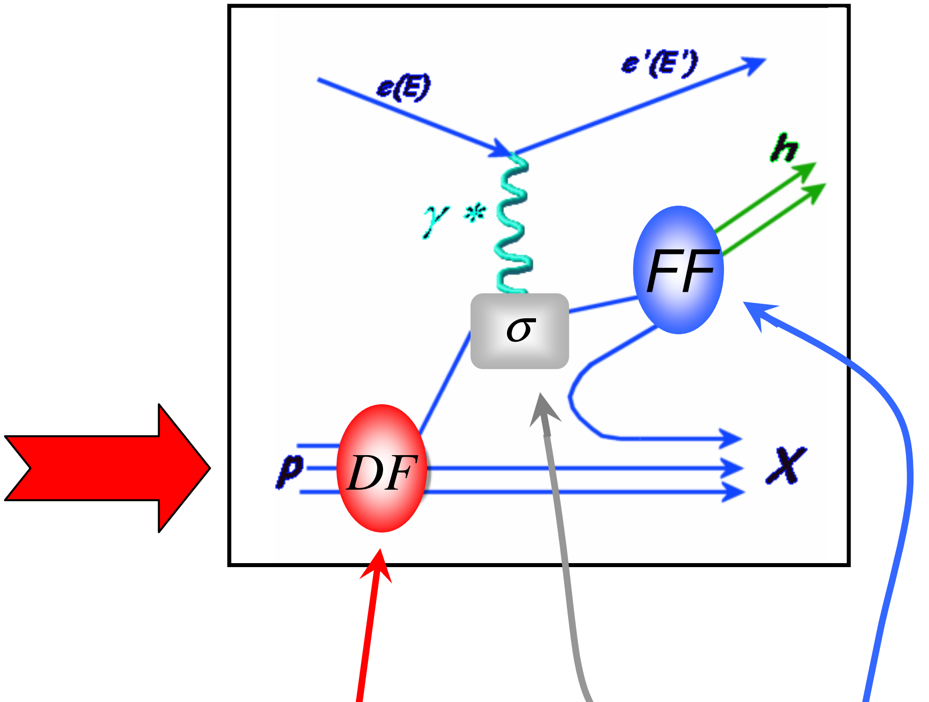


functions in green box are chirally odd

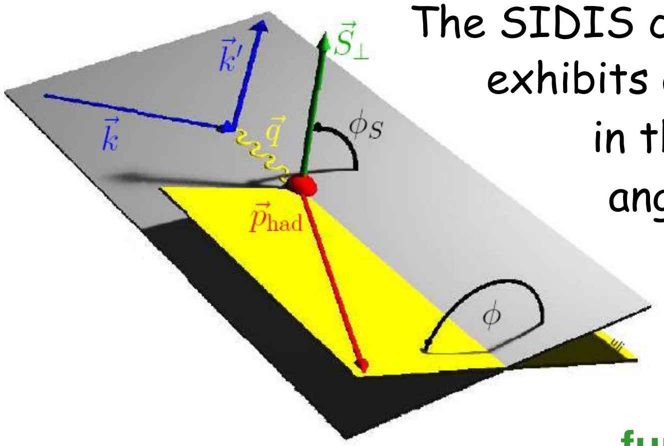
TMDs can be studied by measuring azimuthal asymmetries in SIDIS

Distribution Functions (DF)

		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 $h_{1T}^\perp$



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



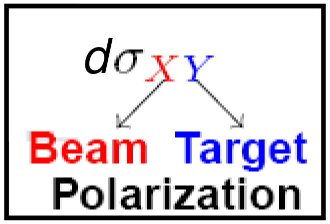
The SIDIS cross section exhibits asymmetries in the azimuthal angles ϕ and ϕ_S

Fragmentation Functions (FF)

		quark		
		U	**L**	**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

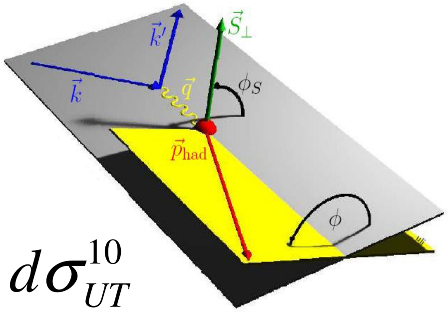


$d\sigma_{XY}$

Beam **Target**

Polarization

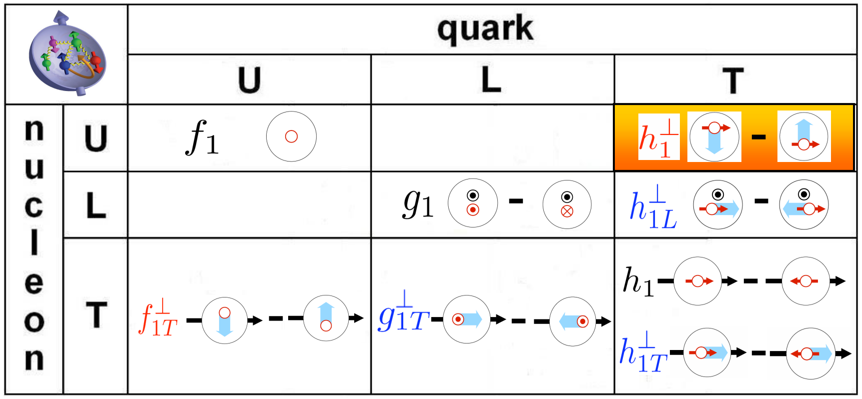
$$
\begin{aligned}
d\sigma = {} & d\sigma_{UU}^{0} + \cos 2\phi \, d\sigma_{UU}^{1} + \frac{1}{Q}\cos\phi \, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma_{LU}^{3} \\
& + S_L \left\{ \sin 2\phi \, d\sigma_{UL}^{4} + \frac{1}{Q}\sin\phi \, d\sigma_{UL}^{5} + \lambda_e \left[d\sigma_{LL}^{6} + \frac{1}{Q}\cos\phi \, d\sigma_{LL}^{7} \right] \right\} \\
& + S_T \Big\{ \sin(\phi-\phi_S) \; d\sigma_{UT}^{8} + \sin(\phi+\phi_S) \; d\sigma_{UT}^{9} + \sin(3\phi-\phi_S) \; d\sigma_{UT}^{10} \\
& \quad + \frac{1}{Q}\sin(2\phi-\phi_S) \; d\sigma_{UT}^{11} + \frac{1}{Q}\sin\phi_S d\sigma_{UT}^{12} \\
& \quad + \lambda_e \left[\cos(\phi \, - \phi_S) \; d\sigma_{LT}^{13} + \frac{1}{Q}\cos\phi_S d\sigma_{LT}^{14} + \frac{1}{Q}\cos(2\phi \, - \phi_S) d\sigma_{LT}^{15} \right] \Big\}
\end{aligned}
$$



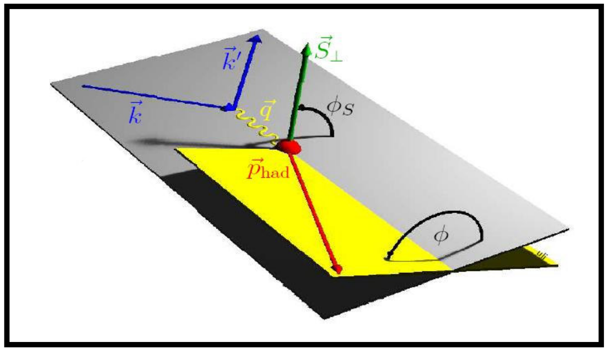
How can we disentangle all these contributions ?

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 amplitudes 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 $h_{1T}^\perp$



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

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

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

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

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

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

The Boer-Mulders effect

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

Boer-Mulders effect

Cahn effect

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

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

The Boer-Mulders effect

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

Boer-Mulders effect

Cahn effect

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

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

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

BINNING
900 kinematical bins x 12 ϕ_η-bins

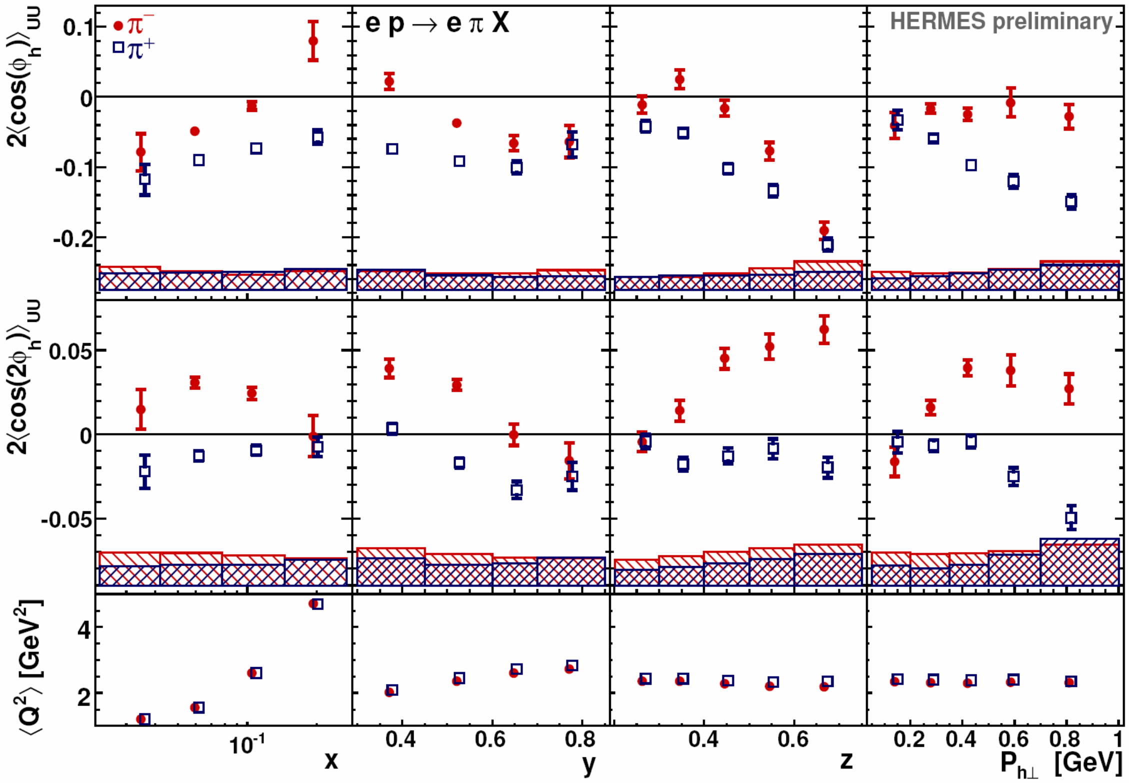
Variable	Bin limits							#
x	0.023	0.042	0.078	0.145	0.27	0.6		5
y	0.2	0.3	0.45	0.6	0.7	0.85		5
z	0.2	0.3	0.4	0.5	0.6	0.75	1	6
Pt	0.05	0.2	0.35	0.5	0.7	1	1.3	6

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

Probability that an event generated with kinematics w is measured with kinematics w'

Includes the events smeared into the acceptance

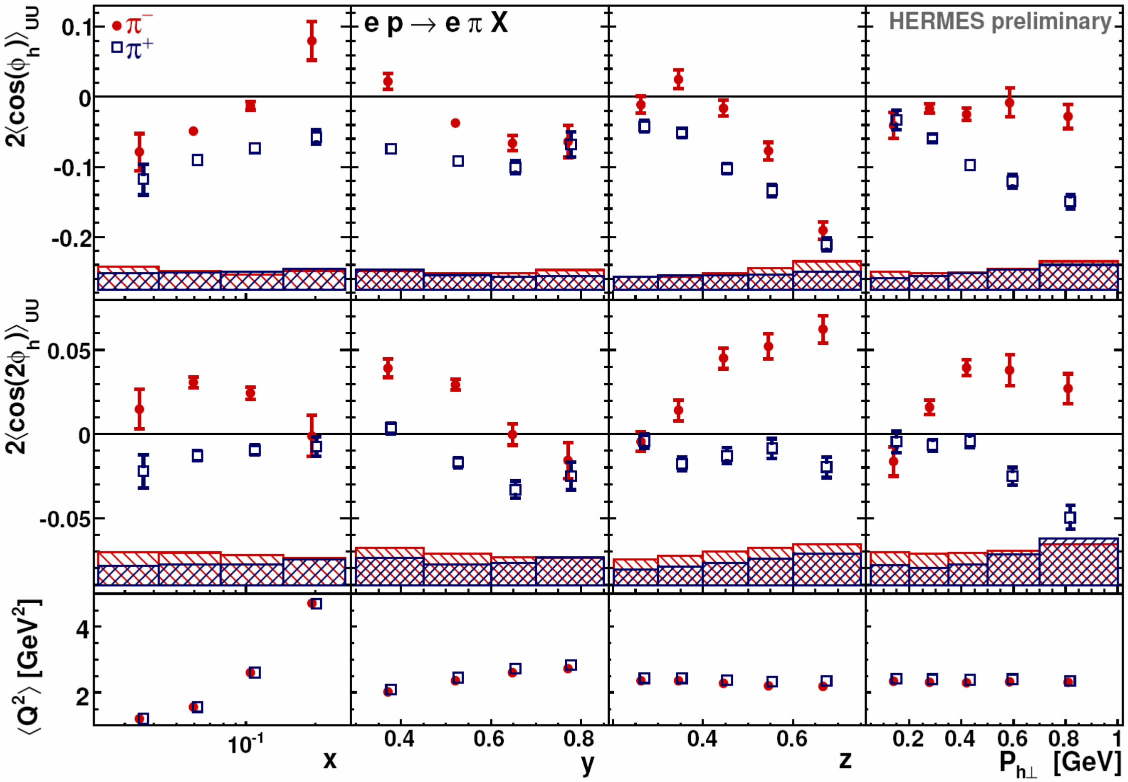
The Boer-Mulders effect (Hydrogen target)



- $\langle\cos(\phi)\rangle_{UU} \propto \mathrm{I}[-h_1^{\perp}H_1^{\perp} - f_1 D_1]$
- **negative cos(φ) amplitudes for both π⁺ and π⁻**
- $\langle\cos(w\phi)\rangle_{UU} \propto \mathrm{I}[-h_1^{\perp}H_1^{\perp}]$
- **cos(2φ) ampl. positive for π⁻ and slightly negative for π⁺**

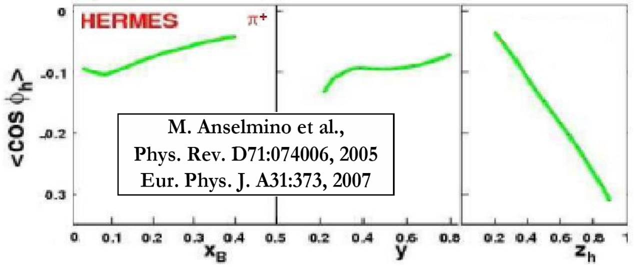
Similar results for D target

The Boer-Mulders effect (Hydrogen target)

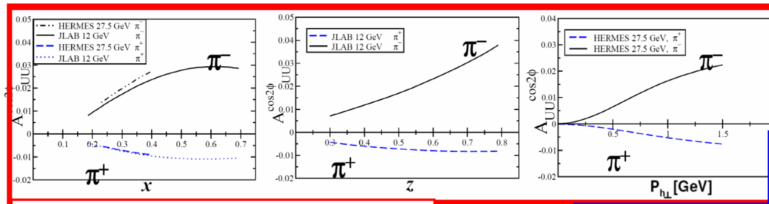


- $\langle\cos(\phi)\rangle_{UU} \propto \mathrm{I}[-h_1^\perp H_1^\perp - f_1 D_1]$
- **negative cos(ϕ) amplitudes for both π^+ and π^-**
- $\langle\cos(w\phi)\rangle_{UU} \propto \mathrm{I}[-h_1^\perp H_1^\perp]$
- **cos(2ϕ) ampl. positive for π^- and slightly negative for π^+**

Similar results for D target

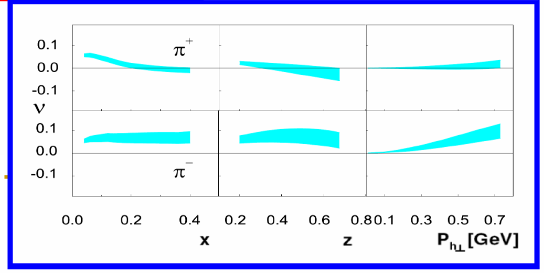


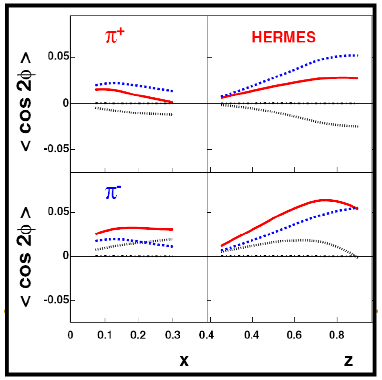
M. Anselmino et al.,
Phys. Rev. D71:074006, 2005
Eur. Phys. J. A31:373, 2007



L. P. Gamberg and G. R. Goldstein,
Phys. Rev. D77:094016, 2008

B. Zhang et al.,
Phys. Rev. D78:034035, 2008





V. Barone et al.
Phys.Rev. D78:045022, 2008

All contributions
Boer-Mulders
Cahn (twist 4)

Accessing the polarized cross section through SSAs

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

The Fourier amplitudes of the yields for opposite transverse target spin states were extracted through a ML fit alternately binned in x, z, and $P_{h\perp}$ but unbinned in ϕ and ϕ_S:

$$\boxed{PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \tfrac{1}{2}\{1 + P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\ \sin(\phi\pm\phi_s) + \ldots)\}}$$

This is equivalent to perform a Fourier decomposition of the cross section asymmetry:

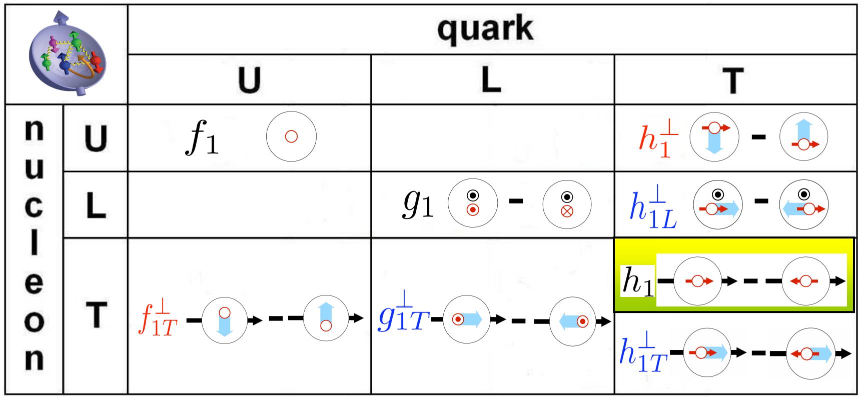
$$A_{UT}^{h}(\phi,\phi_S) = \frac{1}{|P_T|}\frac{d\sigma^h(\phi,\phi_S) - d\sigma^h(\phi,\phi_S+\pi)}{d\sigma^h(\phi,\phi_S) + d\sigma^h(\phi,\phi_S+\pi)}$$

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

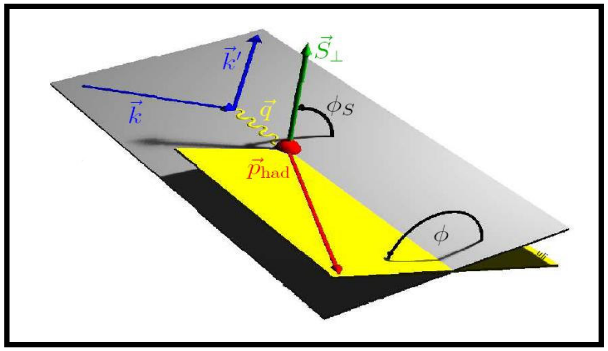
$$+ \quad \sin(\phi-\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{p_T}\cdot\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M} f_{1T}^{\perp,q}(x,p_T^2)\,D_1^q(z,k_T^2)\right] + \ldots$$

in the limit of very small ϕ and ϕ_S bins.

$\mathcal{I}$[...]: 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 - ○ - - - ○ $h_{1T}^\perp$ - ○ - - - ○



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

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

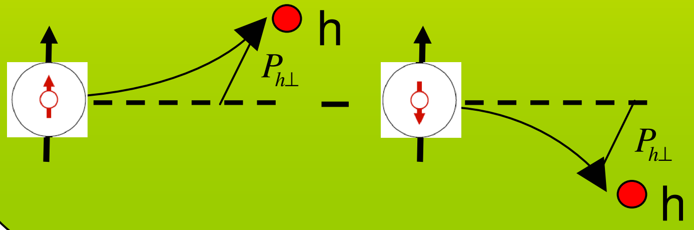
$$+ \boxed{\sin(\phi+\phi_S) \;\; d\sigma^9_{UT}} + \sin(3\phi-\phi_S) \;\; d\sigma^{10}_{UT}$$

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

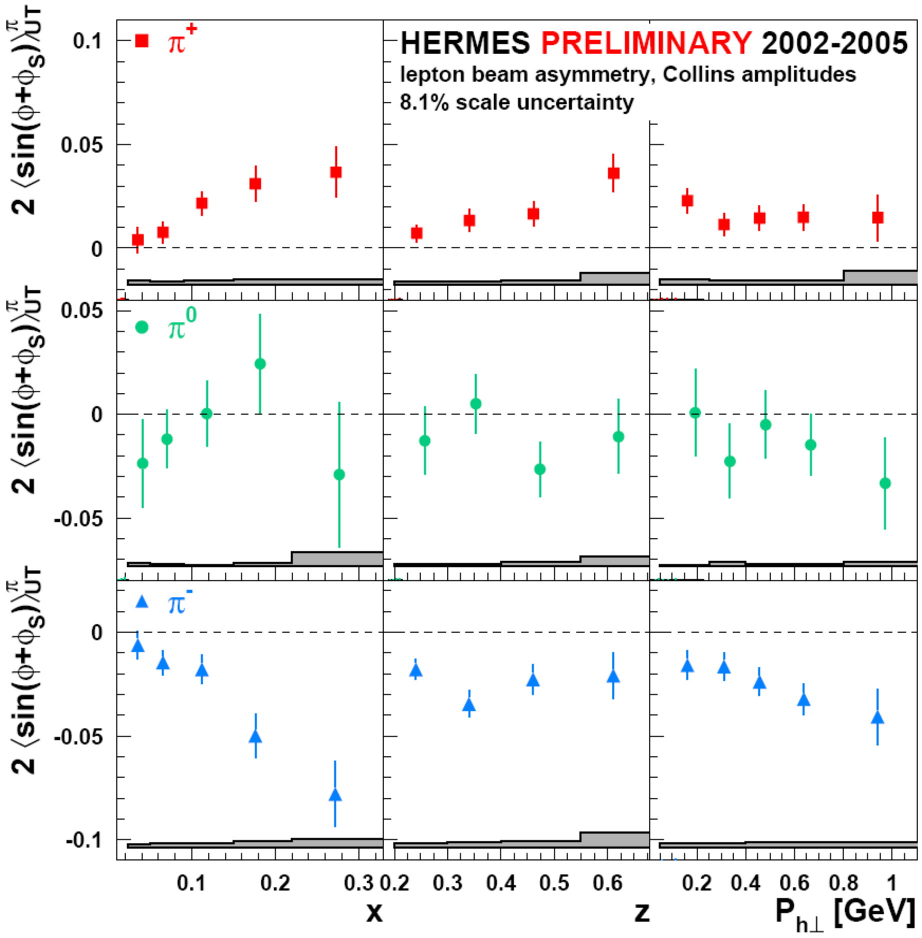
$$\sigma^{13}_{LT} + \frac{1}{Q}\cos\phi_S d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi \; - \phi_S) d\sigma^{15}_{LT} \Bigg] \Bigg\}$$

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

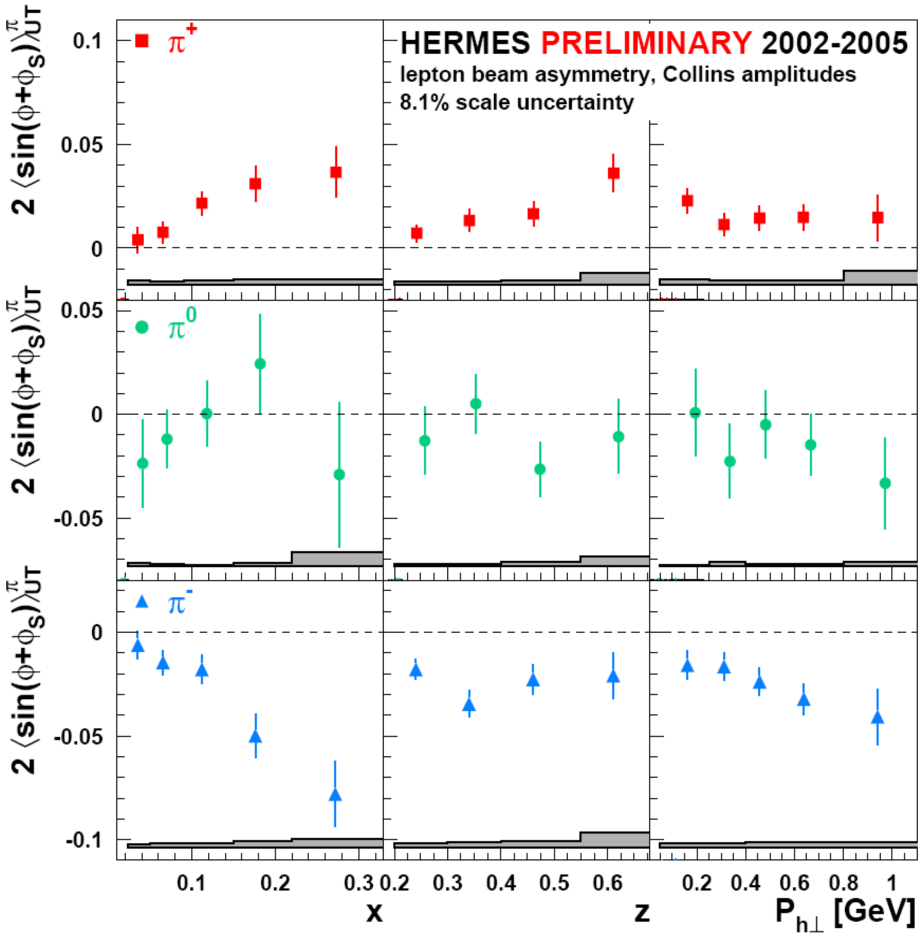


Collins pions amplitudes



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

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**

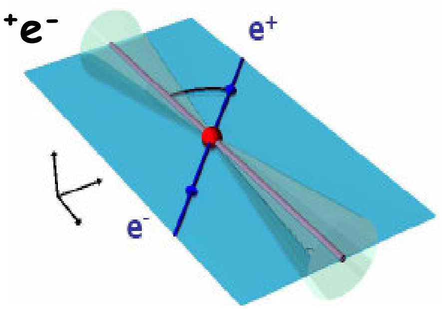
the large negative π^- amplitude suggests disfavored Collins FF with opposite sign:

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

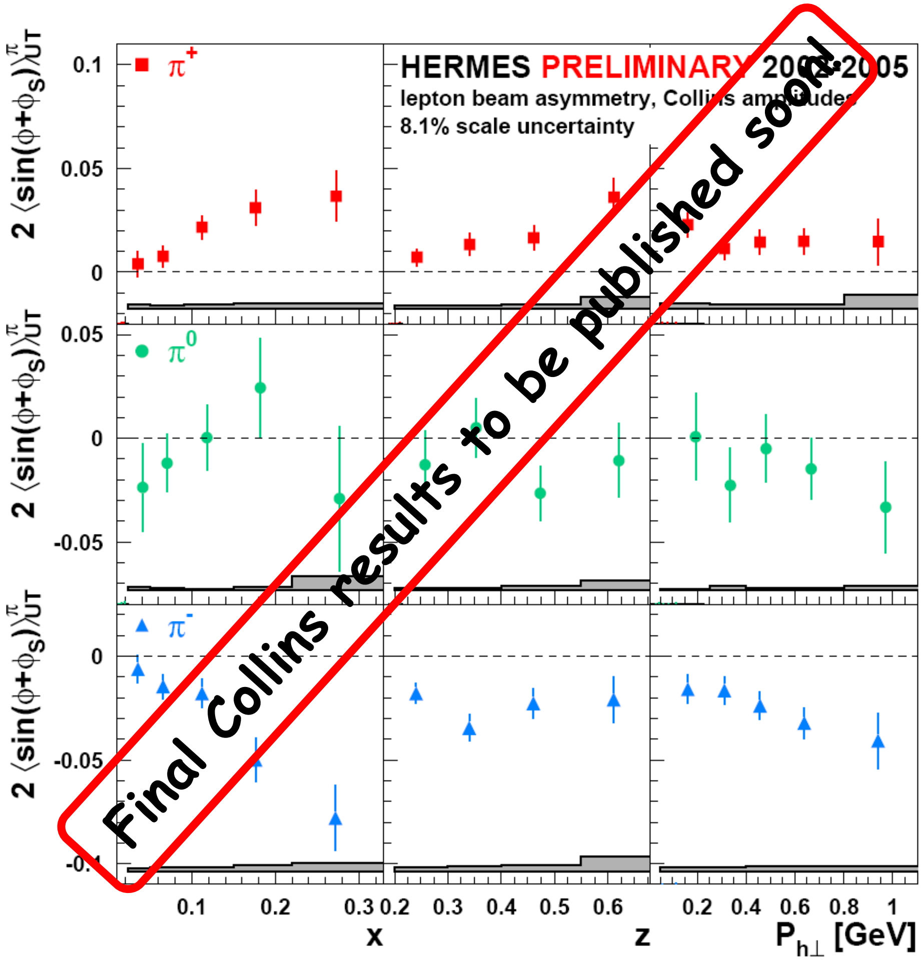
- positive for π^+
- consistent with zero for π^0
- negative for π^-

measurement at e^+e^- collider machines

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



Collins pions amplitudes



Final Collins results to be published soon!

☑ **Non-zero Collins effect observed**

☑ **Both transversity and Collins function sizeable!**

☑ **Ampl. increase with x, i.e. towards the valence region**

☑ **Isospin symmetry fulfilled**

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measurement at e^+e^-

collider machines

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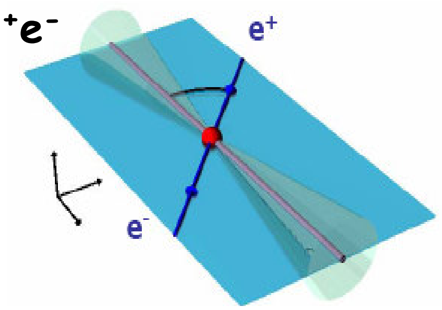
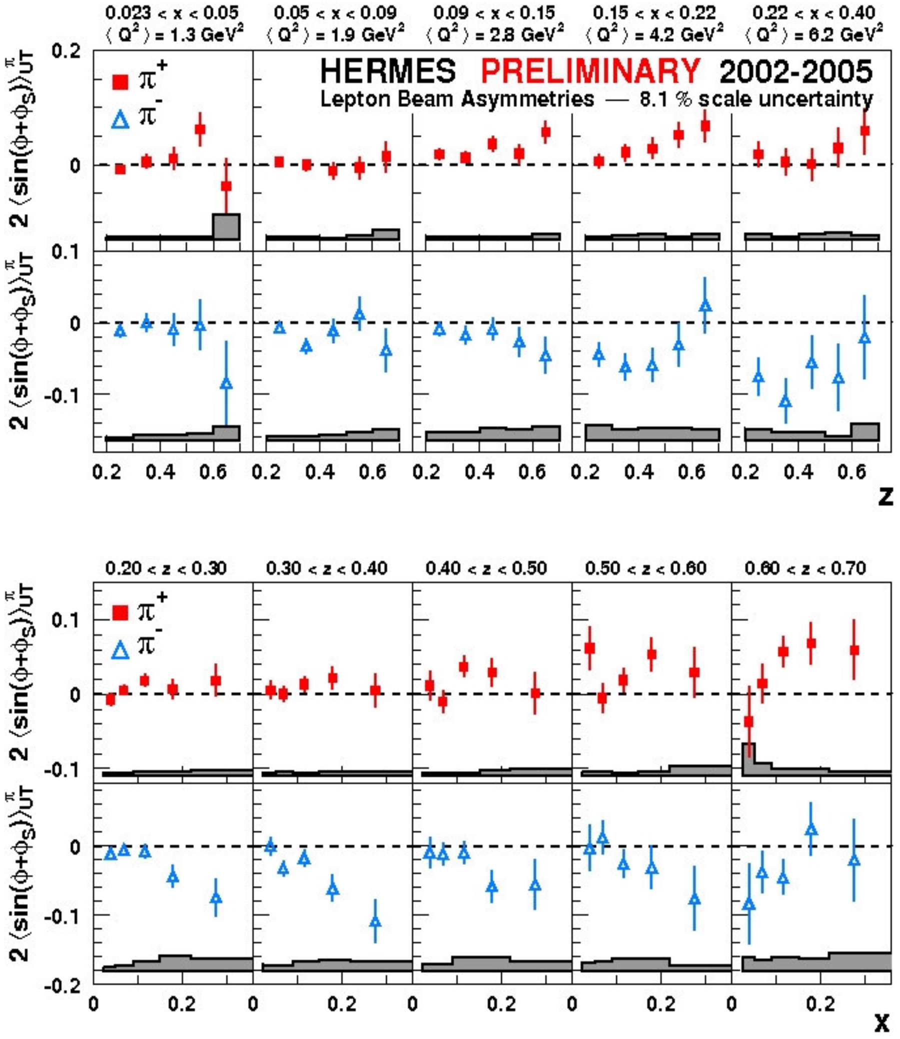


2-D Collins pions amplitudes

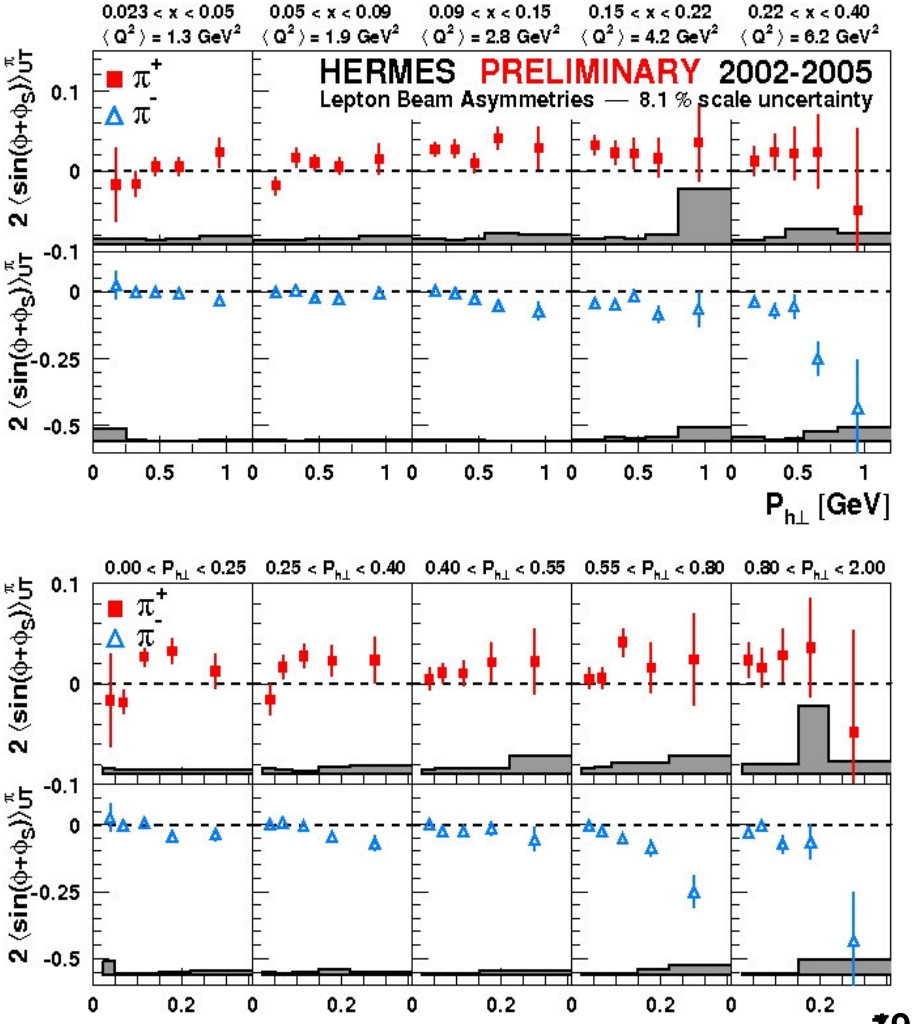
Kinematic dependencies often don't factorize → correlations among variables

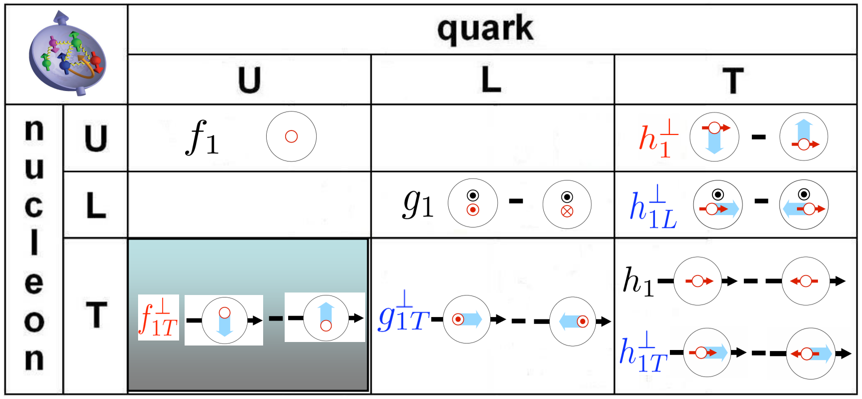
bin in as many independent variables as possibles (multidim. analysis)

X vs. Z

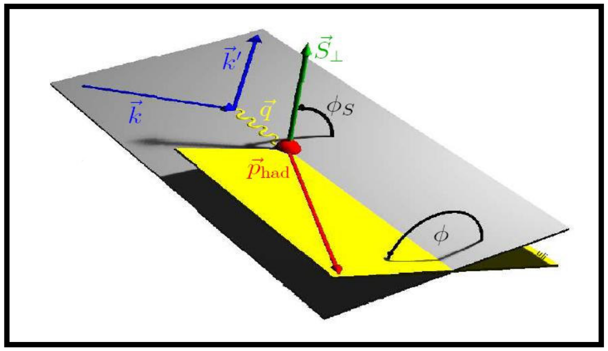


X vs. $P_{h\perp}$





		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 $h_{1T}^\perp$



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

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

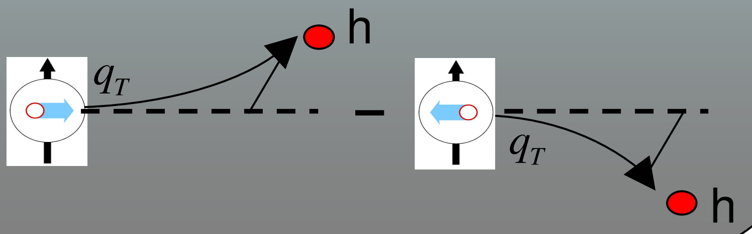
$$+ S_T \left\{ \boxed{\sin(\phi-\phi_S)\ d\sigma_{UT}^{8}} + \sin(\right.$$

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

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

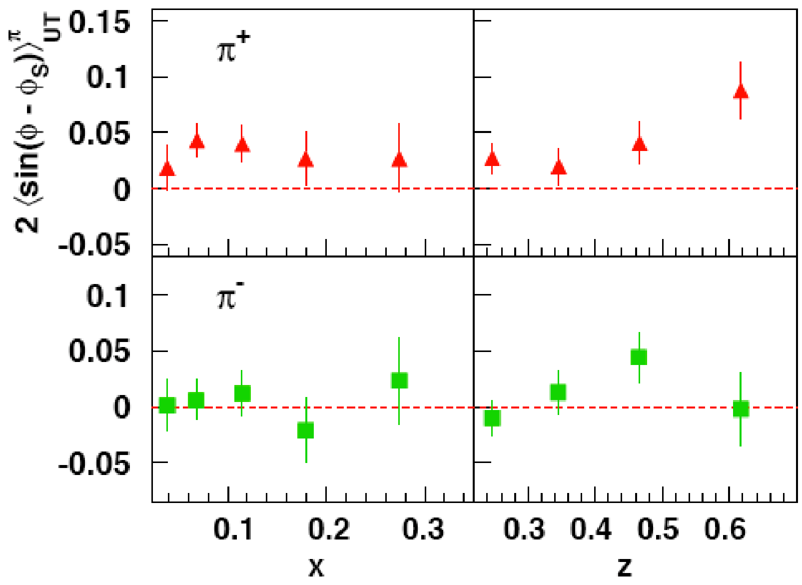
Sivers effect

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

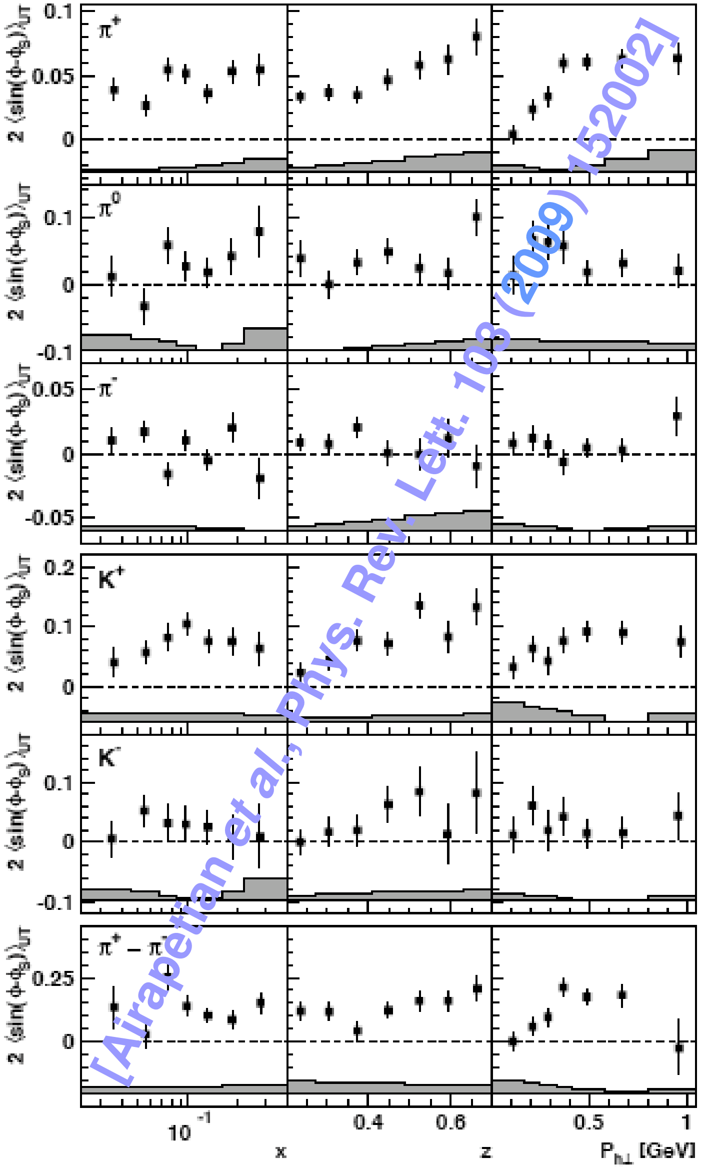


Sivers amplitudes

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

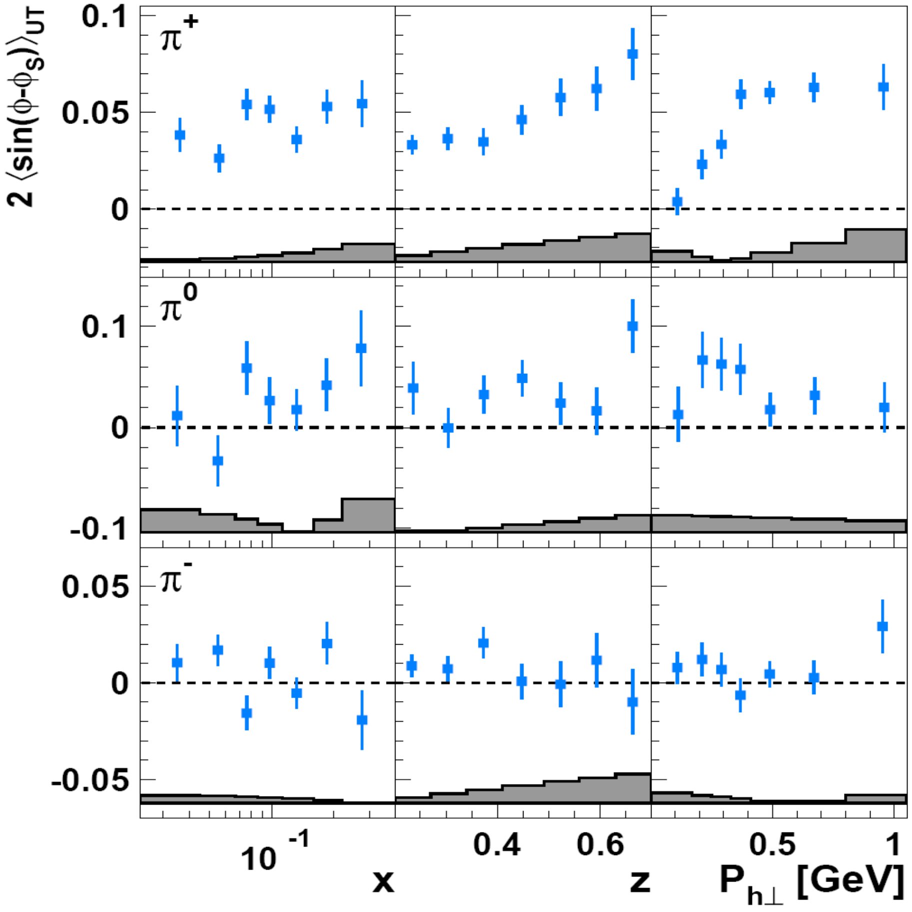


- ☑ **First observation of T-odd Sivers effects in SIDIS!**
- ☑ **U-quark dominance suggests sizeable u-quark orbital motion!**
- ☑ **Main features confirmed by new high-statistics results**



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

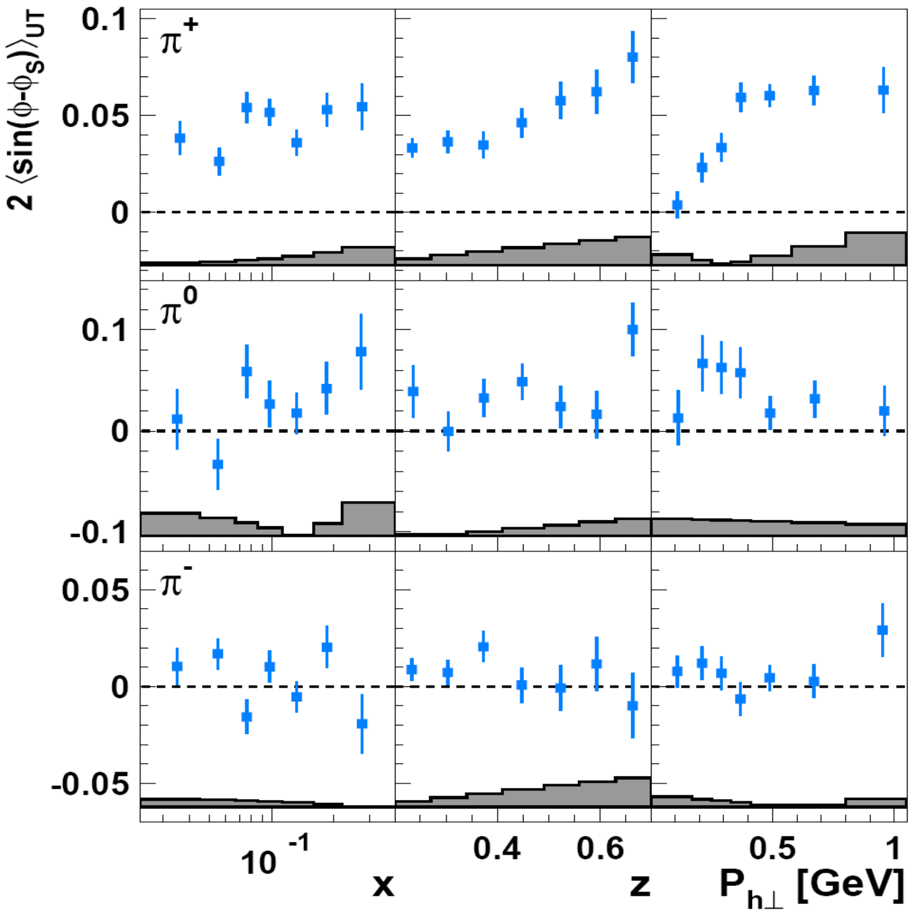
Sivers pions amplitudes



- 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**

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:

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

→ **u-quark Sivers DF < 0**

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

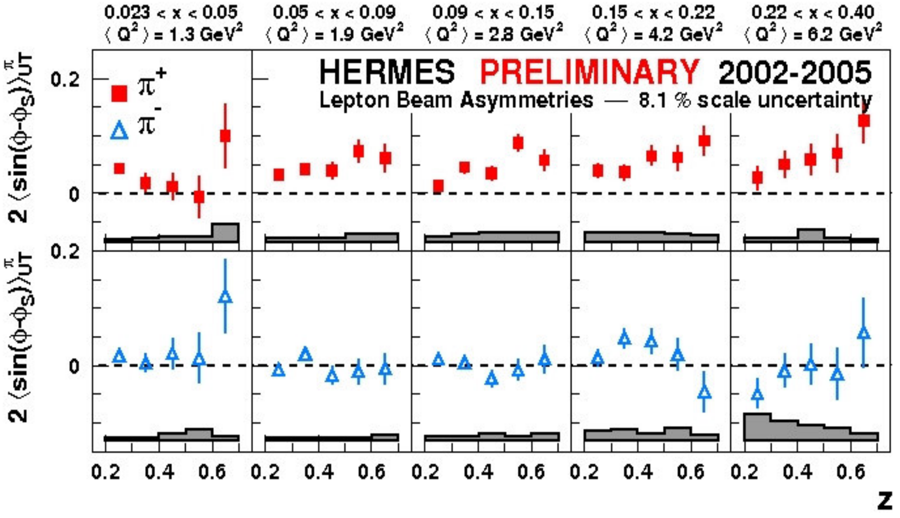
Confirmed by phenomenological fits (Torino group) and theoretical predictions (Gamberg)!

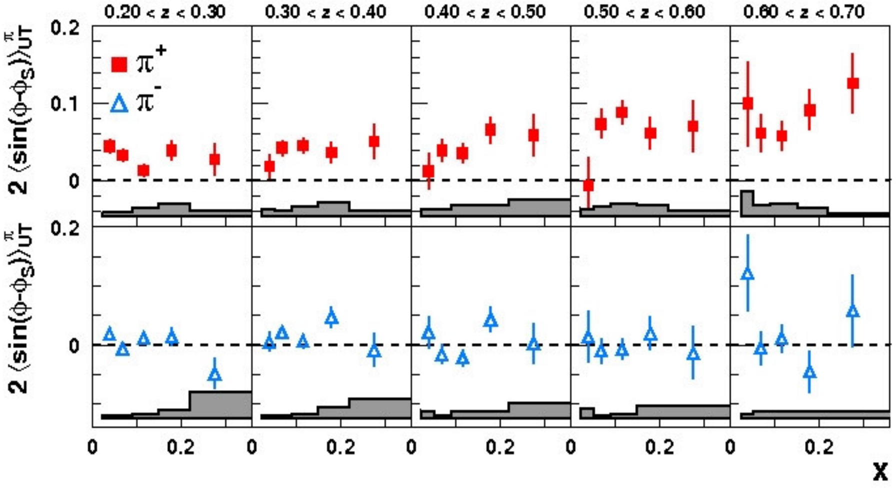
2-D Sivers pions amplitudes

Kinematic dependencies often don't factorize → correlations among variables

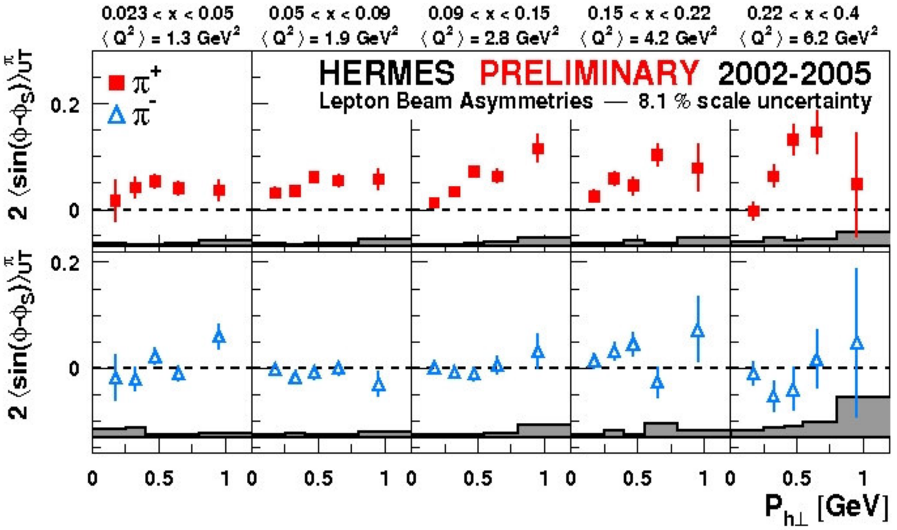
→ **bin in as many independent variables as possibles (multidim. analysis)**

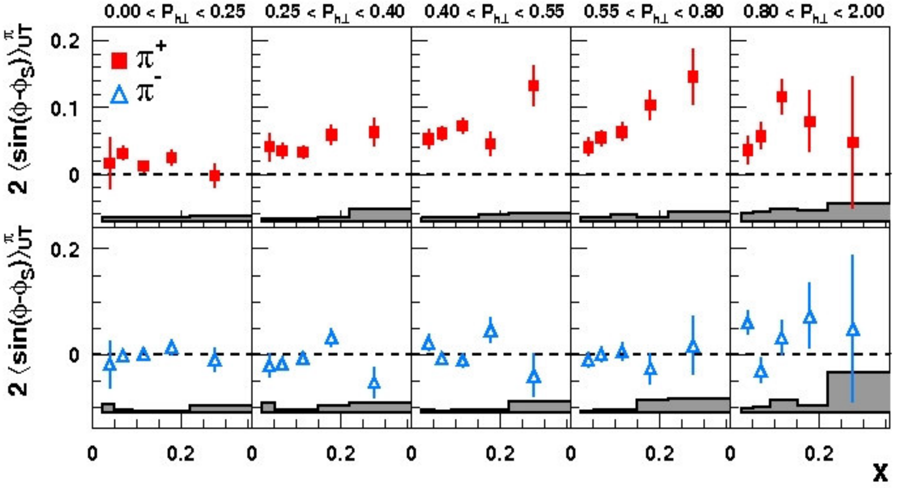
X vs. Z





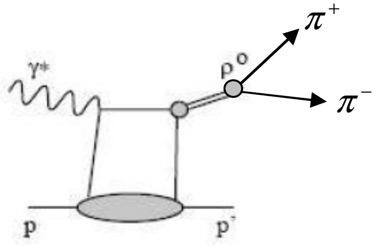
X vs. $P_{h\perp}$

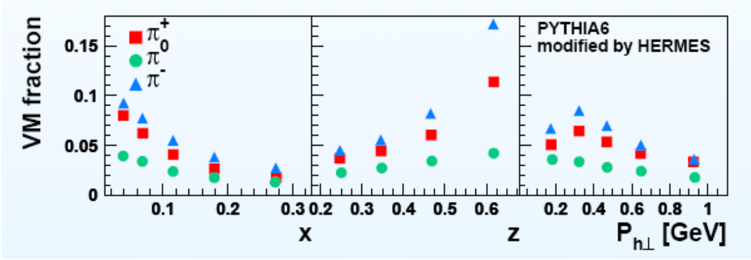




The pion-difference asymmetry

Contribution by decay of exclusively produced vector mesons is not negligible

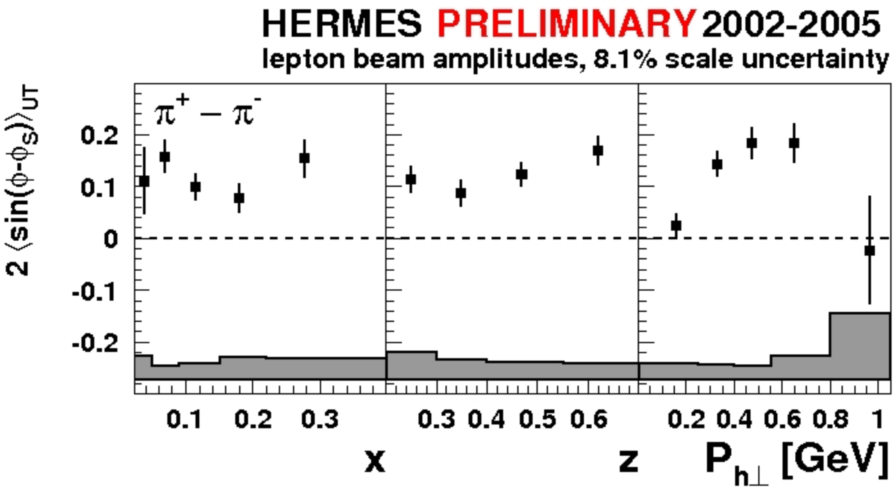


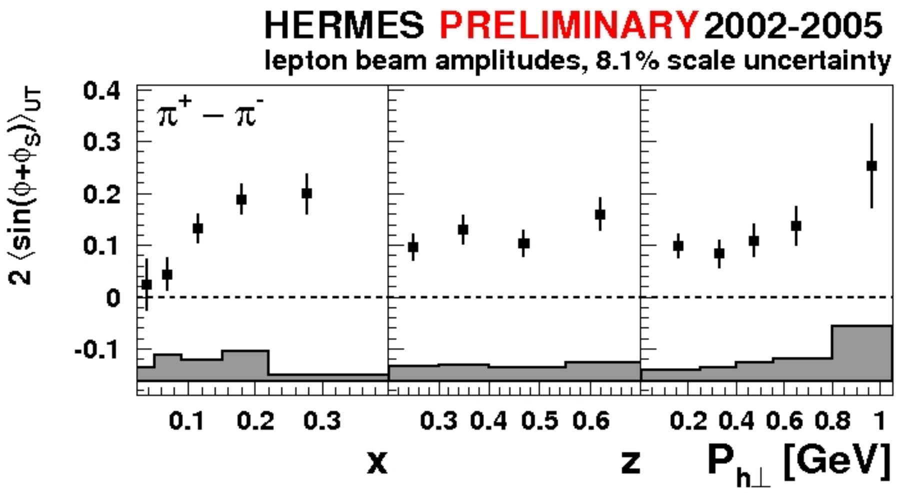


a new observable

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

Contribution from exclusive ρ^0 largely cancels out!

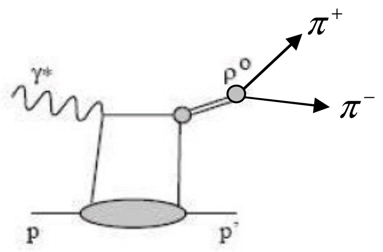


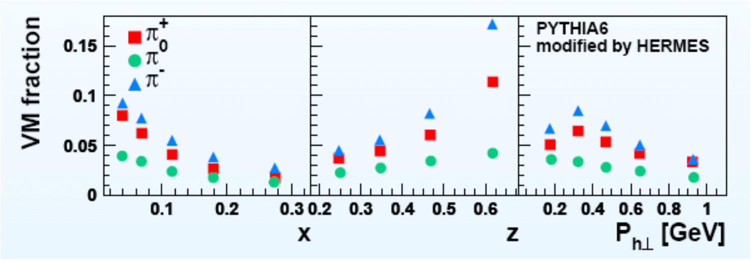


- significantly positive Sivers and Collins amplitudes are obtained
- measured amplitudes are not generated by exclusive VM contribution

The pion-difference asymmetry

Contribution by decay of exclusively produced vector mesons is not negligible

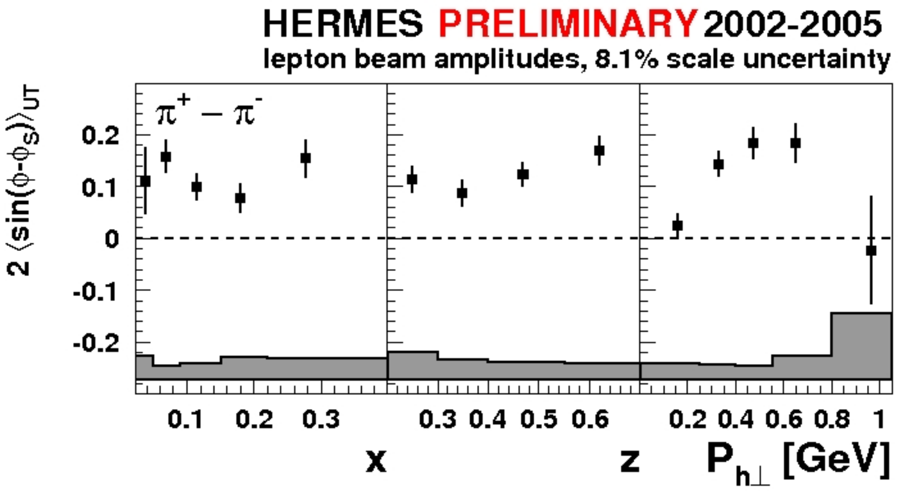




a new observable

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

Contribution from exclusive ρ^0 largely cancels out

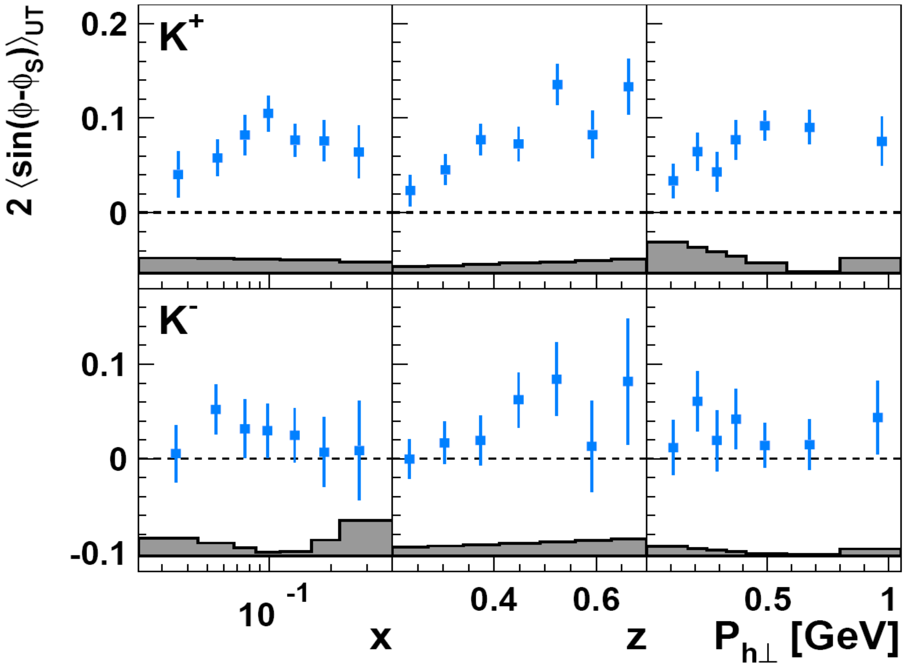


$$A_{UT}^{\pi^+-\pi^-} = -\frac{4f_{1T}^{\perp,u_v}-f_{1T}^{\perp,d_v}}{4f_1^{u_v}-f_1^{d_v}}$$

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

provides access to Sivers u-valence distribution!

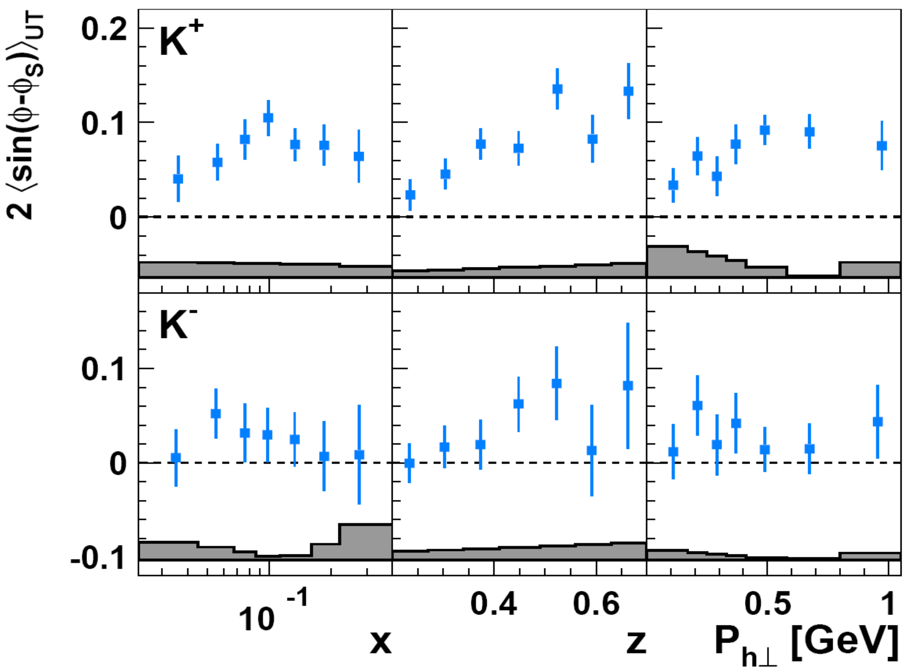
Sivers kaons amplitudes



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

- Sligthly positive

Sivers kaons amplitudes



- Slignificantly positive
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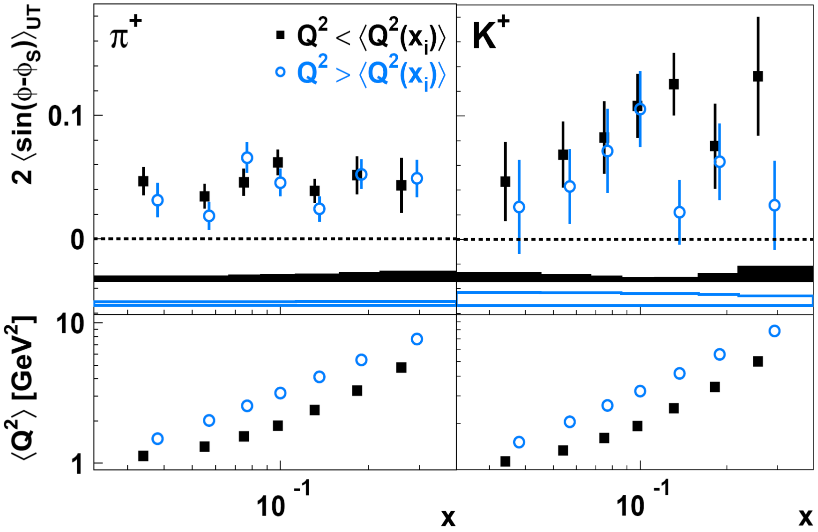
- Sligthly positive



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

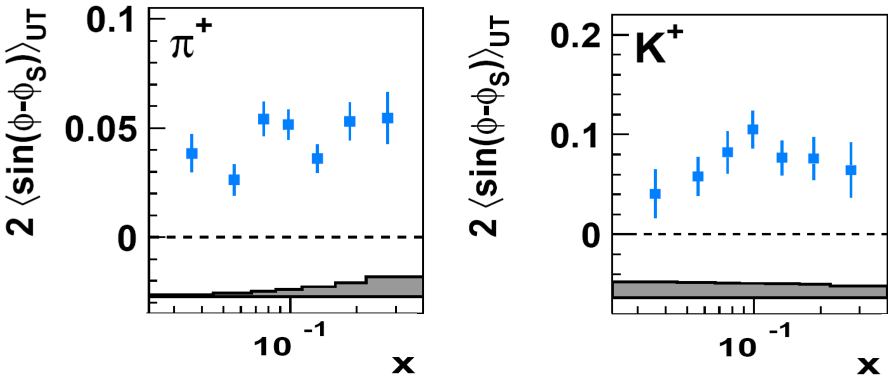
separate each x-bin in two Q^2 bins

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

The Sivers π^+/K^+ riddle

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

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

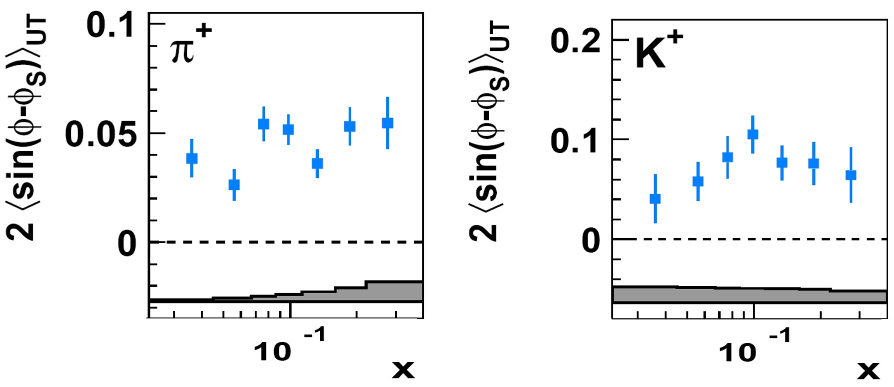


- ? $\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle$ → non trivial role of sea quarks
- ? impact of different k_T dependence of FFs in the convolution int. $\otimes_W$

The Sivers π^+/K^+ riddle

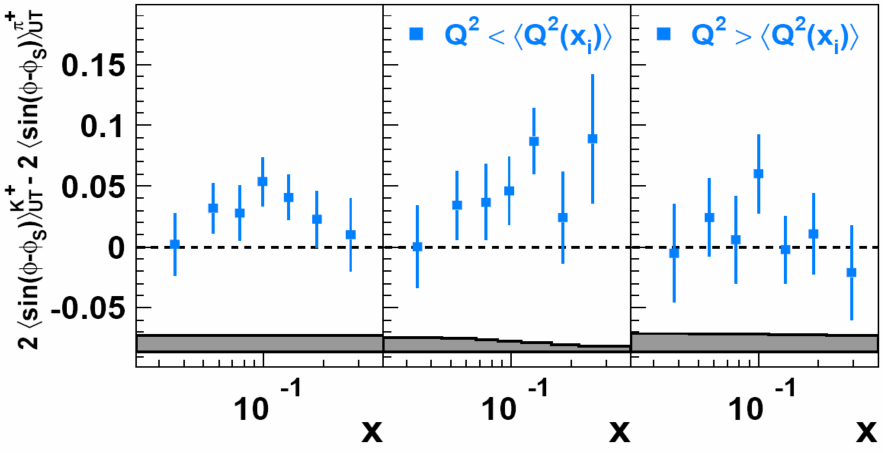
π^+/K^+ production dominated by scattering off u-quarks:

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



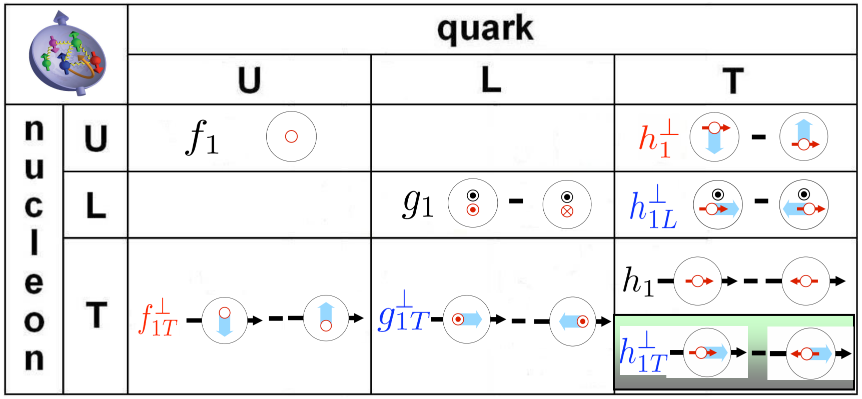
? $\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle \ \rightarrow$ non trivial role of sea quarks

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

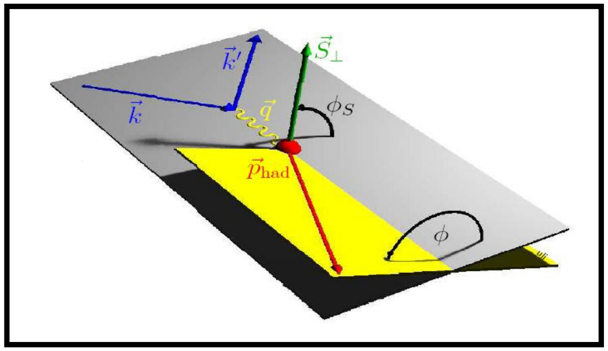


- Difference of π^+ and K^+ amplitudes
- Separate each x-bin in two Q^2 bins
- only in low-Q^2 region significant (90% c.l.) deviation is observed

? Higher-twist contrib. for Kaons



		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 $h_{1T}^\perp$



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

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

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

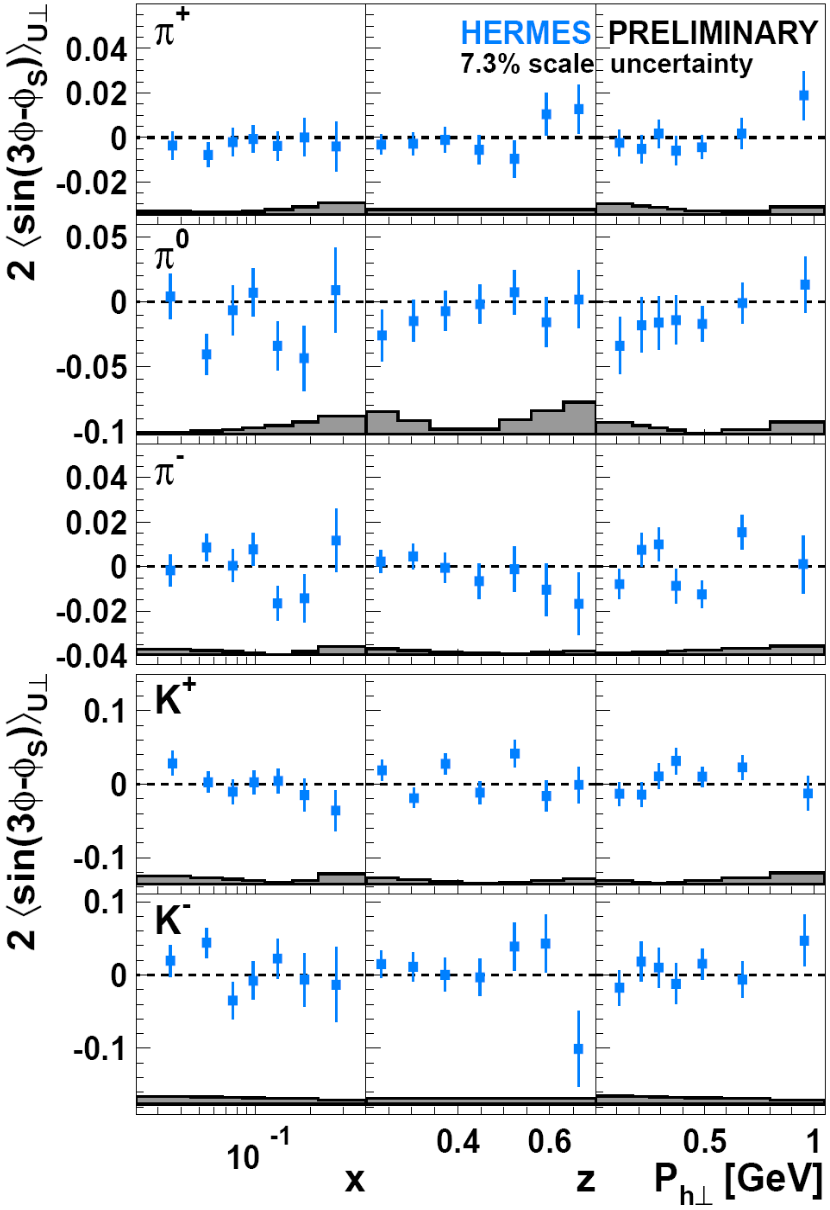
$$d\sigma^{11}_{UT} + \frac{1}{Q}\sin\phi_S d\sigma^{12}_{UT}$$

$$\frac{1}{Q}\cos(2\phi \; - \phi_S) d\sigma^{15}_{LT} \Big] \Big\}$$

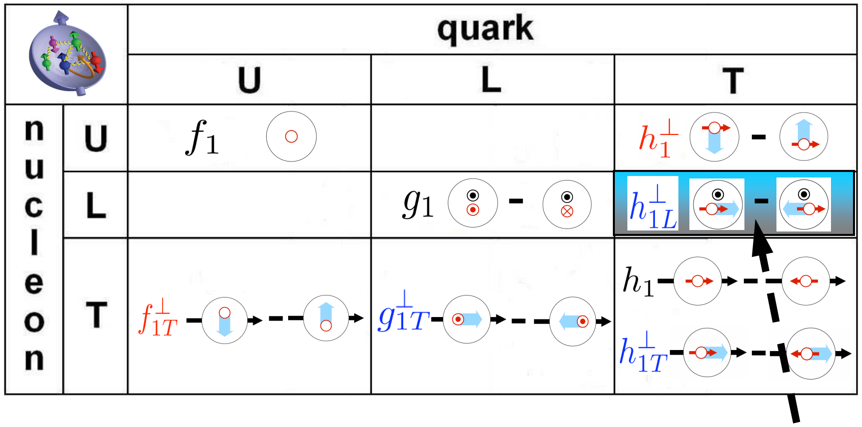
pretzelosity

- $\propto h_{1T}^\perp(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$
- correlation between parton transverse momentum and parton transverse polarization in a transversely polarized nucleon
- can be linked to the shape of the nucleon (deviation from a sphere)
- suppressed by two powers of $P_{h\perp}$ with respect to Collins and Sivers amplitudes

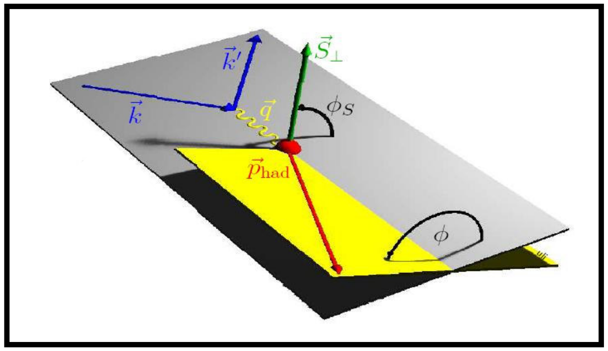
The sin($3\phi-\phi_S$) Fourier component



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



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

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

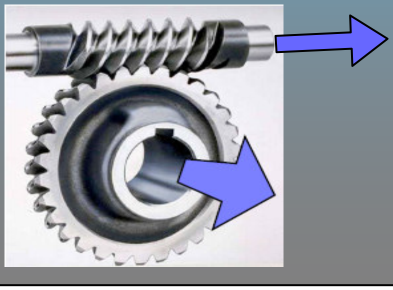
$$+\mathbf{S_T}\left\{\sin(\phi-\phi_S)\; d\sigma^8_{UT} + \sin(\right.$$

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

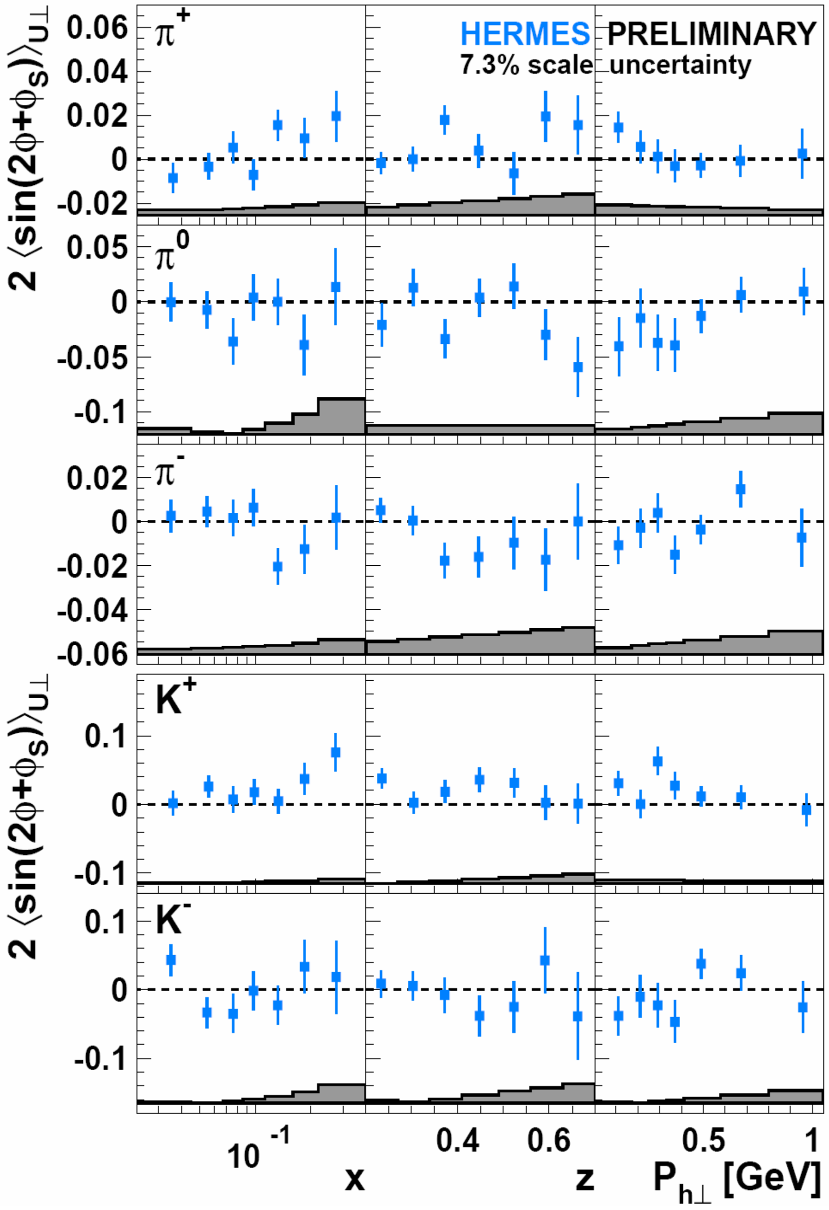
$$+\lambda_e\left[\cos(\phi-\phi_S)\; d\sigma^{13}_{LT} + \frac{1}{Q}\right.$$

Worm-gear (UL)

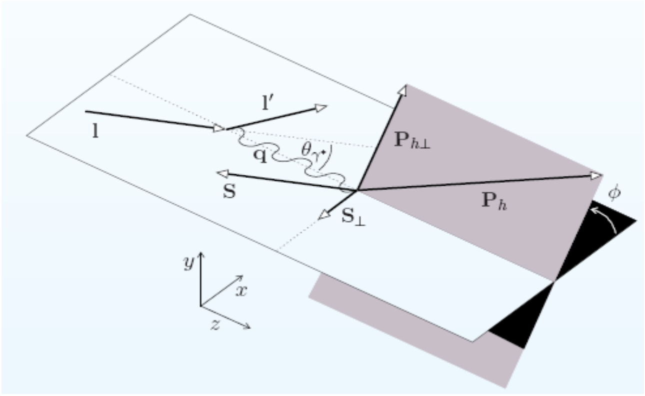
- $\propto h_{1L}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$
- correlation between parton transverse momentum and parton transverse polarization in a longitudinally polarized nucleon
- accessible in UT measurements through sin(2ϕ+ϕ$_S$) Fourier component



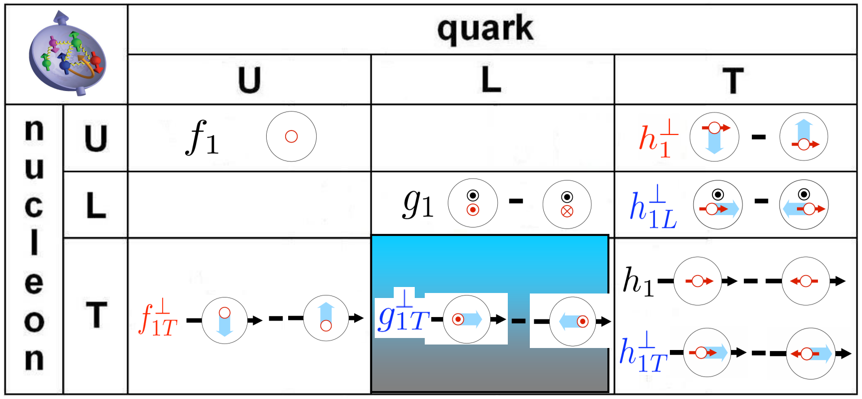
The sin($2\phi+\phi_S$) Fourier component



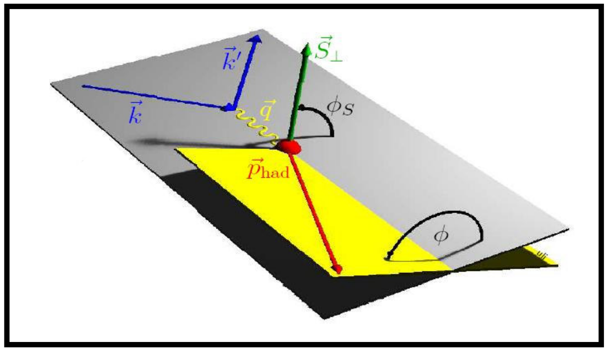
- arises solely from longitudinal (w.r.t. virtual-photon direction) component of the target spin



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



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



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

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

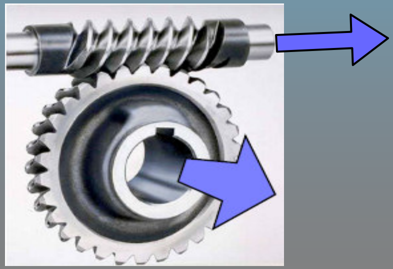
$$+ S_T \left\{ \sin(\phi - \phi_S)\;\; d\sigma^8_{UT} + \sin(\phi \right.$$

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

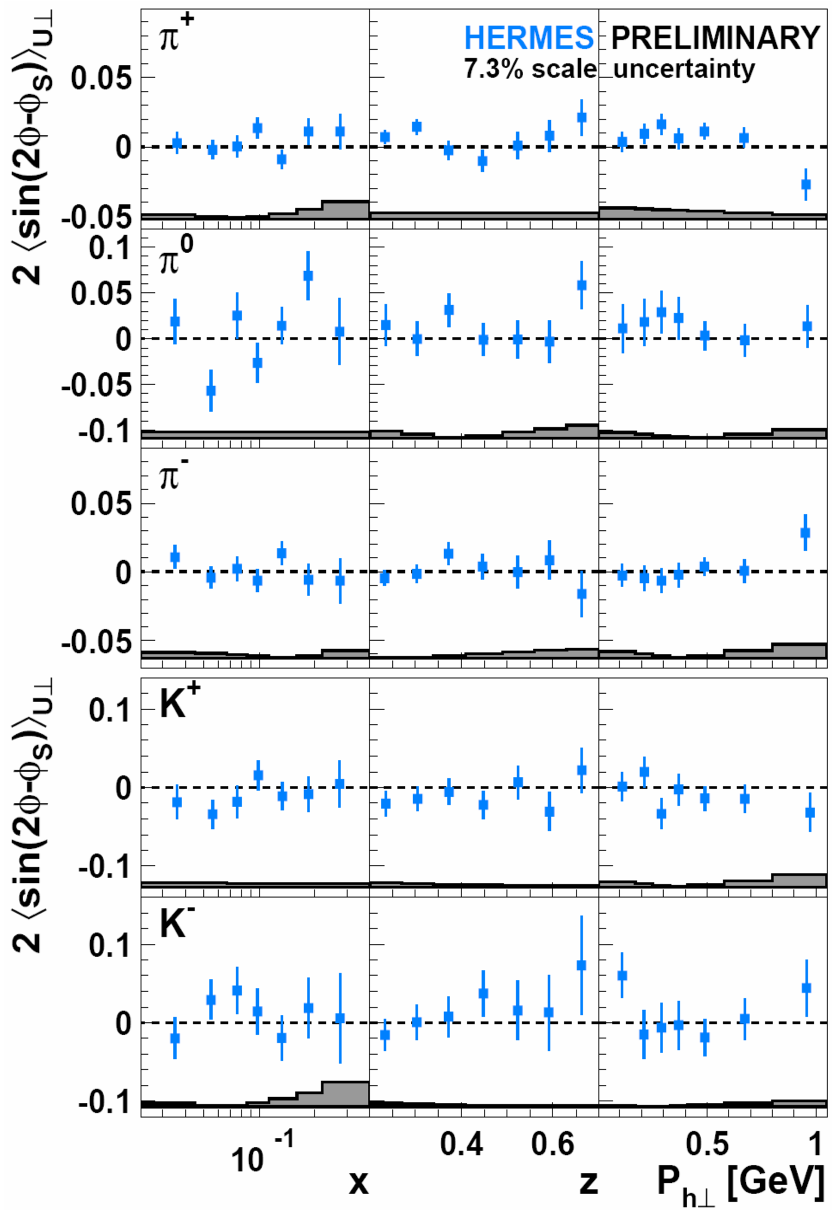
$$+ \lambda_e \left[\boxed{\cos(\phi\; - \phi_S)\;\; d\sigma^{13}_{LT}} + \frac{1}{Q} \right.$$

Worm-gear (LT)

- $\propto g_{1T}^\perp(x, p_T^2) \otimes D_1(z, k_T^2)$
- correlation between parton transverse momentum and parton longitudinal polarization in a transversely polarized nucleon
- accessible in UT measurements through sub-leading sin(2ϕ-ϕ$_S$) Fourier comp.



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



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

$$\propto \mathcal{W}_1(p_T,k_T,P_{h\perp})\left(x f_T^{\perp} D_1 - \frac{M_h}{M} h_{1T}^{\perp}\frac{\tilde{H}}{z}\right)$$

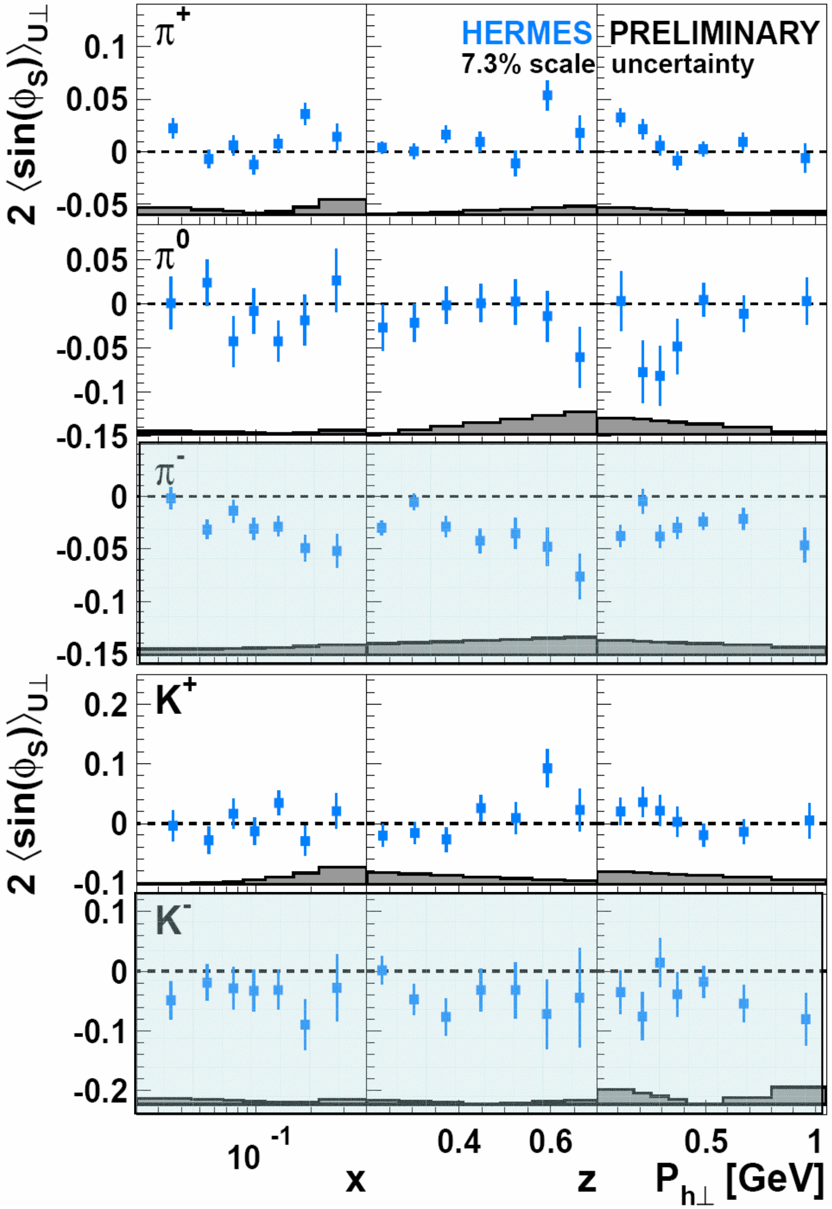
$$- \mathcal{W}_2(p_T,k_T,P_{h\perp})\left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^{\perp}}{z}\right)\right.$$

$$\left.+\left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\right)\right]$$

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

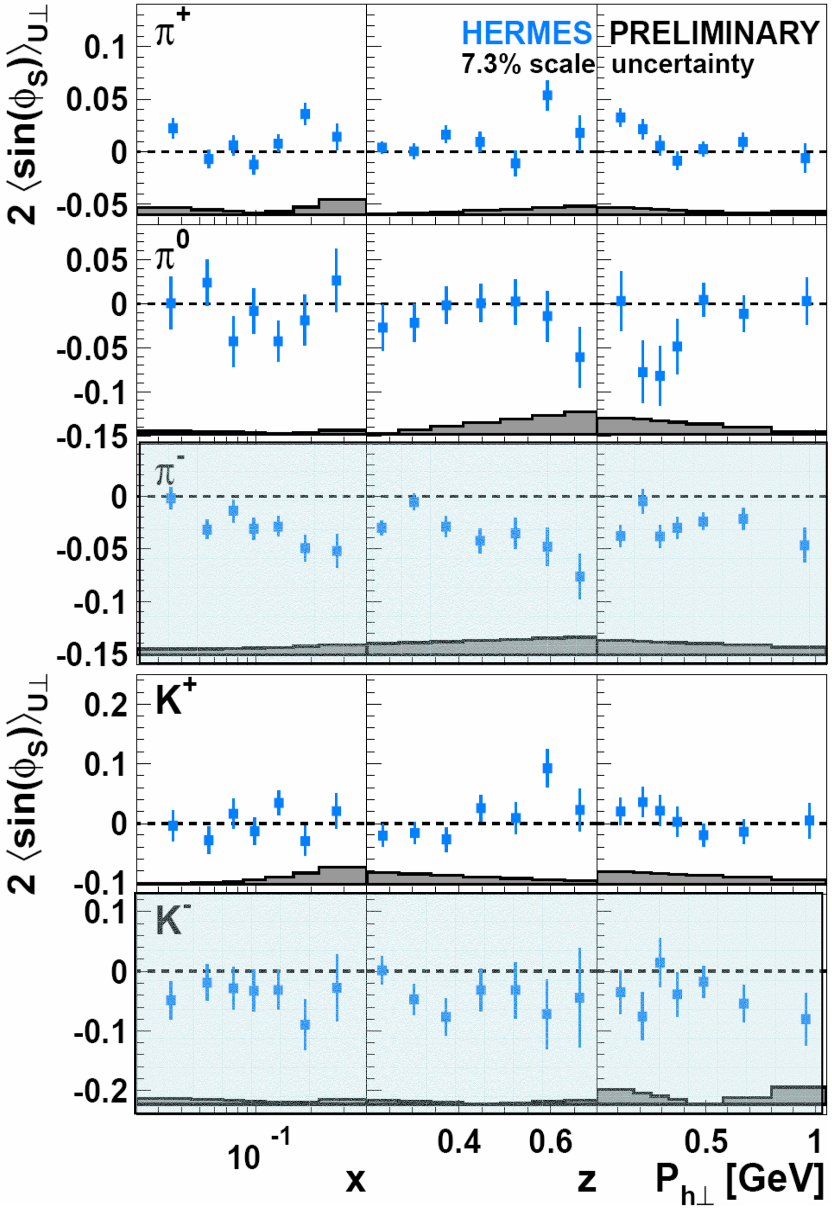
- **no significant non-zero signal observed**

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



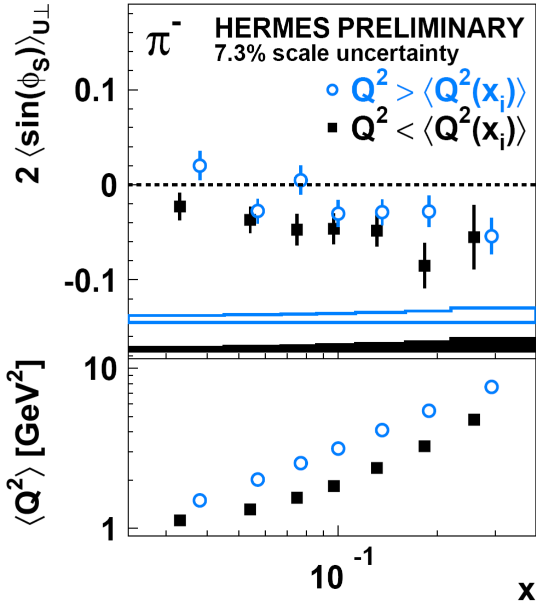
- sensitive to **worm-gear** $g_{1T}^{\perp}$, **Sivers function**, **Transversity**, etc
- **significant non-zero signal observed for π^- and K^- !**

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^- !**

Q^2 dependence observed in π^- signal:



Conclusions

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

- **Non-zero Boer-Mulders effect observed for identified charged pions**

→ clear evidence of non-zero Boer-Mulders function and Collins FF

- **significant Collins amplitudes observed for charged π-mesons**

→ enabled first extraction of transversity and Collins FF

- **significant Sivers amplitudes observed for π^+ and K^+**

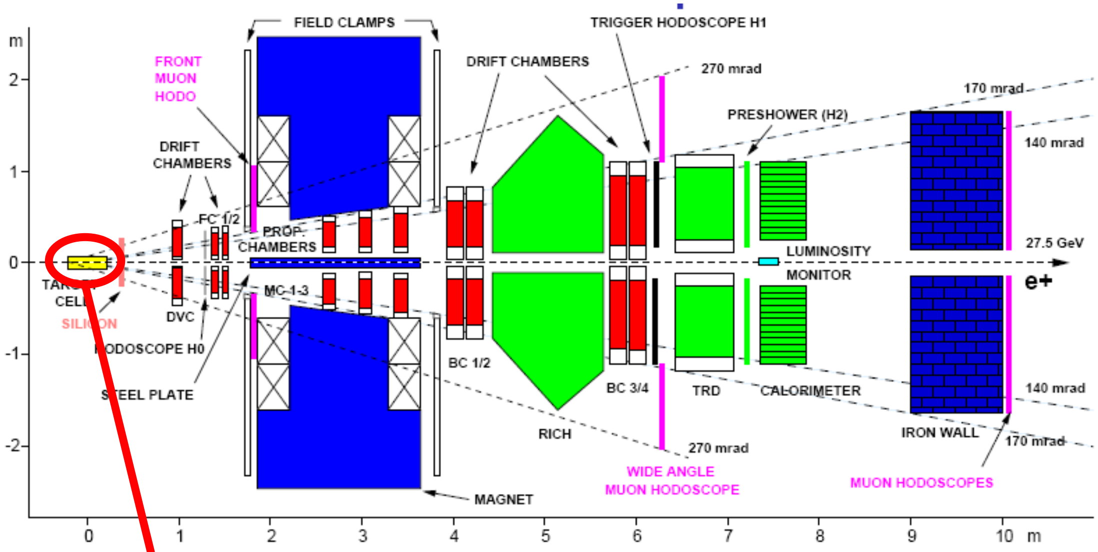
→ clear evidence of non-zero Sivers function
→ (indirect) evidence for non-zero quark orbital angular momentum
→ hint of non-trivial role of sea quarks and of higher-twist contrib. for positive kaons

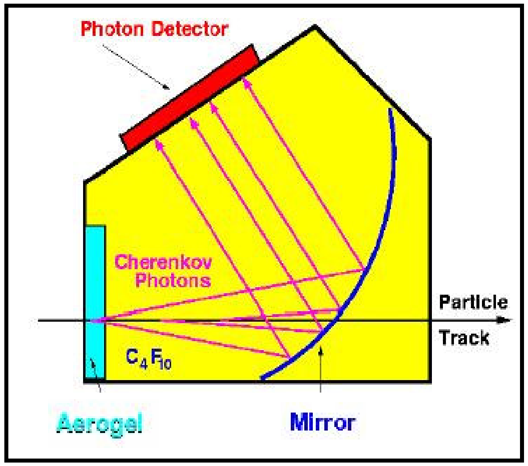
- **additional Fourier components recently extracted**

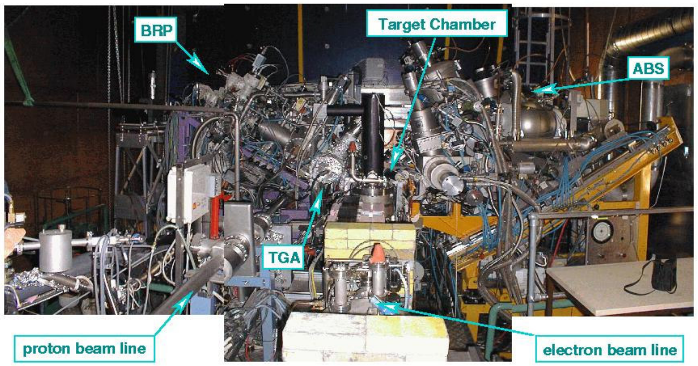
→ no evidence of non-zero pretzelosity (though amplitude kinematically suppressed)
→ first glimpse on worm-gears $h_{1L}^{\perp}$ and $g_{1T}^{\perp}$ related observables
→ significant non-zero $\langle \sin(\phi_S) \rangle_{UT}^{h}$ amplitudes for negatively charged mesons

Back-up slides

The HERMES experiment at HERA

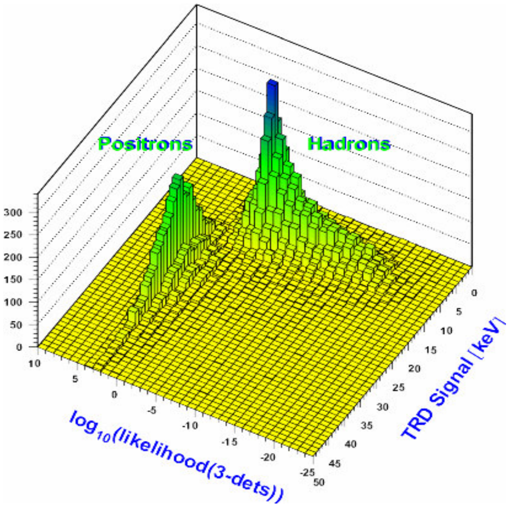




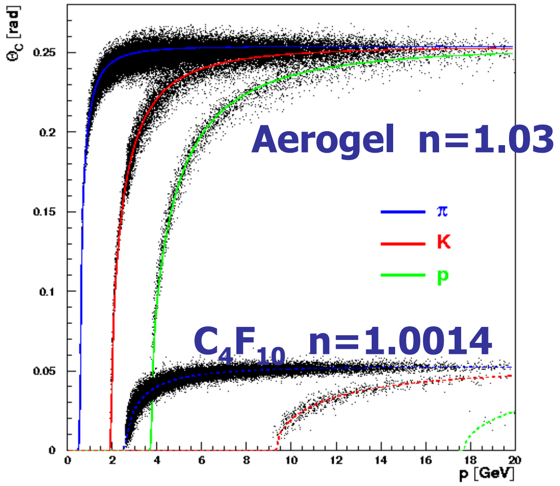


TRD, Calorimeter, preshower, RICH:

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

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

Probability that an event generated with kinematics w is measured with kinematics w'

Includes the events smeared into the acceptance

🟨 = Kinematic range of integration

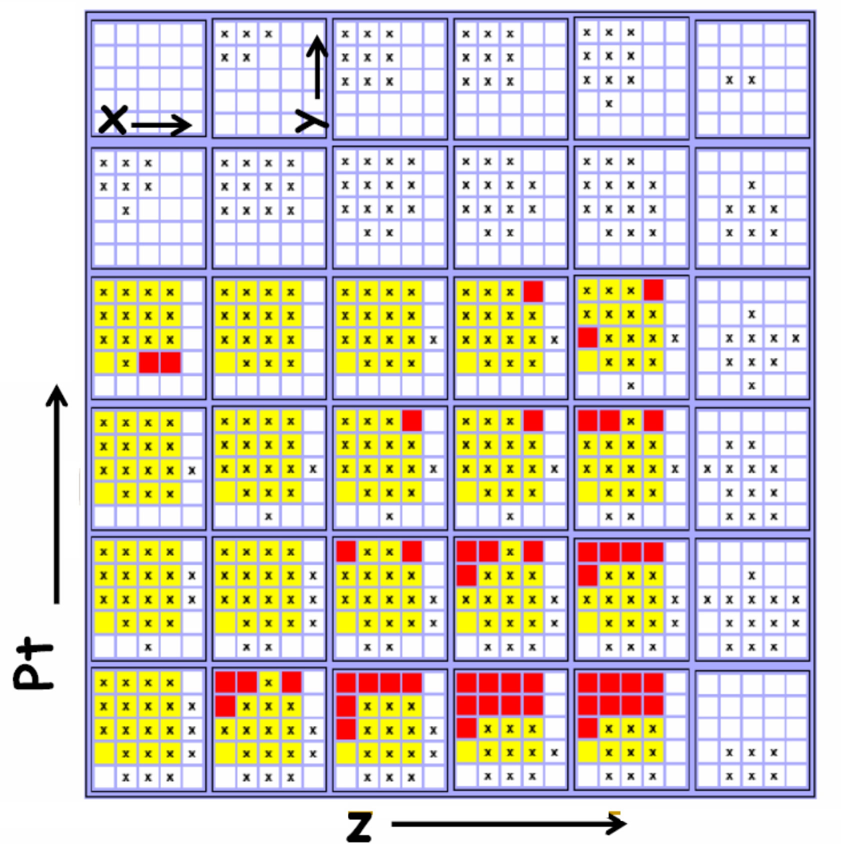
BINNING
900 kinematical bins x 12 ϕ_η-bins

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

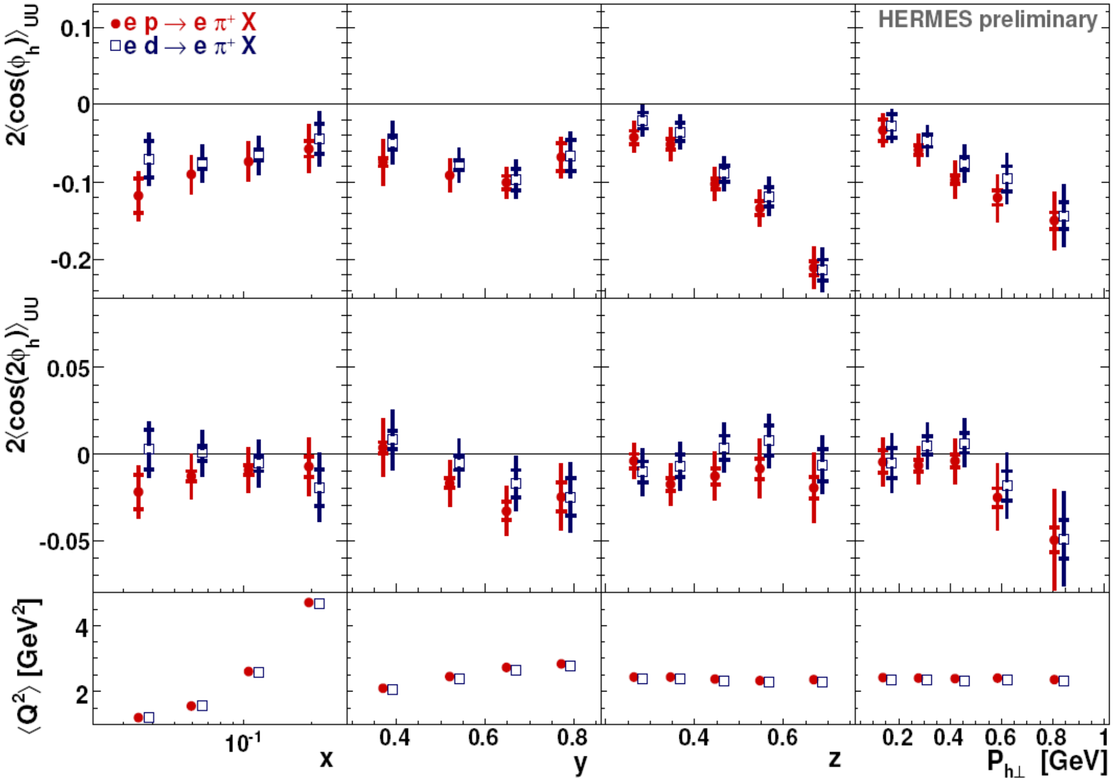
🟨 = signal not expected and not observed

🟨 x = signal expected and observed

🟥 = signal expected but not observed

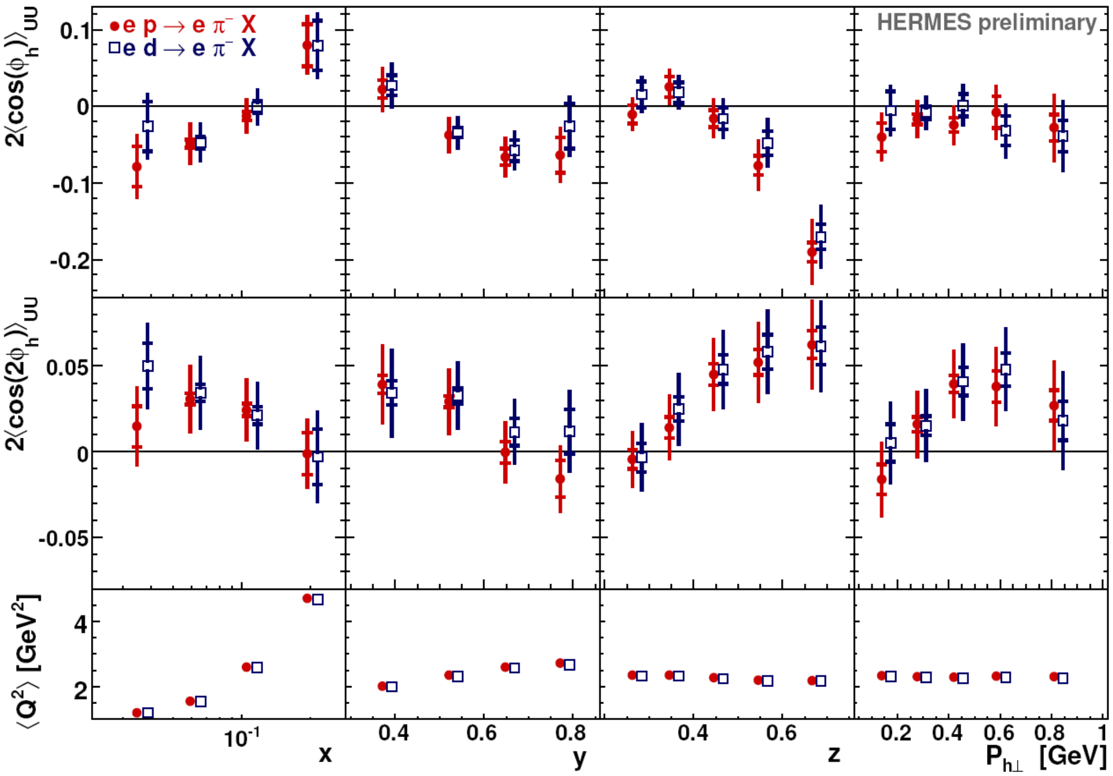


The Boer-Mulders effect for π^+



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

The Boer-Mulders effect for π^-

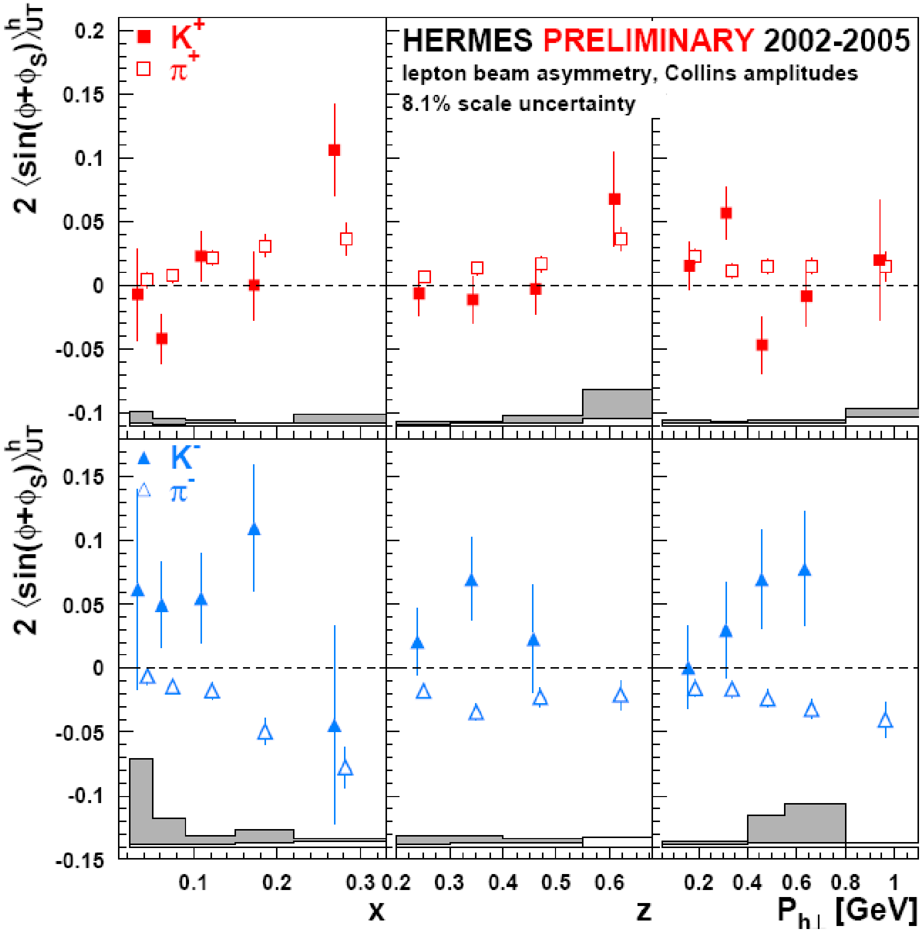


- **Hydrogen vs. Deuteron target data**
- **The two samples are compatible**

Standard cuts

inclusive DIS	semi–inclusive DIS
$Q^2 > 1\,\mathrm{GeV}^2$	$Q^2 > 1\,\mathrm{GeV}^2$
$W^2 > 4\,\mathrm{GeV}^2$	$W^2 > 10\,\mathrm{GeV}^2$
$0.1 < y < 0.95$	$y < 0.95$
$0.023 < x < 0.4$	$0.023 < x < 0.4$
	$\theta_{\gamma^* h} > 0.02\,\mathrm{rad}$
	$2\,\mathrm{GeV} < P_h < 15\,\mathrm{GeV}$
	$0.2 < z < 0.7$

Collins moments: Pion-kaon comparison

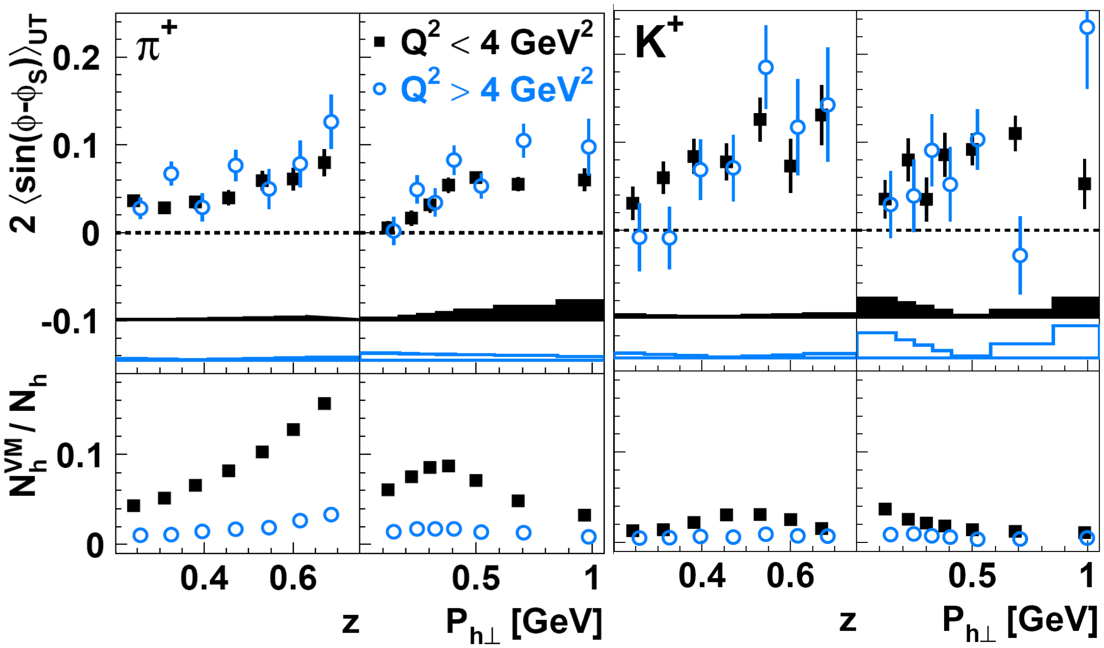


- K^+ and π^+ amplitudes consistent (u-quark dominance)

- K^- and π^- amplitudes with opposite sign

  (but $K^-(\overline{u}s)$ originates from fragmentation of sea quarks)

Siver samplitudes: additional studies

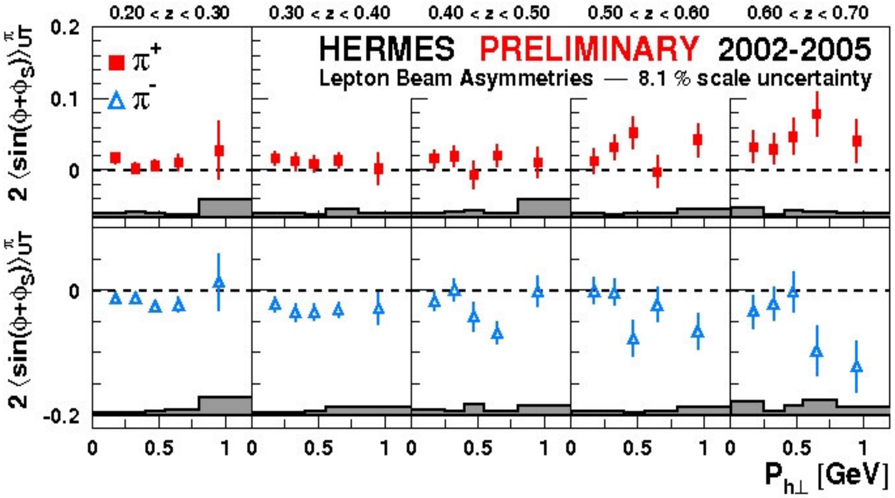


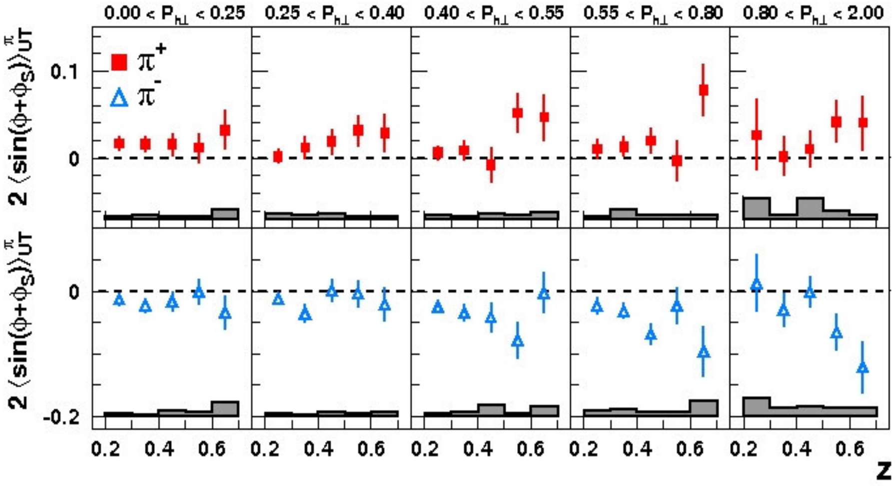
- No systematic shifts observed between high and low Q^2 amplitudes for both π^+ and K^+

No indication of important contributions from exclusive VM

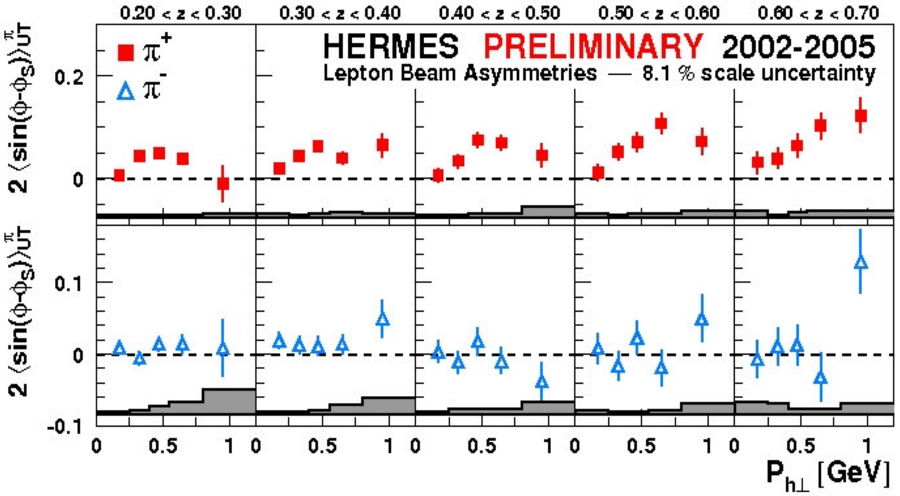
2-D moments for $\pi^{\pm}$: z vs. $P_{h\perp}$

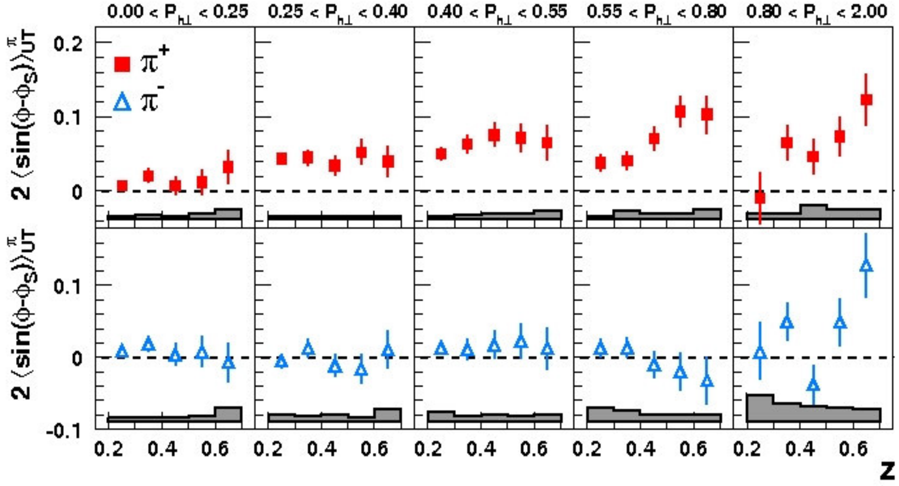
Collins



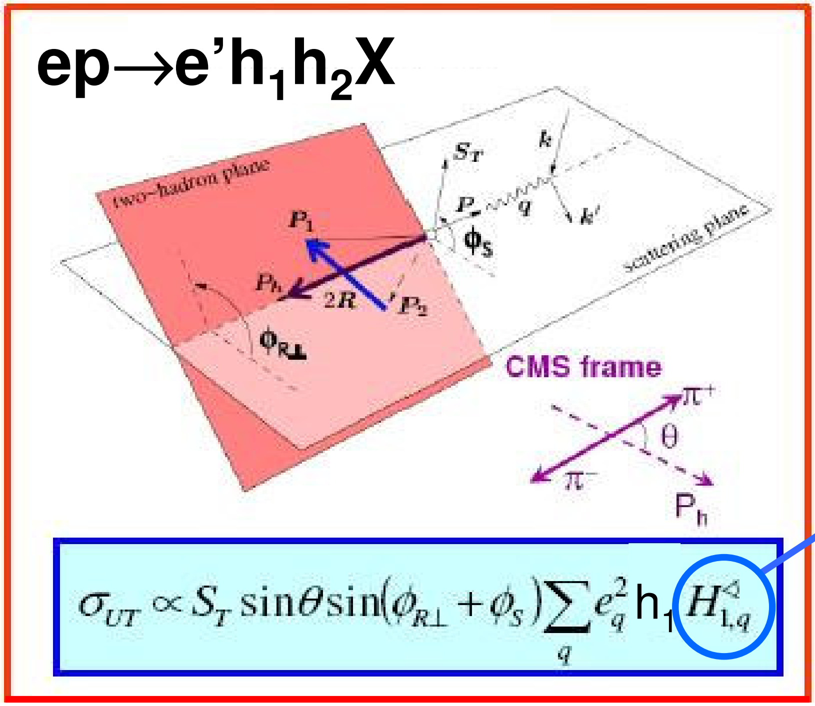


Sivers





An alternative channel to access transversity



$ep \rightarrow e'h_1h_2X$

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

Interference FF

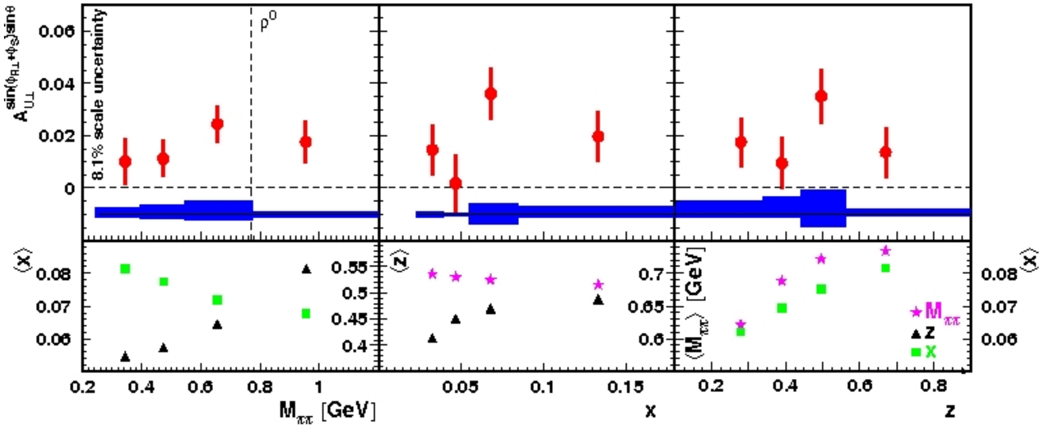
(does not depend on quark transv. momentum)

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.



- Independent way to access transversity
- No complications due to convolution integral → interpretation more transparent
- ...but limited statistical power (v.r.t. single-hadron SSAs)
- published on JHEP 06 (2008) 017

The extraction of the Distribution Functions

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

Convolution integral on transverse momenta p_T and k_T

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

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

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

hermes

$lp \rightarrow l' hX$

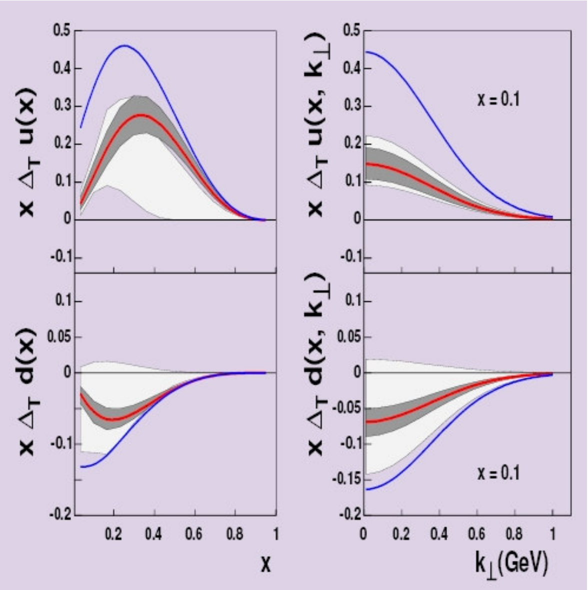
COMPASS

$ld \rightarrow l' hX$

BELLE

$e^+e^- \rightarrow h_1 h_2 X$

First extraction of Transversity!



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

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

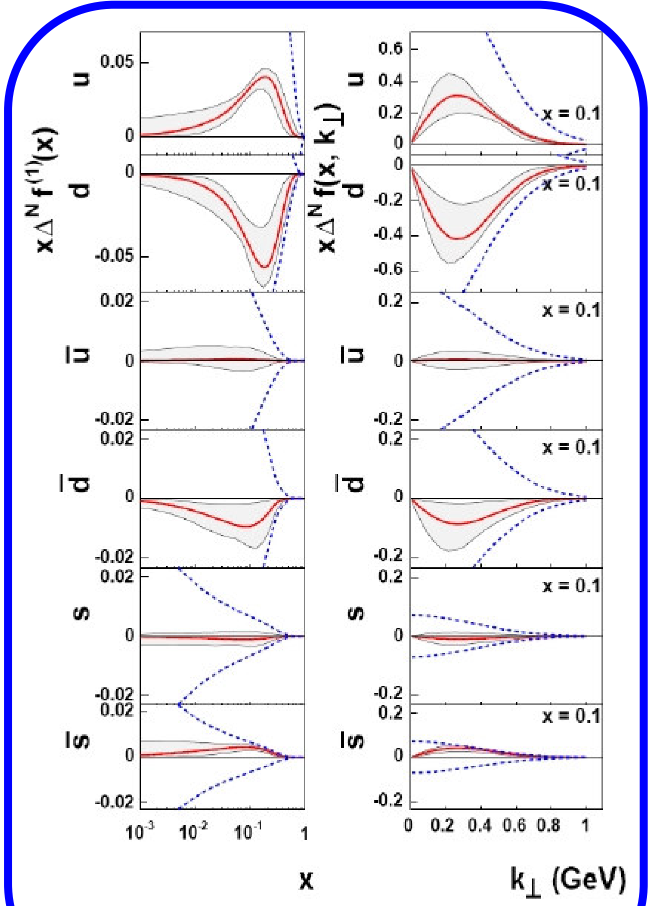
Known

hermes

$lp \rightarrow l' hX$

COMPASS

$ld \rightarrow l' hX$



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