Latest HERMES Results on Transverse-Spin Effects in Hadron Structure and Formation

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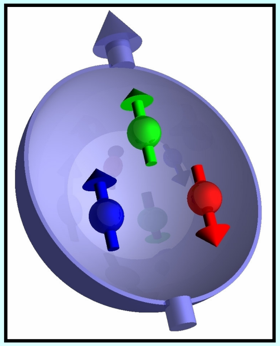
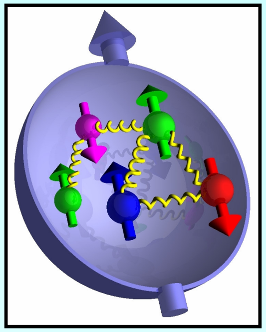
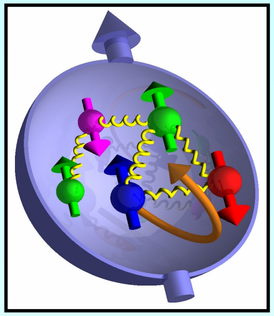
for the hermes collaboration

Outline

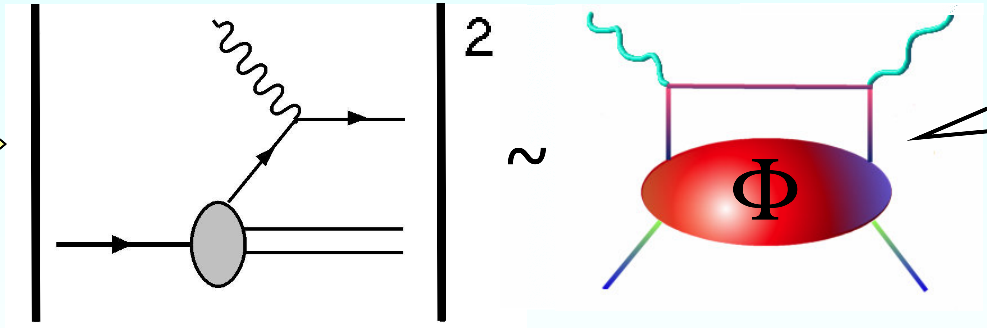
- Polarized DIS and leading-twist distribution functions
- The Semi-Inclusive DIS and the Collins and Sivers effects
- The HERMES experiment at HERA
- Preliminary HERMES results on Collins and Sivers moments
- Conclusions

$$S_N = \frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_s) + \Delta G + \Delta L_z^q + \Delta L_z^g$$

Spin distribution of the nucleon ➡ **polarized DIS** (polarised beam and/or target)

Optical theorem



forward scattering amplitude

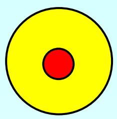
$$\Phi(p,P,S) = \frac{1}{2}[q(x)\not{P} + \lambda_N \Delta q(x)\gamma_5 \not{P} + \delta q(x)\not{P}\gamma_5 \not{S}_T]$$

quark-quark correlator

$$\Phi(p,P,S)=\frac{1}{2}\left[q(x)\not{P}+\lambda_N\,\Delta q(x)\,\gamma_5\not{P}+\delta q(x)\,\not{P}\gamma_5\not{S}_T\right]$$

Unpolarized DF

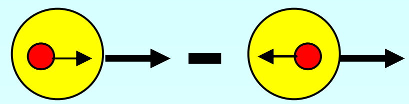
$$q(x,Q^2)=q^+ + q^-$$



WELL KNOWN

Helicity DF

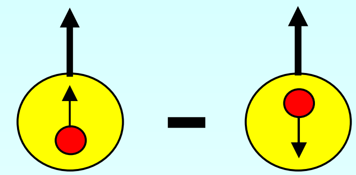
$$\Delta q(x,Q^2)=q^+ - q^-$$



KNOWN

Transversity DF

$$\delta q(x,Q^2)=q^\uparrow - q^\downarrow$$



FIRST GLIMPSE!!!

[Anselmino et al. PRD75 (2007)]

All equally important for a complete description of momentum and spin distribution of the nucleon at leading-twist.

Positivity limit

$$|\delta q(x)| < q(x)$$

Soffer bound

$$|\delta q(x)| < \frac{1}{2}\left(q(x)+\Delta q(x)\right)$$

$$\begin{cases}\delta q(x)=\Delta q(x) & \text{non-relativistic regime}\\ \delta q(x)\neq \Delta q(x) & \text{relativistic regime}\end{cases}$$

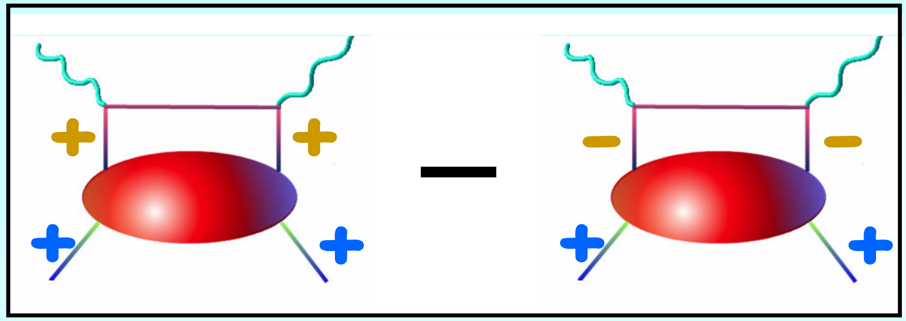
Probes relativistic nature of quarks

Due to angular momentum conservation, there is no gluon transversity in the nucleon

Completely different Q^2-evolution for Δq and δq !!

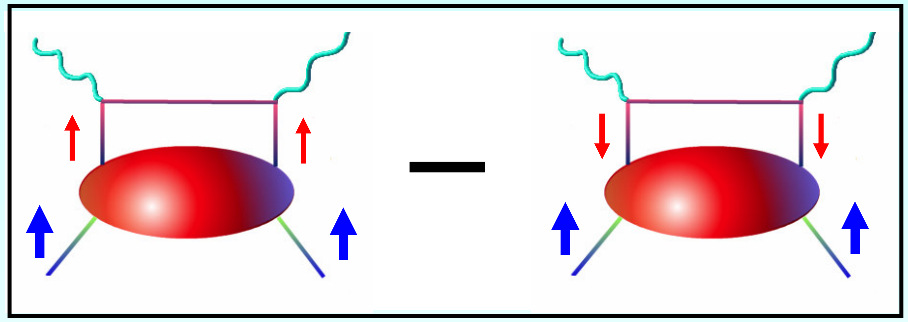
$$\Delta q(x,Q^2)$$

Helicity basis: $|+\rangle, |-\rangle$



$$\delta q(x,Q^2)$$

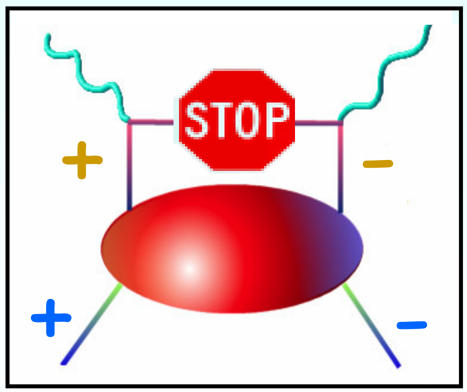
Transverse spin basis: $|\uparrow\rangle, |\downarrow\rangle$



But…

δq in helicity basis?

$$\begin{cases} |+\rangle = \frac{1}{\sqrt{2}}\left(|\Uparrow\rangle + |\Downarrow\rangle\right) \\ |-\rangle = \frac{1}{\sqrt{2}i}\left(|\Uparrow\rangle - |\Downarrow\rangle\right) \end{cases}$$



δq is chiral-odd object

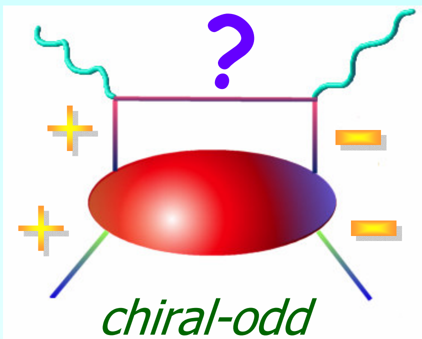
associated with a helicity flip of the struck quark

EM and strong interactions cannot flip the chirality of the probed quark

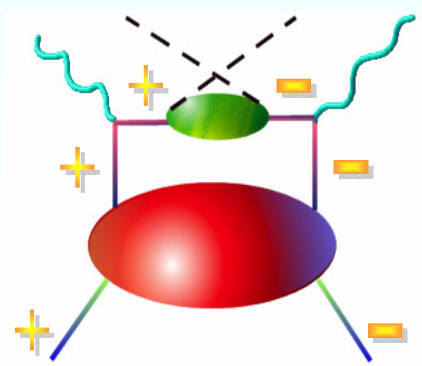
Transversity is not measurable in inclusive DIS

How can one measure transversity?

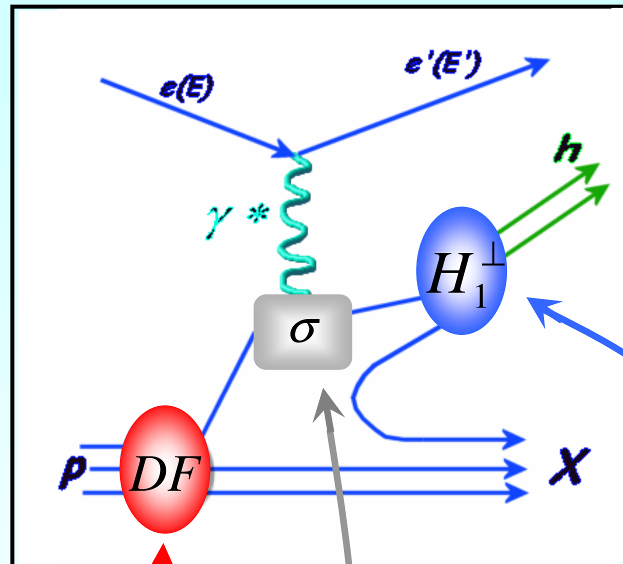
Need another chiral-odd object!



chiral odd
fragmentation
function



SIDIS: $l\,N^{\uparrow} \rightarrow l'\,h\,X$

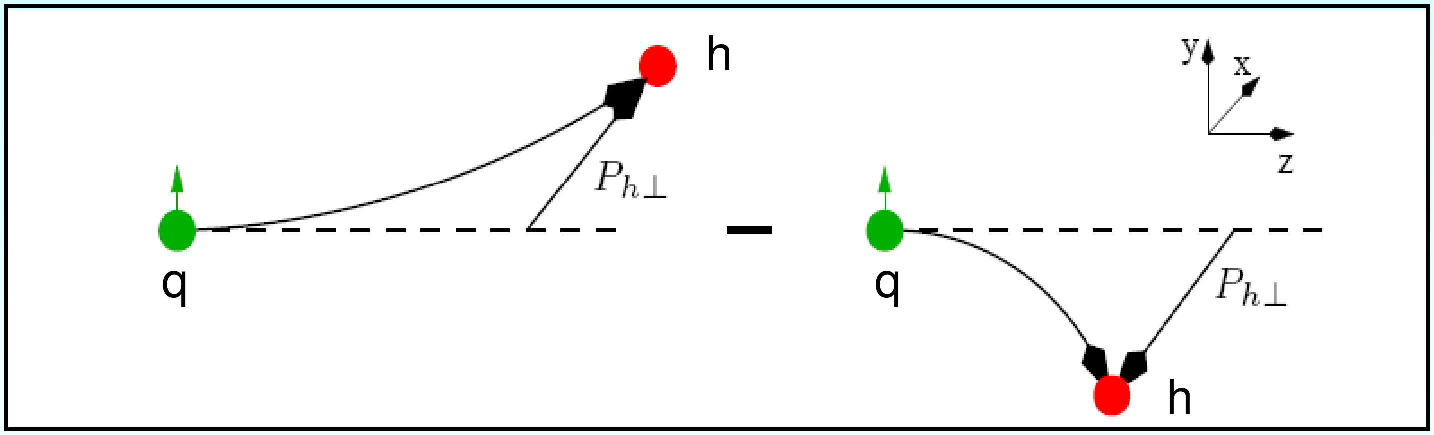


$$\sigma^{ep\rightarrow ehX} = \sum_q \delta q \otimes \sigma^{eq\rightarrow eq} \otimes H_1^{\perp}$$

chiral even! — **Transversity** — **Collins FF**

The "Collins effect"

The **Collins FF** $H_1^{\perp}(z, k_T^2)$ accounts for the correlation between the transverse spin of the fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced (unpolarized) hadron



…and generates **left-right (azimuthal) asymmetries** in the direction of the outgoing hadrons

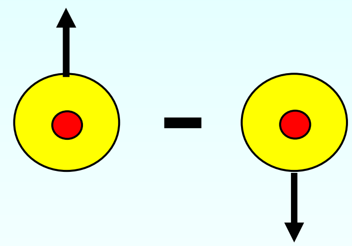
We have an observable to look at!!!

Is this observable unique?

The "**Sivers effect**":

"Correlation between p_T and transverse spin of the nucleon"

Sivers distribution function $f_{1T}^{\perp q}(x, p_T^2)$ describes the probability to find an unpolarized quark with transverse momentum p_T in a transversely polarized nucleon.

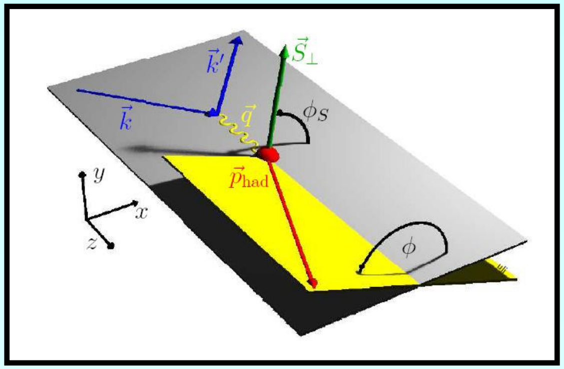


…and (also!) generates **left-right (azimuthal) asymmetries** in the direction of the outgoing hadrons.

Sivers function requires **non-zero orbital angular momentum**

[M. Burkardt, *Physical Review* **D66**, 114005 (2002)]

The SIDIS cross-section at leading order in 1/Q



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

$$d\sigma = d\sigma_{UU}^{(0)} + \cos 2\phi \; d\sigma_{UU}^{(1)} + S_L \left\{ \sin 2\phi \; d\sigma_{UL}^{(2)} + \lambda_e d\sigma_{LL}^{(3)} \right\} + \lambda_e \cos(\phi - \phi_S) \; d\sigma_{LT}^{(4)}$$

$$+ S_T \left\{ \underbrace{\sin(\phi + \phi_S) \; d\sigma_{UT}^{(5)}}_{\text{Collins}} + \underbrace{\sin(\phi - \phi_S) \; d\sigma_{UT}^{(6)}}_{\text{Sivers}} + \sin(3\phi - \phi_S) \; d\sigma_{UT}^{(7)} + \sin \phi_S d\sigma_{UT}^{(8)} \right\}$$

$$d\sigma_{UT}^{Collins} \propto |S_T| \sin(\phi + \phi_S) \cdot \sum_q e_q^2 I \left[\frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} \delta q(x, p_T^2) \otimes H_1^{\perp q}(z, k_T^2) \right]$$

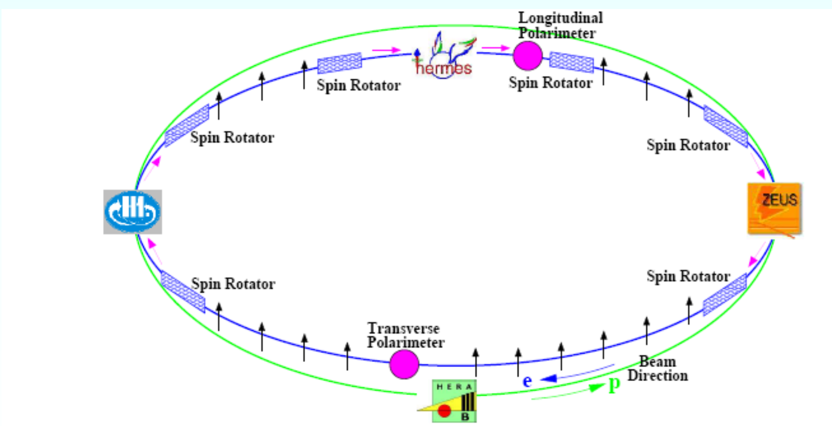
Two distinctive signatures if $\phi_S \neq 0$ (transversely polarized target)

$$d\sigma_{UT}^{Sivers} \propto |S_T| \sin(\phi - \phi_S) \cdot \sum_q e_q^2 I \left[\frac{\vec{p}_T \cdot \hat{P}_{h\perp}}{M_h} f_{1T}^{\perp q}(x, p_T^2) \otimes D_1^q(z, k_T^2) \right]$$

hermes

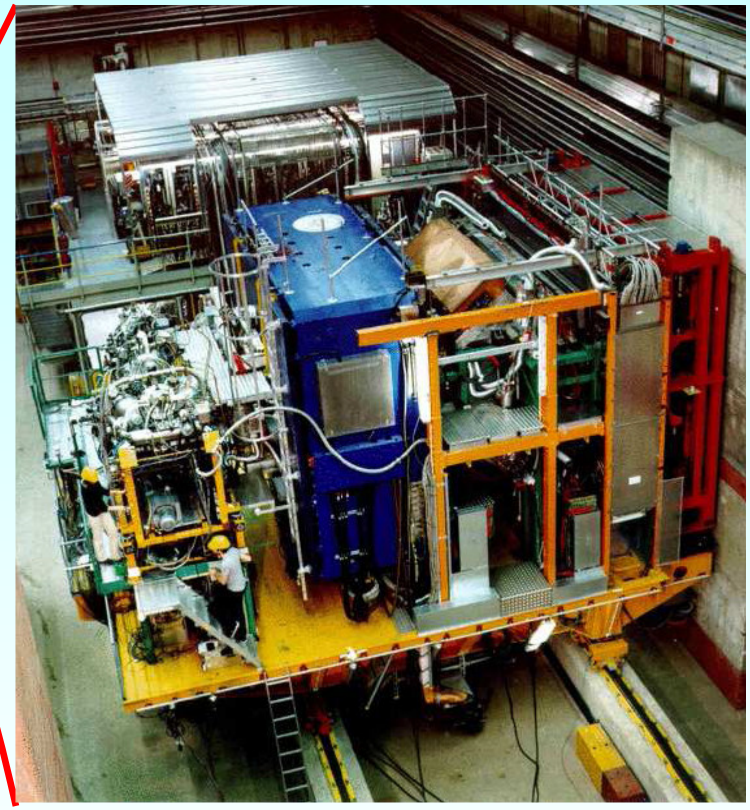
$I[...]$ = convolution integral over initial $(\vec{p}_T)$ and final $(\vec{k}_T)$ quark transverse momenta

The HERA storage ring (DESY)

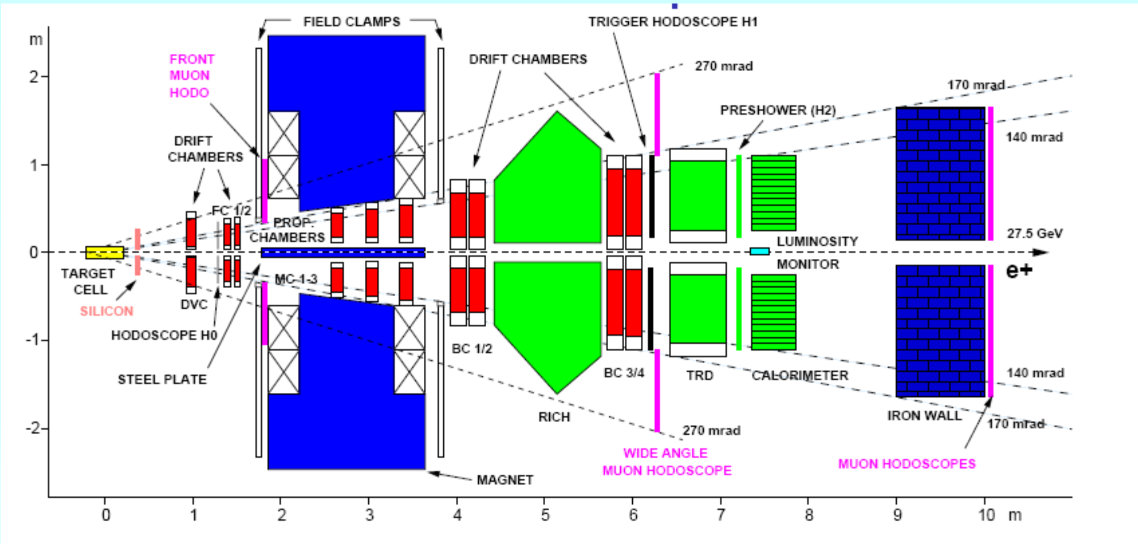


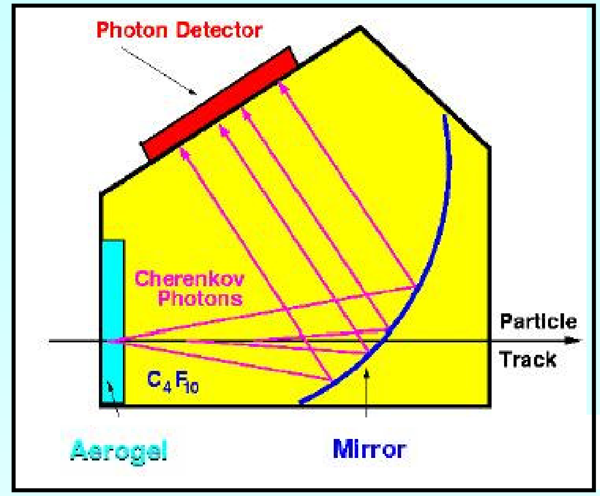
- 27.5 GeV e^+/e^- beam
- Self-polarizing through Sokolov-Ternov-Effect
- Average beam polarization of about 55%

The HERMES Spectrometer



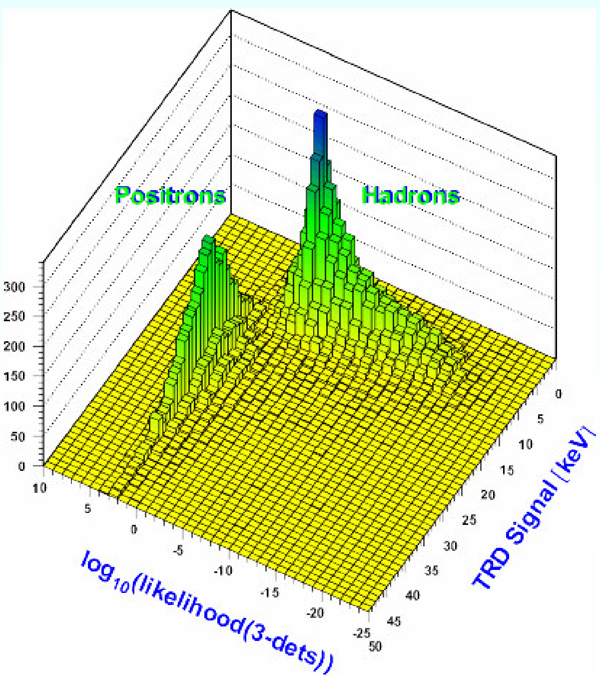
- Fixed target experiment
- Internal polarized gas target
- Relatively large acceptance
- Very good particle identif.





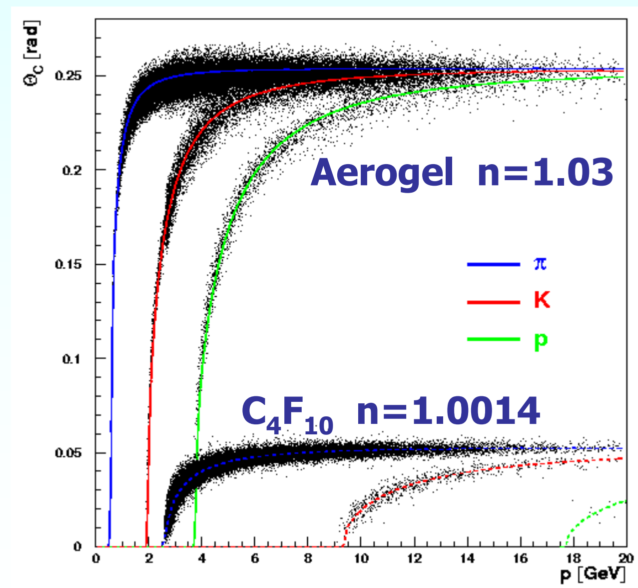
hadron separation

Particle Identification:



TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%



Hadron: π ~ 98%, K ~ 88% , P ~ 85%

Full HERMES transverse data set (2002-2005)

(transversely polarized hydrogen target: $\langle P \rangle \approx 73\,\%$)

	inclusive DIS	semi–inclusive DIS
four momentum transfer	$Q^2 > 1\,\mathrm{GeV}^2$	$Q^2 > 1\,\mathrm{GeV}^2$
squared mass of the final state	$W^2 > 4\,\mathrm{GeV}^2$	$W^2 > 10\,\mathrm{GeV}^2$
fractional energy transfer	$0.1 < y < 0.95$	$y < 0.95$
Bjorken scaling variable	$0.023 < x < 0.4$	$0.023 < x < 0.4$
virtual photon – hadron angle		$\theta_{\gamma^* h} > 0.02\,\mathrm{rad}$
hadron momentum		$2\,\mathrm{GeV} < P_h < 15\,\mathrm{GeV}$
energy fraction (extended range)		$0.2 < z < 0.7$

The selected SIDIS events are used to extract the Collins and Sivers amplitudes through a Maximum Likelihood fit using the PDF:

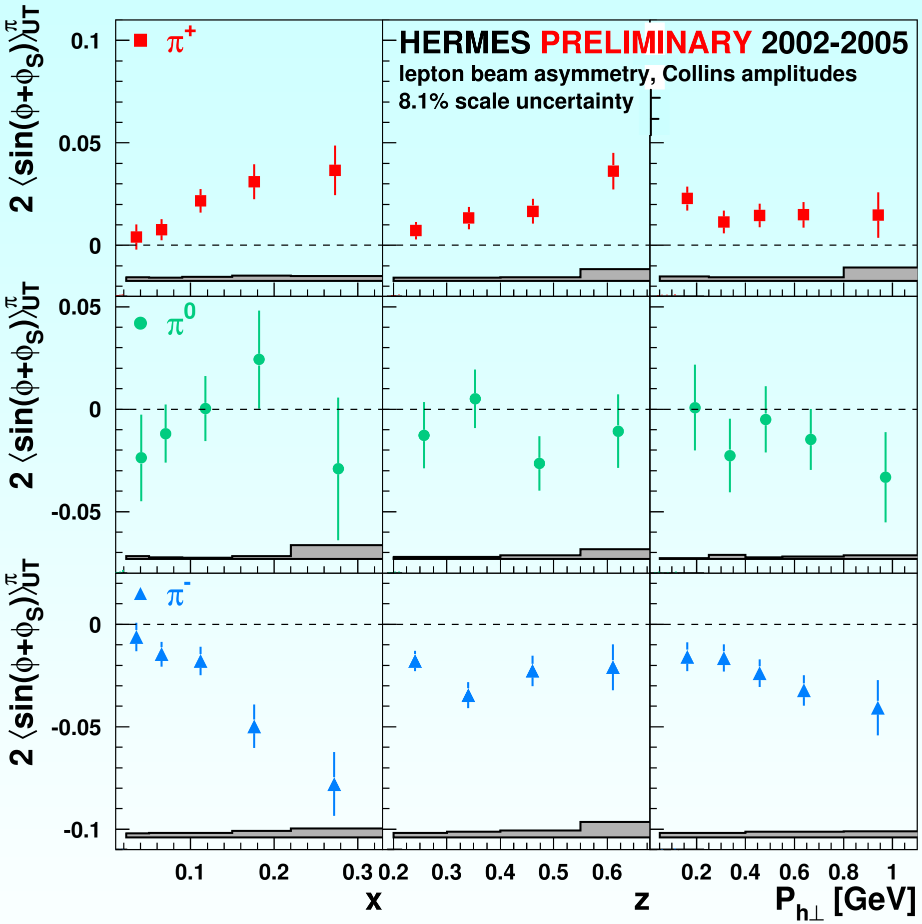
$$L = \prod_i \left(F_i\right)^{w_i}$$

$$F_i\left(\langle \sin(\phi \pm \phi_S)\rangle^h_{UT}, P, \phi, \phi_S\right) \propto 1 +$$

$$P\left[2\langle \sin(\phi + \phi_S)\rangle^h_{UT} \sin(\phi + \phi_S) + 2\langle \sin(\phi - \phi_S)\rangle^h_{UT} \sin(\phi - \phi_S) + \right.$$

$$\left. 2\langle \sin(3\phi - \phi_S)\rangle^h_{UT} \sin(3\phi - \phi_S) + 2\langle \sin(2\phi - \phi_S)\rangle^h_{UT} \sin(2\phi - \phi_S) + 2\langle \sin(\phi_S)\rangle^h_{UT} \sin(\phi_S)\right]$$

Collins moments for pions (2002-2005)



Systematic errors (shaded bands) dominated by hadron misidentification

- positive amplitude for π^+
- ~ 0 amplitude for π^0
- negative amplitude for π^-

$$\begin{cases} u \Rightarrow \pi^+ \ ; \ d \Rightarrow \pi^- \ (fav) \\ u \Rightarrow \pi^- \ ; \ d \Rightarrow \pi^+ \ (unfav) \end{cases}$$

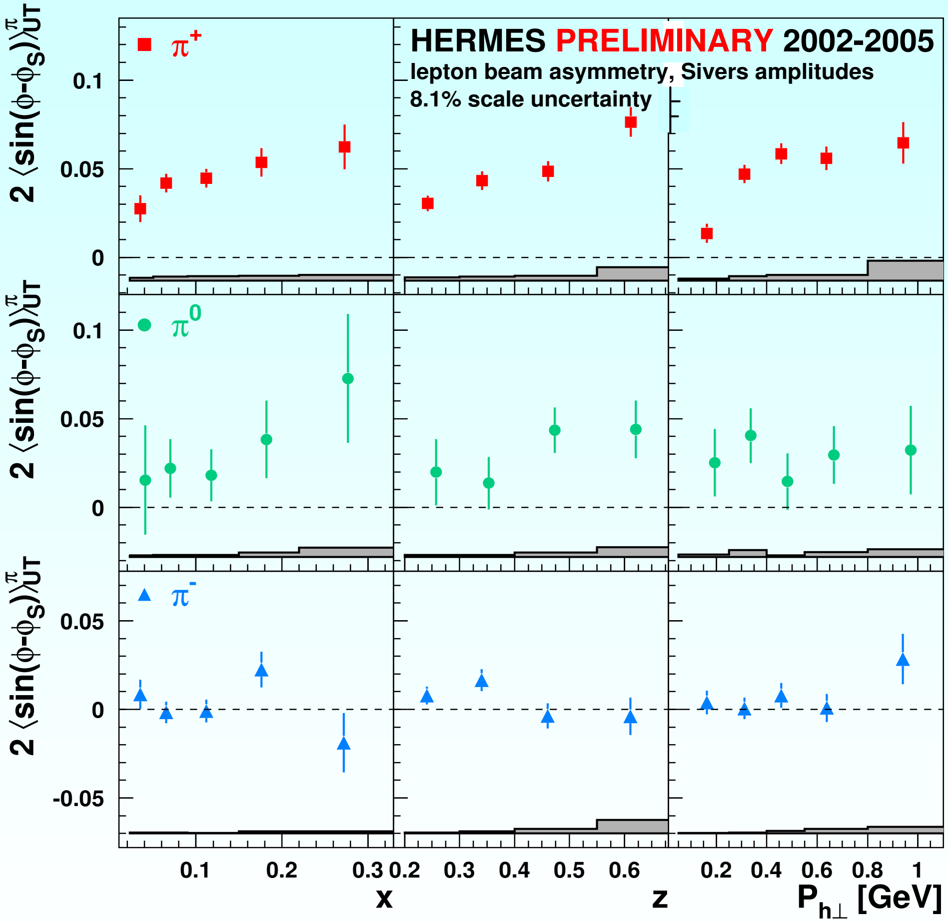
the large negative π^- amplitude suggests disfavored Collins function with opposite sign:

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

$$\propto I[\delta q(x) H_1^{\perp q}(z)] \neq 0$$

first evidence for **non-zero Transversity and Collins functions**

Sivers moments for pions (2002-2005)



- positive amplitude for π^+
- positive amplitude for π^0
- amplitude ~ 0 for π^-

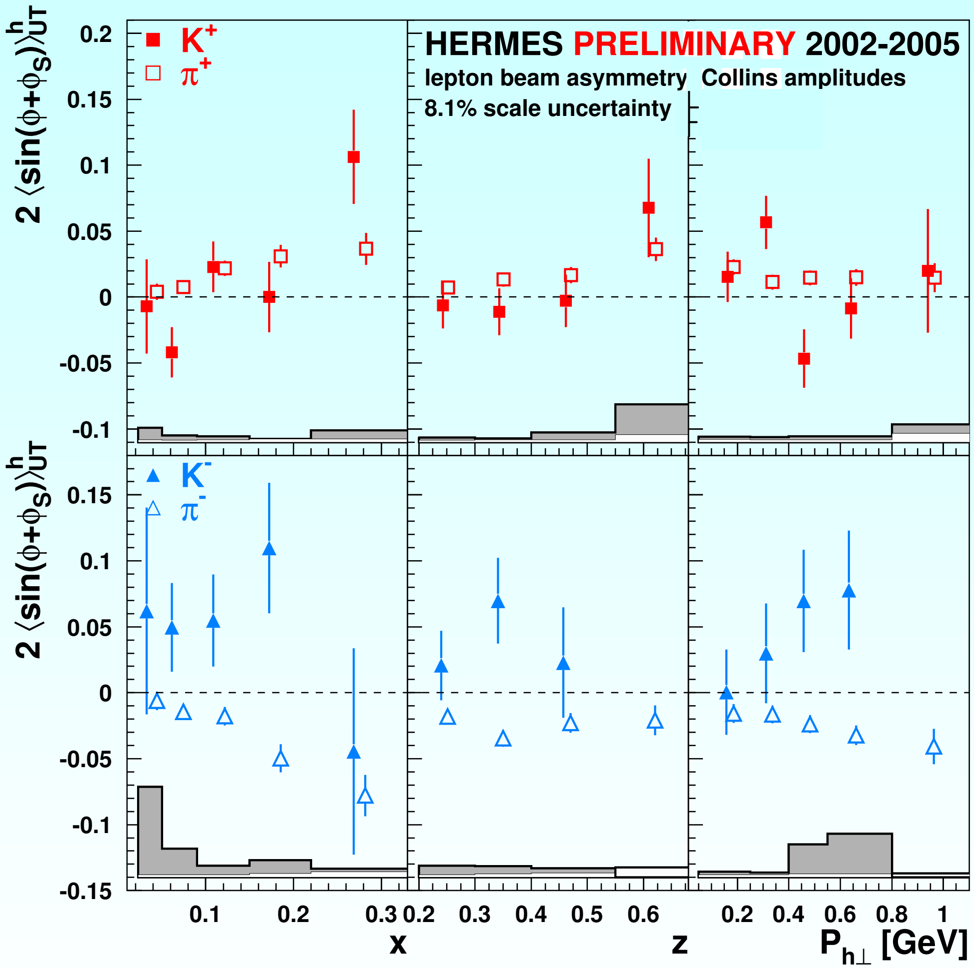
$$\propto I[f_{1T}^{\perp q}(x) D_1^q(z)] \neq 0$$

first evidence for non-zero Sivers func.

indirect evidence of non-zero quark orbital angular momentum

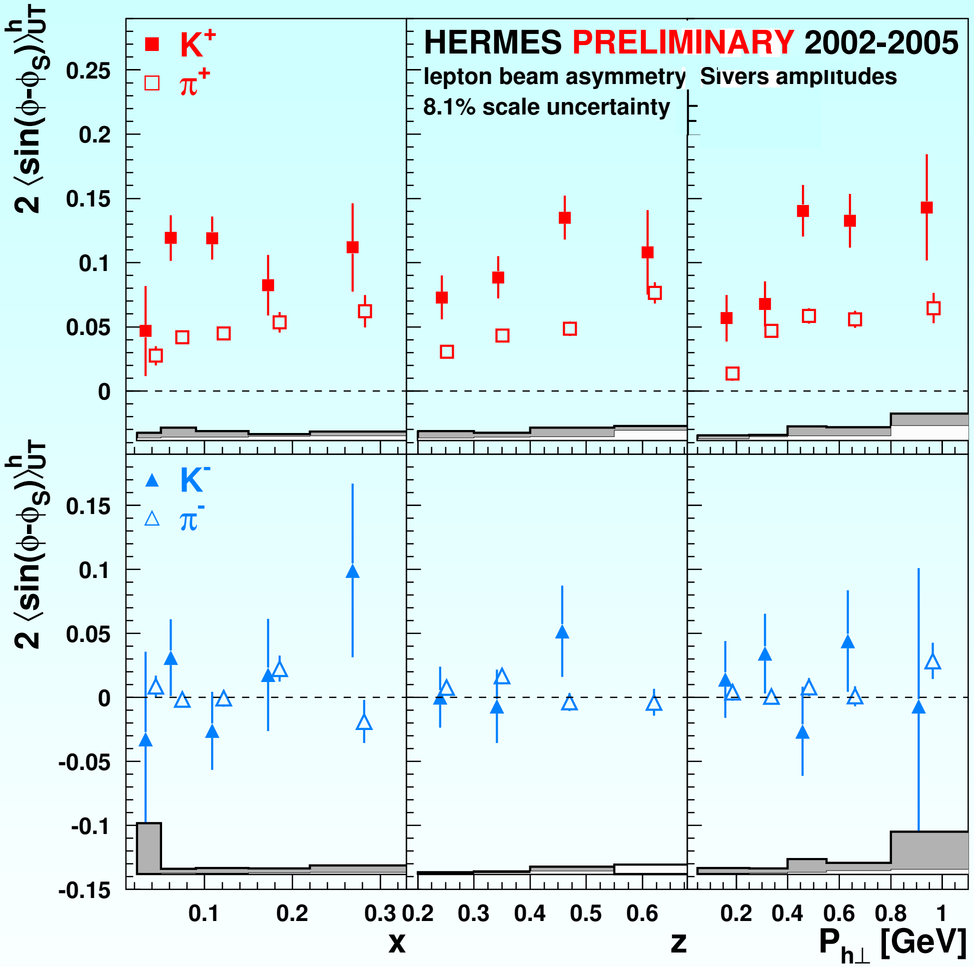
Extraction of the Sivers function is possible since unpol. FF $D_1^q(z)$ is known!

Pions-Kaons comparison: Collins moments



- K^+ amplitudes consistent with π^+ (expected due to u-quark dominance)
- K^- and π^- amplitudes with opposite sign (…but $K^-(\bar{u}s)$ is a fully sea object)

Pions-Kaons comparison: Sivers moments

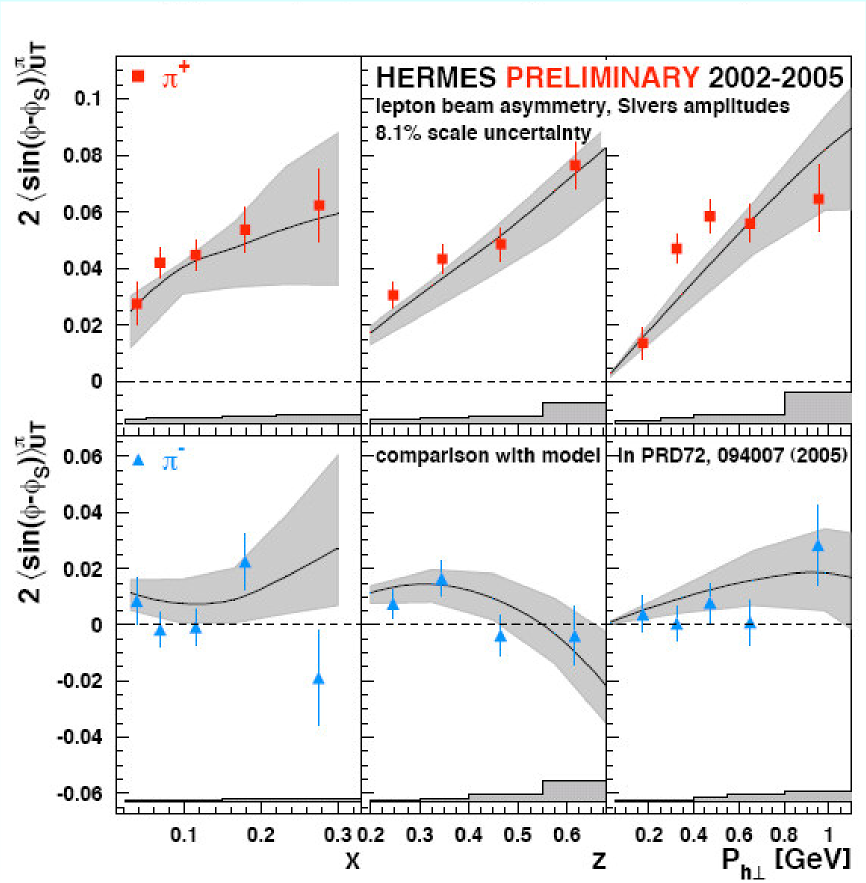


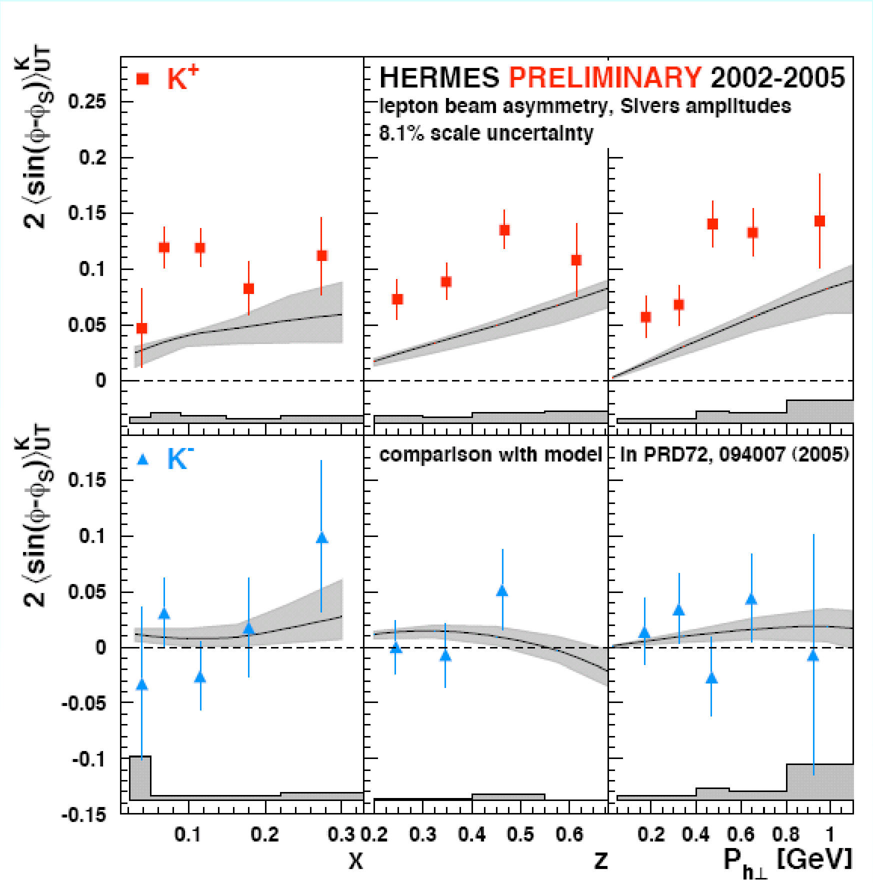
- **K⁺ amplitude is 2.3±0.3 times larger than for π⁺:**
  conflicts with usual expectations based on u-quark dominance
  suggests substantial magnitudes of the Sivers function for the sea quarks

- Both K^- and π^- amplitudes are consistent with zero

Sivers amplitudes vs. Anselmino's fit/predictions

[Anselmino et al., Phys. Rev. D72, 094007]
• using Gaussian widths for intrinsic p_T
• using Kretzer fragmentation functions

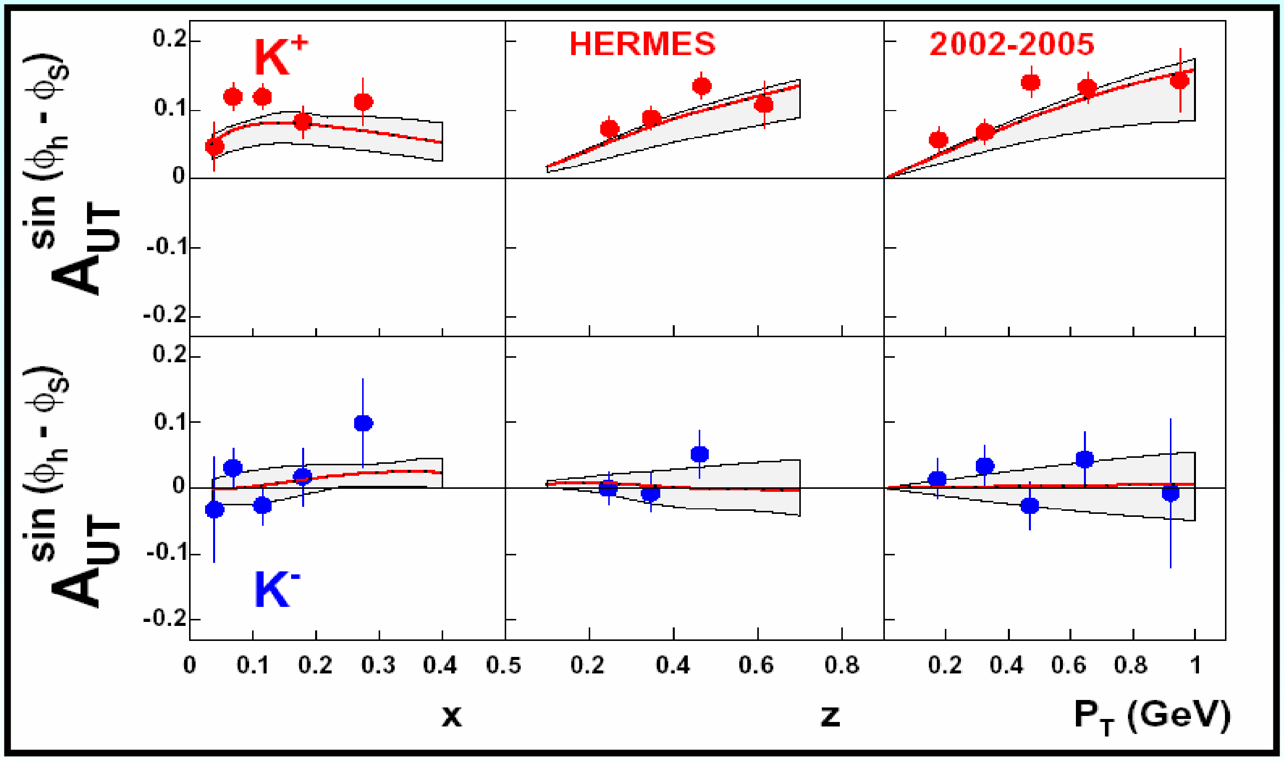




pions don't constrain sea quarks ➡ predictions for K+ fail to reproduce our data

… and using de Florian, Sassot, Stratmann fragmentation functions

[arXiv:hep-ph/0703242v1 22 Mar 2007]



(...from Anselmino's talk @ The 6th Circum-Pan-Pacific Symposium on High Energy Spin Physics July 30 - August 2 2007 Vancouver BC)

Conclusions

HERMES: most precise data on a transversely polarised hydrogen target

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

→ clear evidence of non-zero Sivers function

→ (indirect) evidence for non-zero quark orbital angular momentum

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

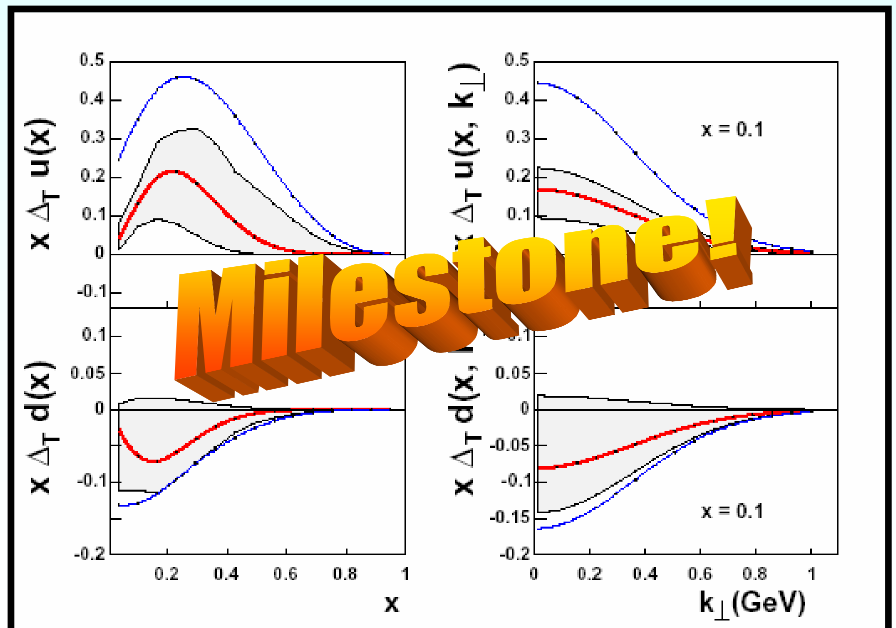
→ enables first extraction of transversity distribution

[Anselmino et al. PRD75 (2007)]

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

(H) (D)

BELLE



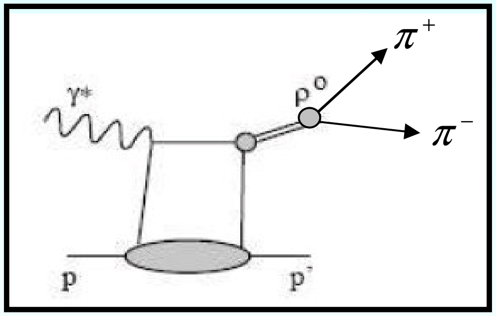
Back-up slides

The isospin triplet of π-mesons is reflected in a relation for any SSA amplitudes:

$$2\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^+}+\left(\frac{\sigma^{\pi^-}}{\sigma^{\pi^+}}\right)\cdot 2\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^-}-\left(1+\frac{\sigma^{\pi^-}}{\sigma^{\pi^+}}\right)\cdot\langle\sin(\phi\pm\phi_S)\rangle_{UT}^{\pi^0}=0$$

fulfilled by the extracted amplitudes !!

"Contamination" by decay of exclusively produced vector mesons is not negligible



up to 16% for pions

What about the kaons?

...below 5%!!!