Transversity & friends from HERMES

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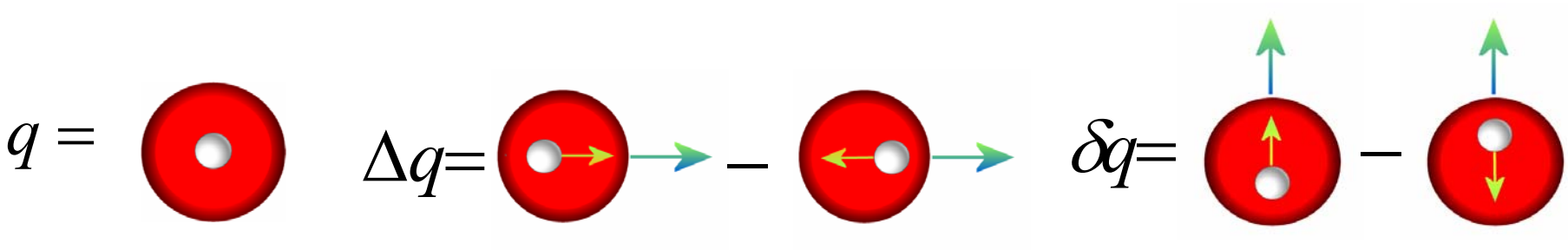
INFN Frascati

outline:

- a very brief introduction
- 1 and 2 hadron production: transversity + Sivers fct.
- theory meets experiments

quark structure of the nucleon



unpolarised quarks and nucleons

longitudinally polarised quarks and nucleons

transversely polarised quarks and nucleons

[also: h_1^q, $\Delta_T q$]

δq: *helicity-flip of both nucleon and quark*

δq is *chiral-odd* → **needs a chiral odd partner:**

$$\sigma^{ep\to ehX} \propto \sum_q \sigma^{eq\to eq} \otimes \delta q(x) \otimes FF^{q\to h}(z)$$

chiral-odd PDF

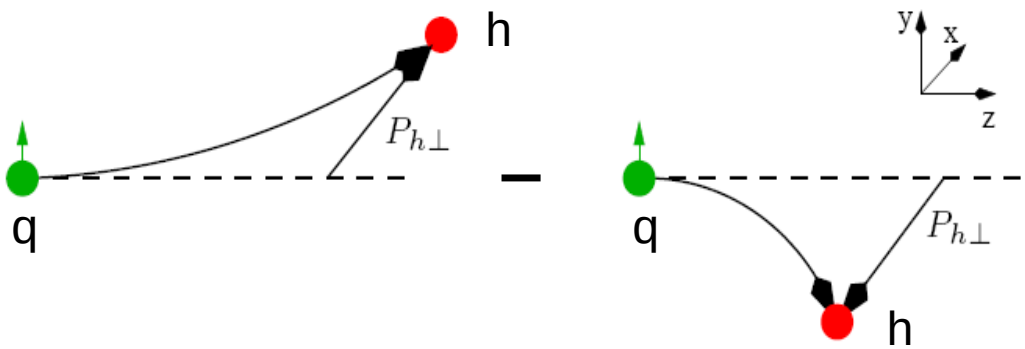
chiral-odd FF

chiral-even

chiral-odd fragmentation function acts as polarimeter of transverse quark polarisation

1hadron production: "*Collins-effect*"

- ***Collins FF*** $H_1^{\perp}(z,k_T^2)$ correlates *transverse spin* of fragmenting quark and *transverse momentum* $P_{h\perp}$ of produced hadron h



→ left-right (azimuthal) asymmetry in the direction of the outgoing hadron

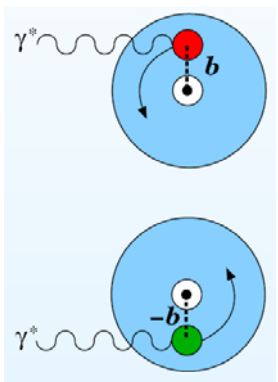
our observable: single-spin azimuthal asymmetry

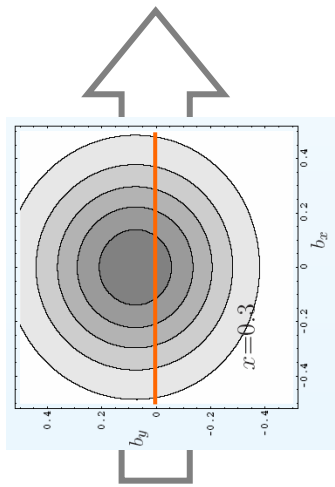
is this observable unique?

"*Sivers-effect*"

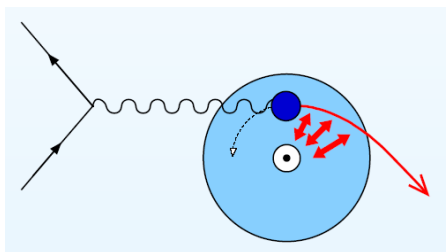
- another mechanism that produces single-spin azimuthal asymmetries:

Sivers distribution function : distribution of unpolarised quarks in a transversely polarised nucleon → describes *spin-orbit correlations*





$u_X\,(x,\boldsymbol{b}_\perp)$



[Matthias Burkardt]

a non-zero Sivers fct. requires non-zero orbital angular momentum !

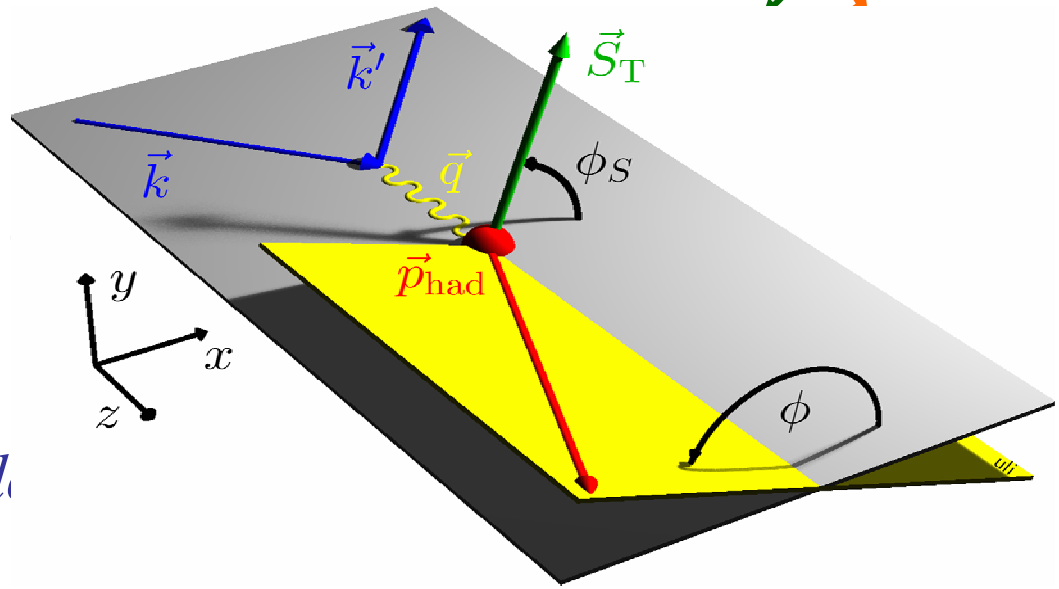
polarised DIS^h cross section

σ_{UU}

$$d\sigma^h(x,y,z,P_{h\perp},\phi,..) =$$

$$d\sigma_{UU} + \cos 2\phi\, d\sigma_{UU} + \frac{1}{Q}$$

$q(x)$



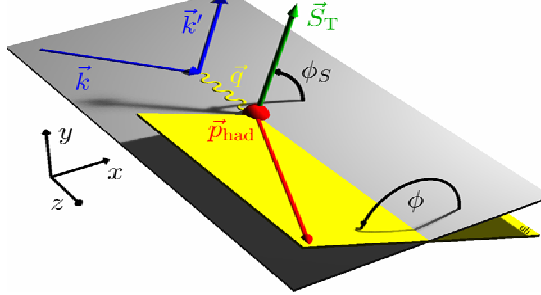
$$+ S_L \left[\sin 2\phi\, d\sigma_{UL} + \frac{1}{Q} \sin\phi\, d\right.$$

$\Delta q(x)$

$$+ S_T \left[\sin(\phi+\phi_S) d\sigma_{UT} + \sin(\phi-\phi_S) d\sigma_{UT} + \sin(3\phi-\phi_S) d\sigma_{UT} + \frac{1}{Q}... \right]$$

$$+ \lambda S_T \left[\cos(\phi-\phi_S) + \frac{1}{Q}... \right] + ...$$

polarised DIS^h cross section



$$d\sigma^h(x,y,z,\boxed{P_{h\perp},\phi,..}) =$$

$$d\sigma_{UU} + \cos 2\phi\, d\sigma_{UU} + \frac{1}{Q}\cos\phi\, d\sigma_{UU} + \lambda\frac{1}{Q}\sin\phi\, d\sigma_{LU}$$

$q(x)$ $h_1^\perp \otimes H_1^\perp$ $\qquad e \otimes H_1^\perp + \ldots$

$$+ S_L\left[\sin 2\phi\, d\sigma_{UL} + \frac{1}{Q}\sin\phi\, d\sigma_{UL}\right] + \lambda S_L\left[d\sigma_{LL} + \frac{1}{Q}\cos\phi\, d\sigma_{LL}\right]$$

$\delta q \otimes H_1^\perp + f_{1T}^\perp \otimes D_1 + h_L \ldots$ $\qquad \Delta q(x)$

$$+ S_T\left[\sin(\phi+\phi_S)d\sigma_{UT} + \sin(\phi-\phi_S)d\sigma_{UT} + \sin(3\phi-\phi_S)d\sigma_{UT} + \frac{1}{Q}\ldots\right]$$

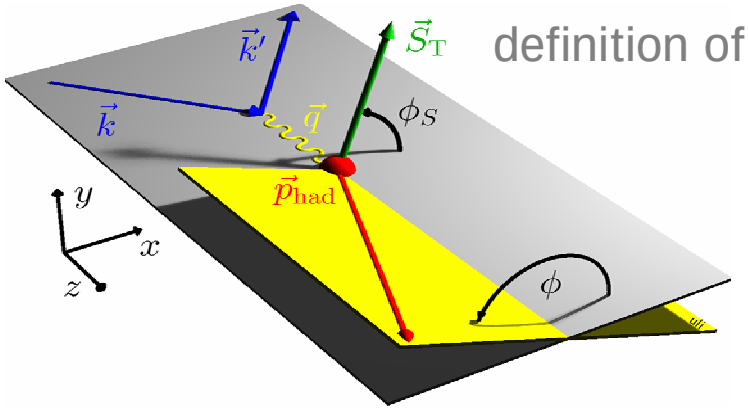
$\delta q \otimes H_1^\perp$ $\qquad f_{1T}^\perp \otimes D_1$

transversity

(Collins effect)

SIDIS with *transversely* polarised targets but not only...

extraction of azimuthal amplitudes



definition of angles + asymmetries acc. to “Trento convention”
[PRD70(2004),117504]

unbinned Maximum Likelihood fit

to the log of the weighted *PDF* :

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

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

$$P[\,2\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{h}\sin(\phi+\phi_S) + 2\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{h}\sin(\phi-\phi_S)$$

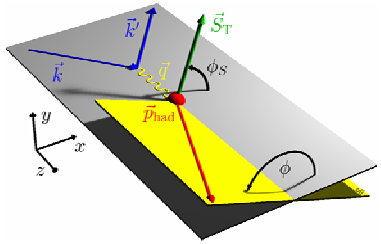
$$+2\left\langle \sin(3\phi-\phi_S)\right\rangle_{UT}^{h}\sin(3\phi-\phi_S) + 2\left\langle \sin(2\phi-\phi_S)\right\rangle_{UT}^{h}\sin(2\phi-\phi_S)$$

$$+2\left\langle \sin(\phi_S)\right\rangle_{UT}^{h}\sin(\phi_S)\,]$$

fixed parameters for: $\left\langle \cos(\phi)\right\rangle_{UU} + \left\langle \cos(2\phi)\right\rangle_{UU}$

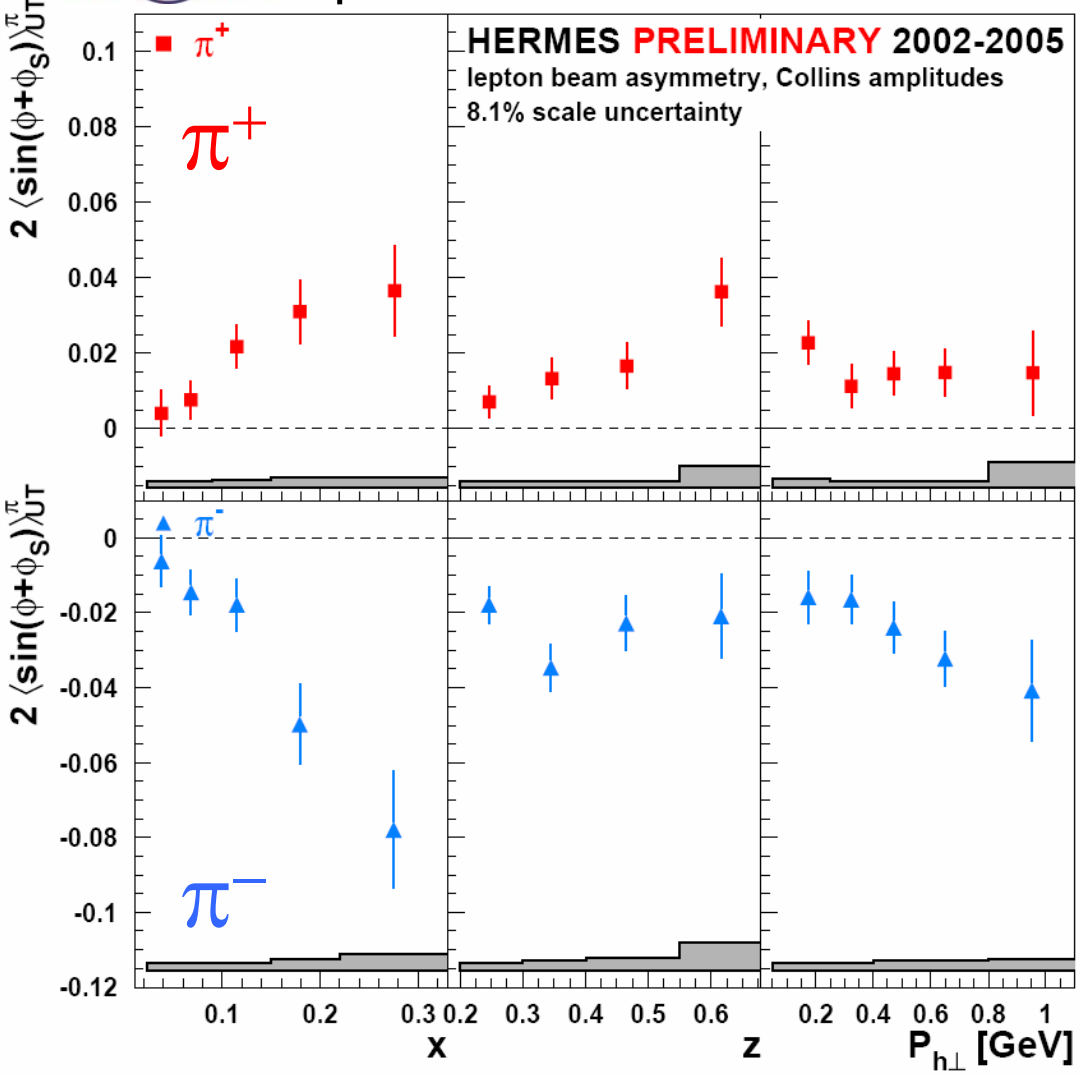
...takes into account cross contamination of moments

Collins asymmetries



$$\delta q(x) \otimes H_1^{\perp q}(z)$$

ep↑→ π X



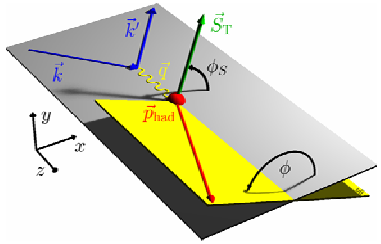
first time: *transversity* & *Collins FF* are **non-zero!**

- π^+ asymmetries positive – no surprise: u-quark dominance and expect $\delta q > 0$ since $\Delta q > 0$

- large negative π^- asymmetries – **ARE** a surprise: suggests the *disfavoured CollinsFF* being large and with oposite sign:

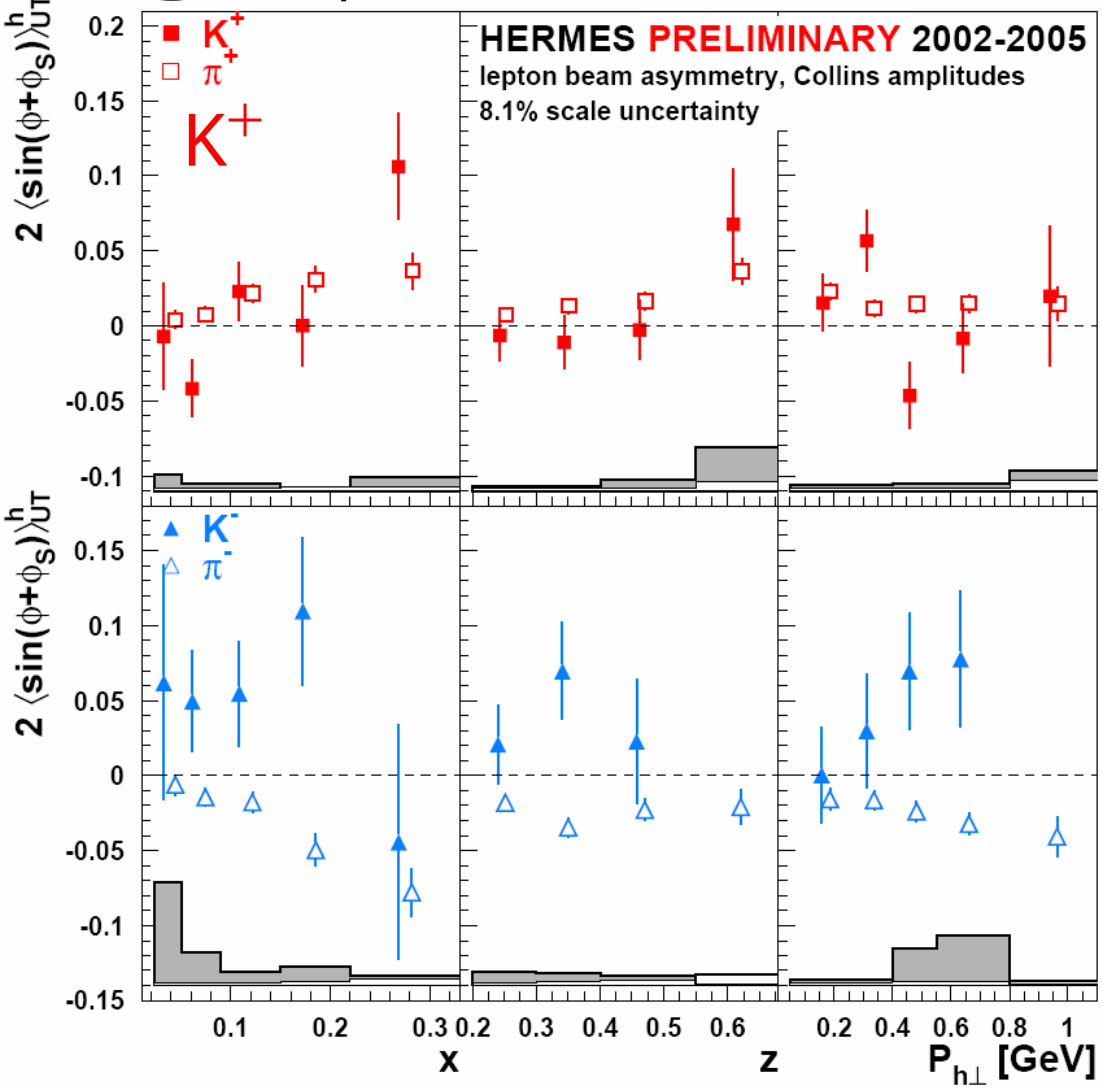
$$H_1^{\perp,\text{disfav}}(z) \approx -H_1^{\perp,\text{fav}}(z)$$

Collins asymmetries



$$\delta q(x) \otimes H_1^{\perp q}(z)$$

ep → K X

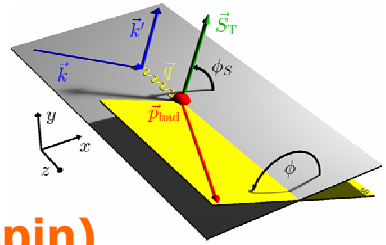


first time: *transversity* & *Collins FF* are **non-zero!**

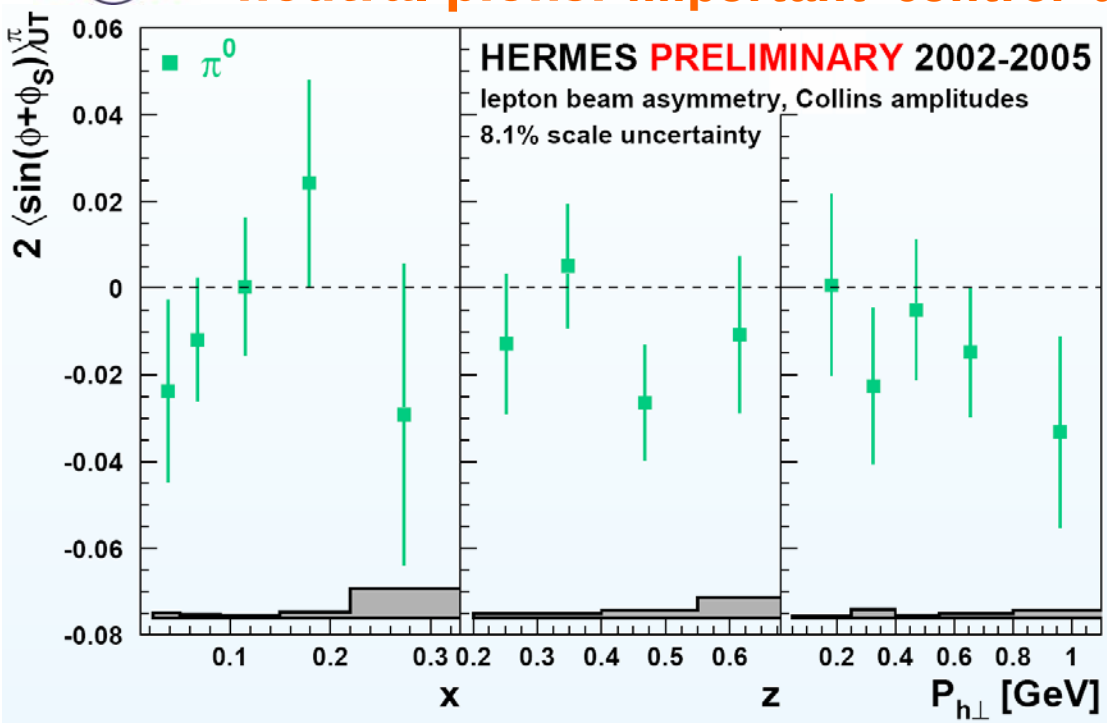
K^+ amplitudes consistent with π^+ amplitudes as expected from u-quark dominance

K^- of opposite sign from π^- (K^- is *all-sea* object)

more Collins asymmetries



neutral pions: important 'control' asymmetry (isospin)



$$\delta q(x) \otimes H_1^{\perp q}(z)$$

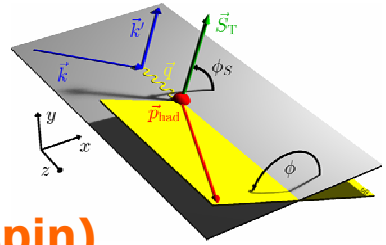
- the isospin triplet of π-mesons is reflected in a relation for any SSA and DSA amplitudes in semi-inclusive DIS ($C = \sigma^{\pi^-}/\sigma^{\pi^+}$):

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

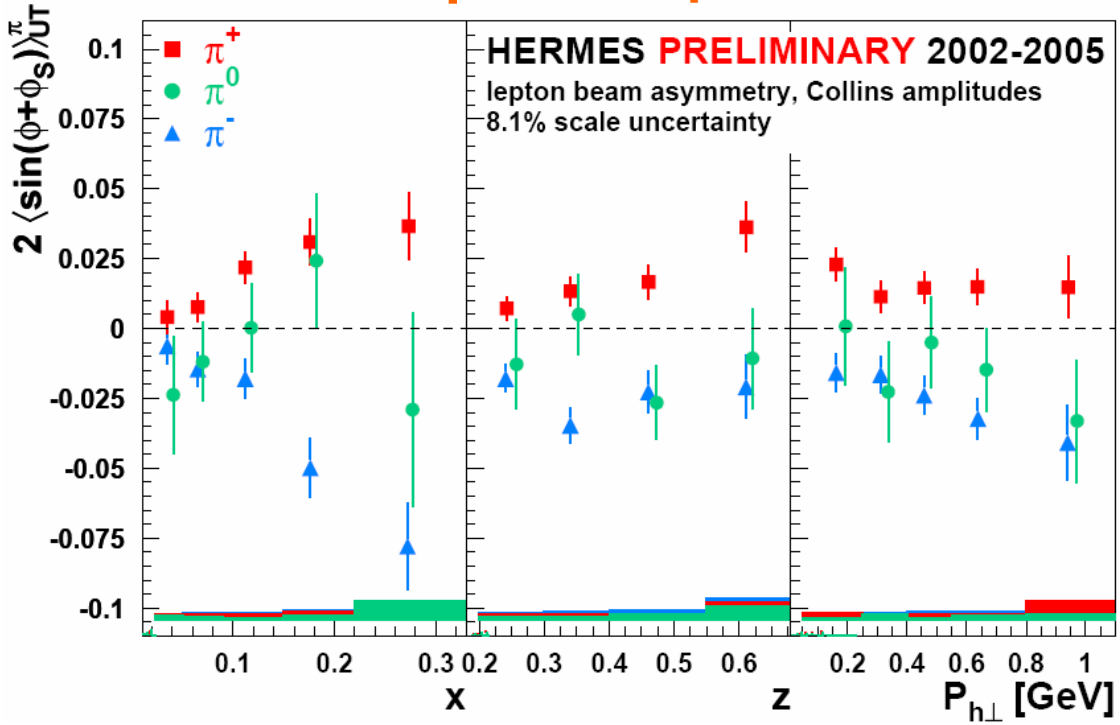
assuming isospin symmetry of the Collins fragmentation function

holds for all tw-2 and tw-3 DF in LO and NLO in α_s

more Collins asymmetries



neutral pions: important 'control' asymmetry (isospin)



$$\delta q(x) \otimes H_1^{\perp q}(z)$$

neutral pions:

results for the three pion charge states are consistent with **isospin symmetry**

- the isospin triplet of π-mesons is reflected in a relation for any SSA and DSA amplitudes in semi-inclusive DIS ($C = \sigma^{\pi^-}/\sigma^{\pi^+}$):

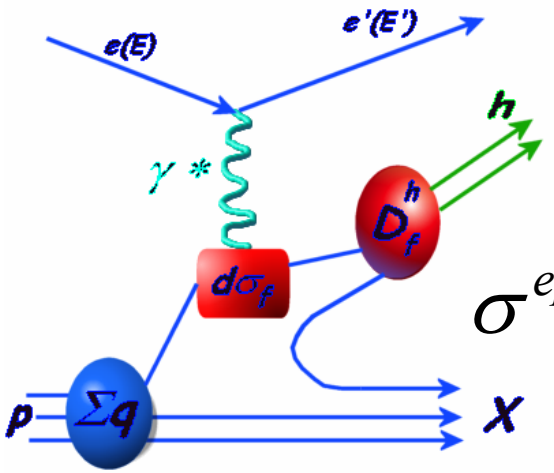
holds for all tw-2 and tw-3 DF in LO and NLO in α_s

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

assuming isospin symmetry of the Collins fragmentation function

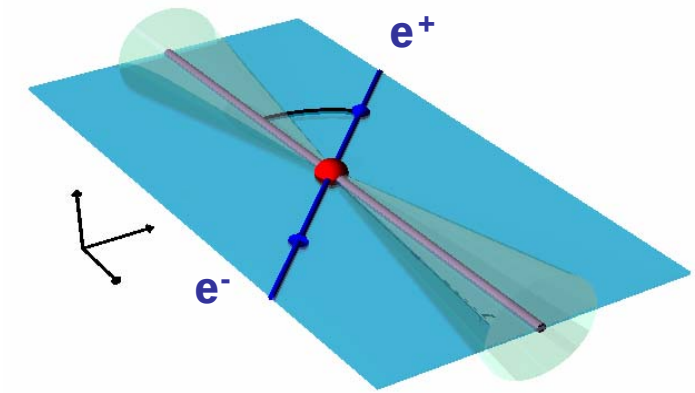
fulfilled!

extracting *transversity*



$$\sigma^{ep\to ehX} \propto \sum_q \sigma^{eq\to eq} \otimes \delta q(x) \otimes FF^{q\to h}(z)$$

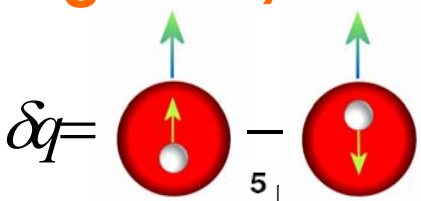
spin-dependent fragmentation function → e^+e^-

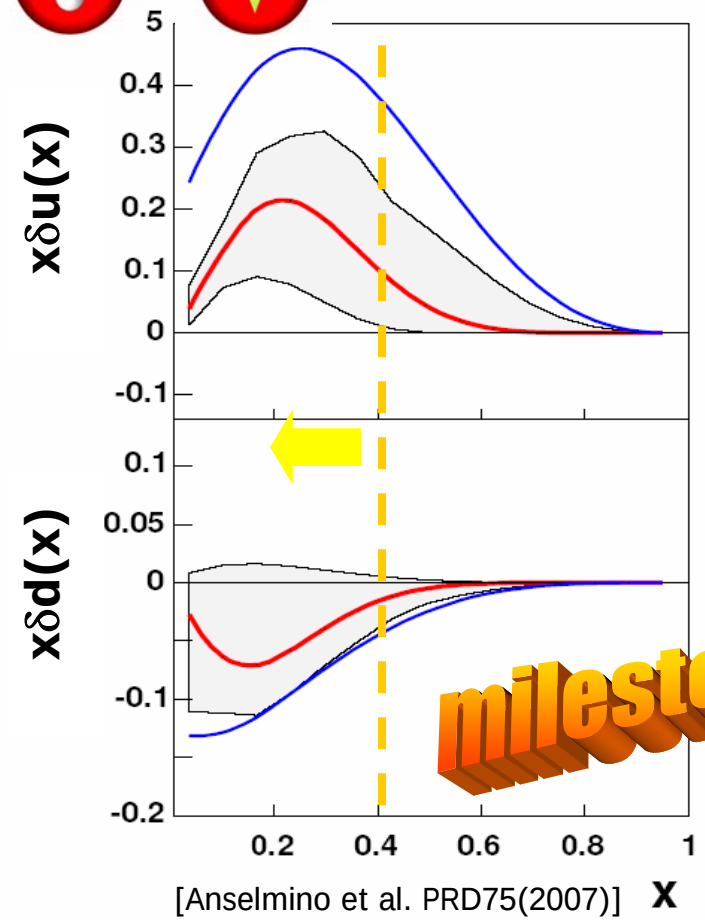


$$e^+e^- \to \pi^+_{\text{jet1}}\ \pi^-_{\text{jet2}}\ X$$

first glimpse of transversity

global, simultaneous fit:

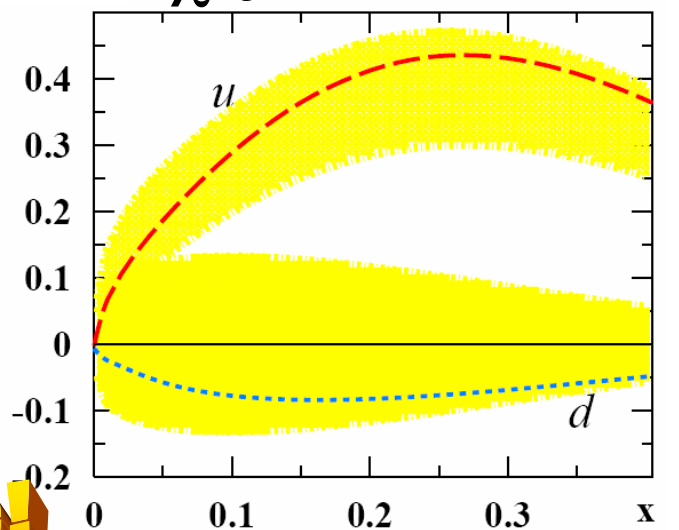




milestone!

compare to a model calculation:

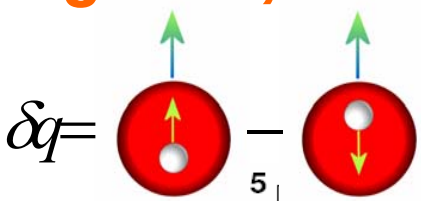
xδq(x) χQSM

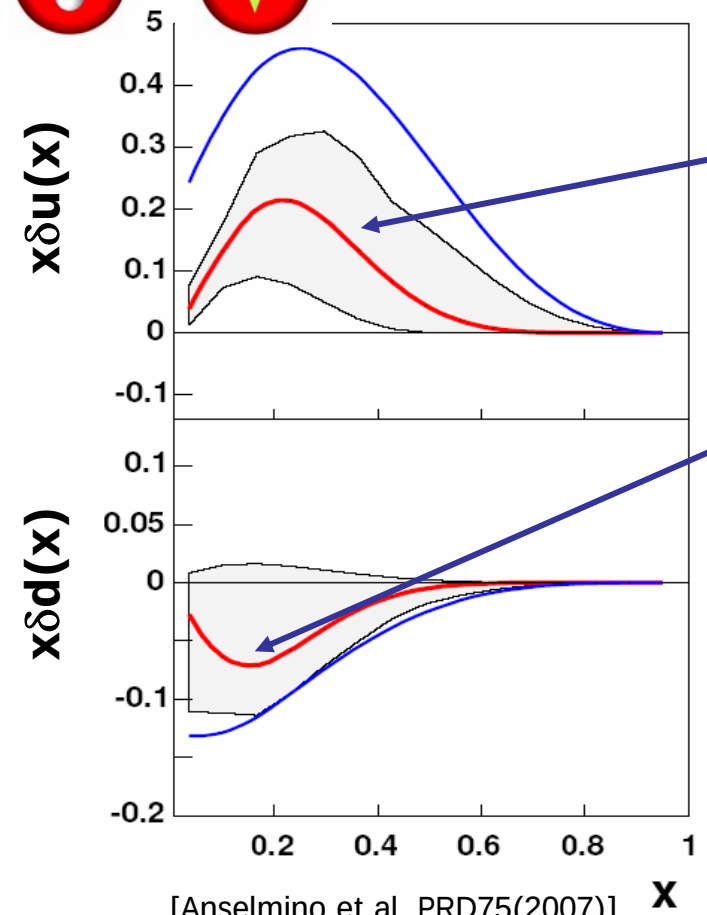


[Efremov,Goeke,Schweitzer PRD73(2006)]

first glimpse of transversity

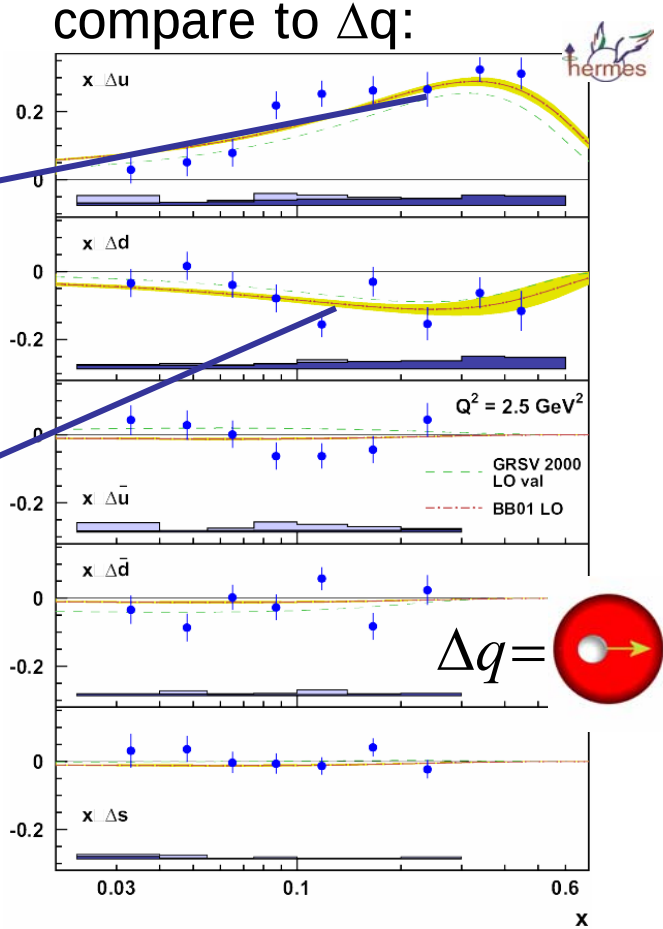
global, simultaneous fit:





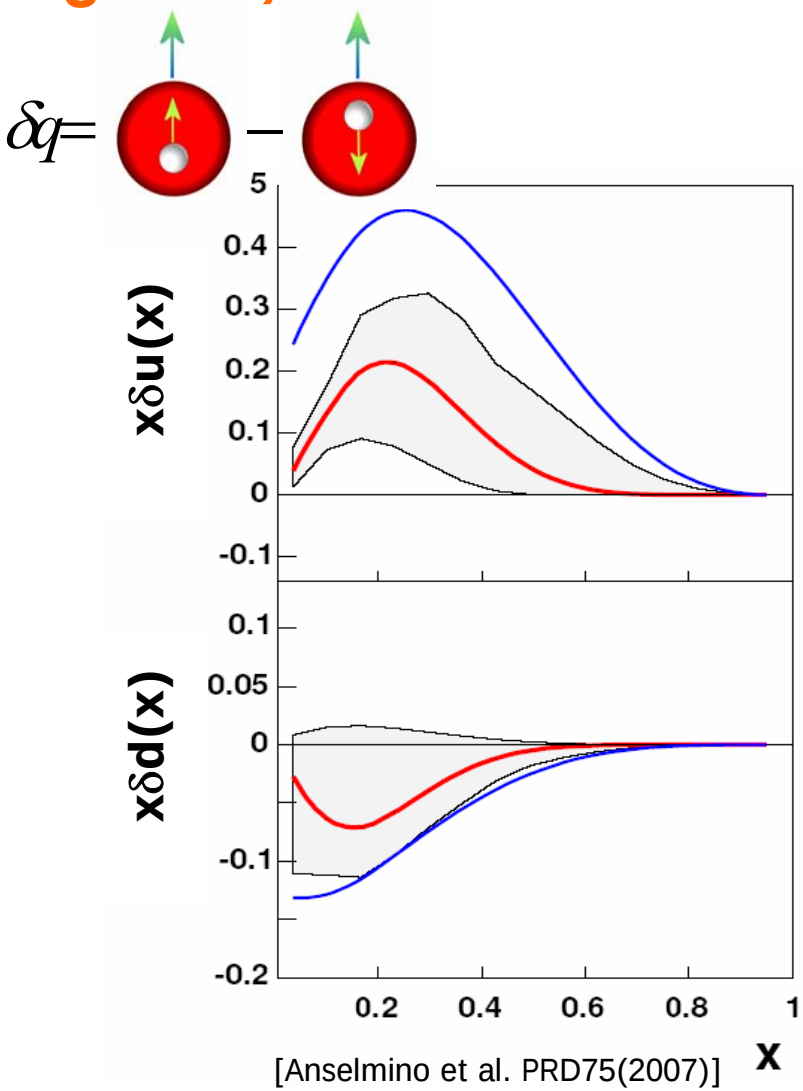
[Anselmino et al. PRD75(2007)]

compare to Δq:



first glimpse of transversity

global, simultaneous fit:



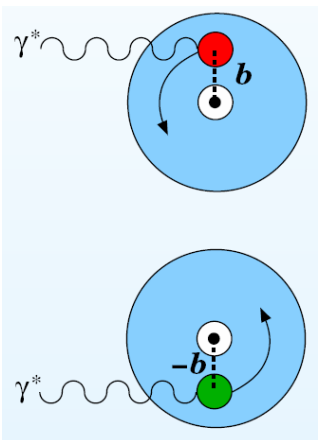
looking forward:

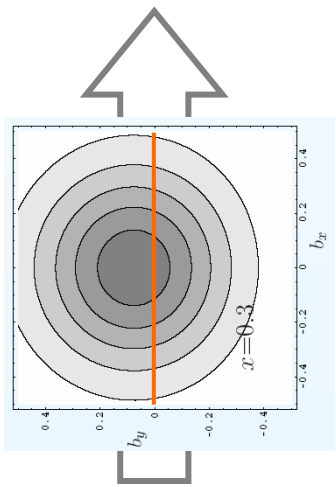
- include new high statistic data from BELLE and HERMES; identified hadrons from COMPASS
- awaiting proton results from COMPASS

→ extending to lower x

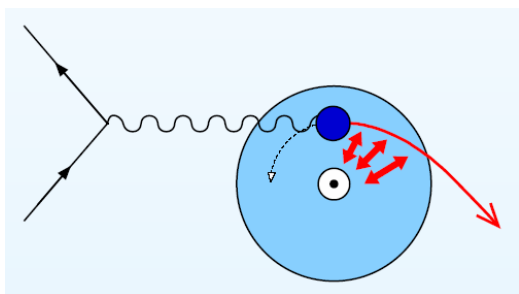
spin-orbit structure

Sivers function:





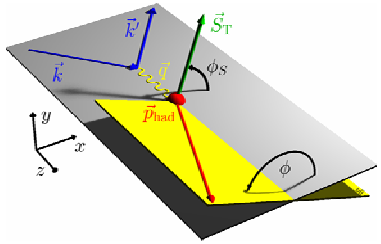
$u_X\,(x,\boldsymbol{b}_\perp)$

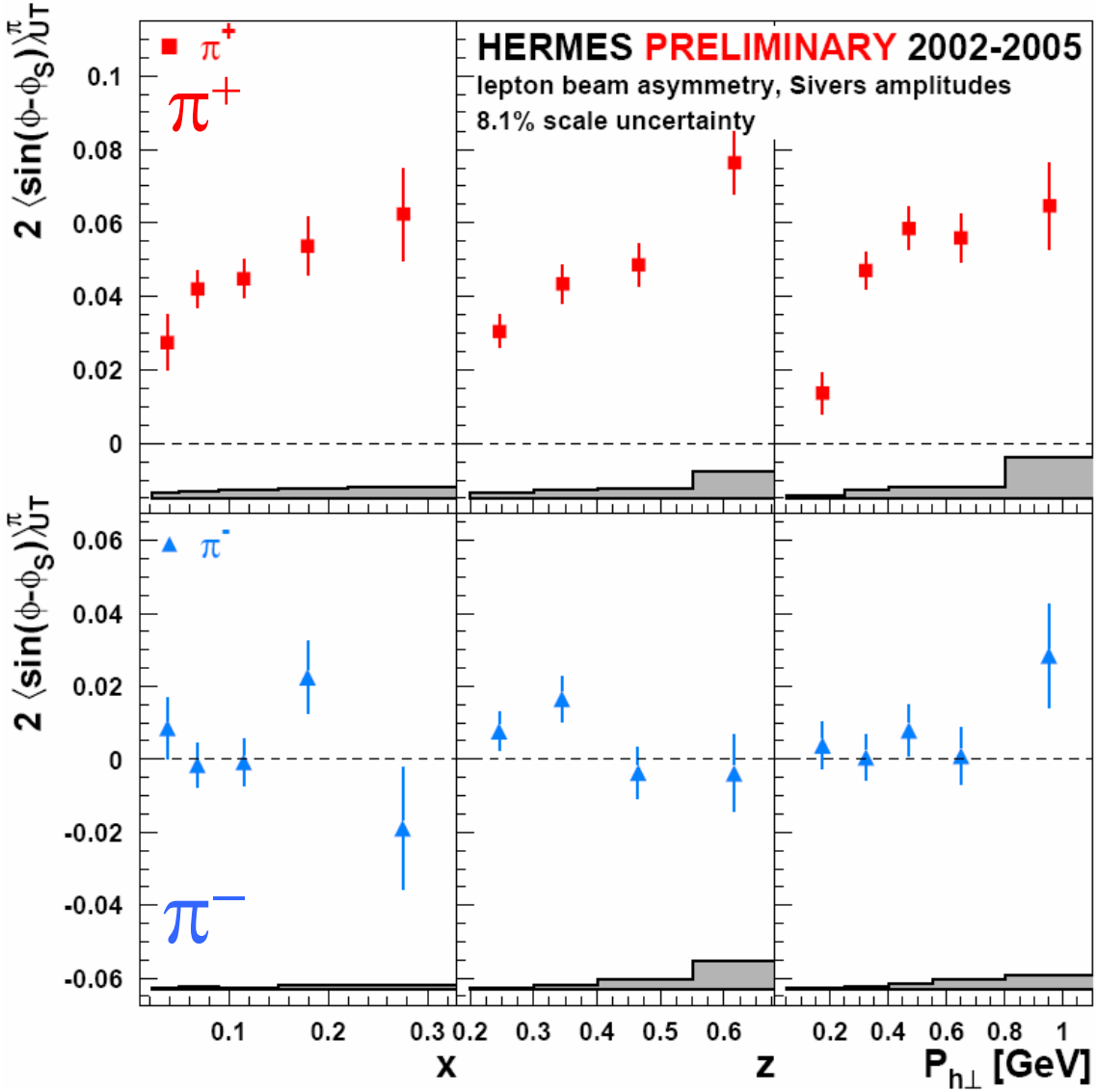


[Matthias Burkardt]

a non-zero Sivers fct. requires non-zero orbital angular momentum !

Sivers asymmetries



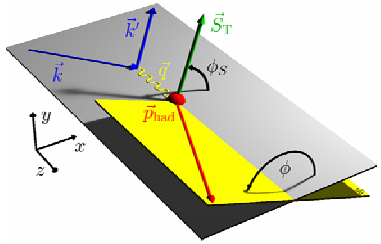


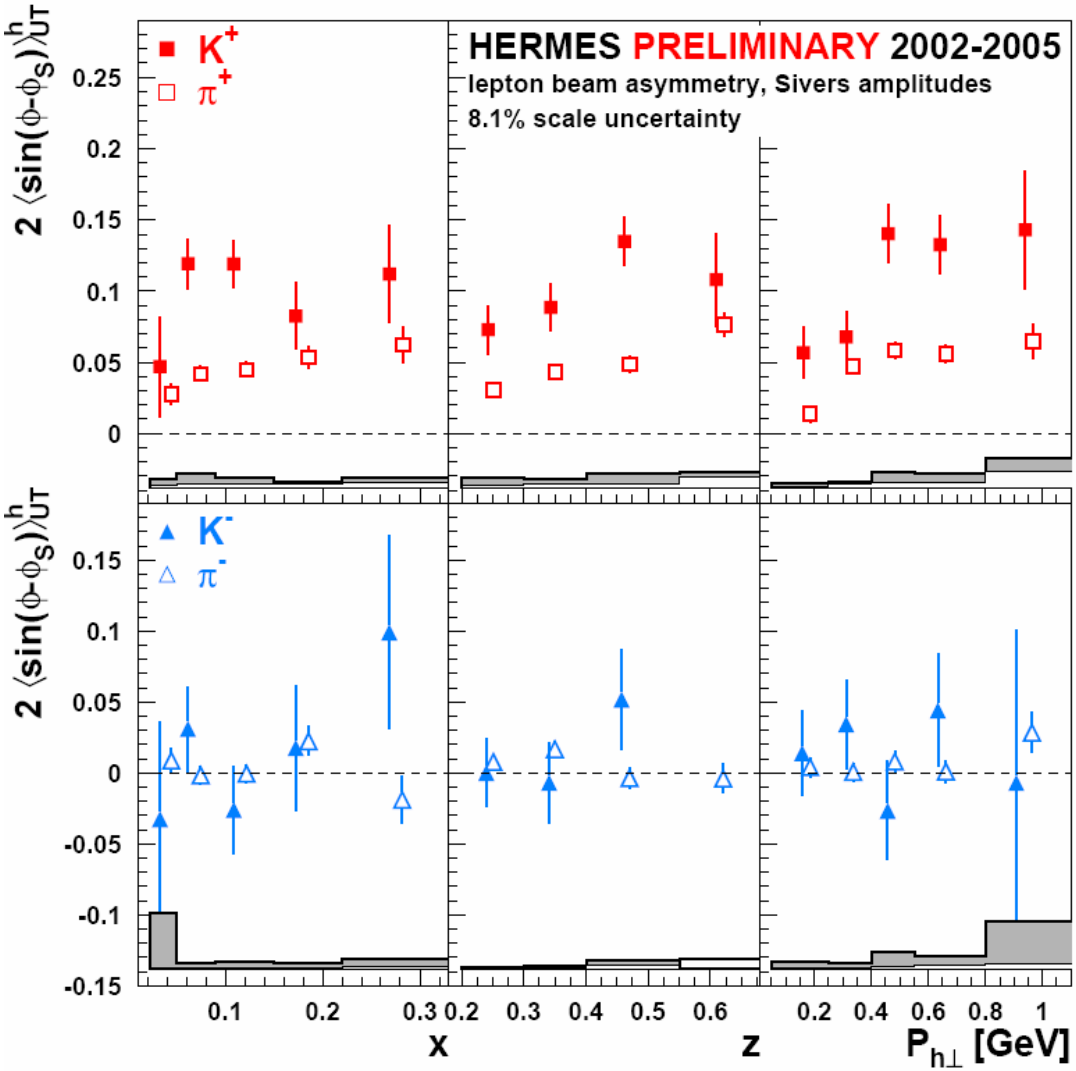
$$f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

π^+ are subtantial and positive:

- first unambiguous evidence for a **non-zero T-odd** distribution function in DIS
- a signature for quark orbital angular momentum !

Sivers asymmetries





$$f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

- SURPRISE:

K^+ amplitude 2.3±0.3 times larger than for π^+

→ conflicts with usual expectations based on u-quark dominance

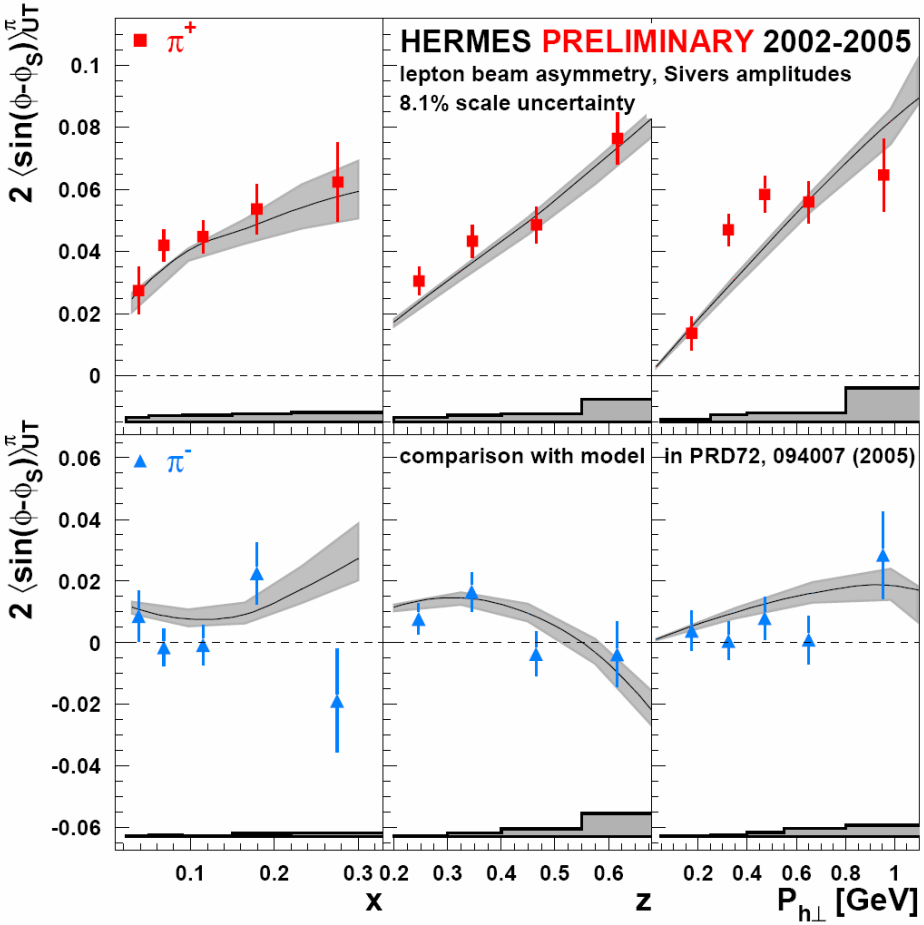
→ suggests substantial magnitude of the Sivers fct. for sea quarks

$$K^+ = |u\bar{s}\rangle \quad \pi^+ = |u\bar{d}\rangle$$

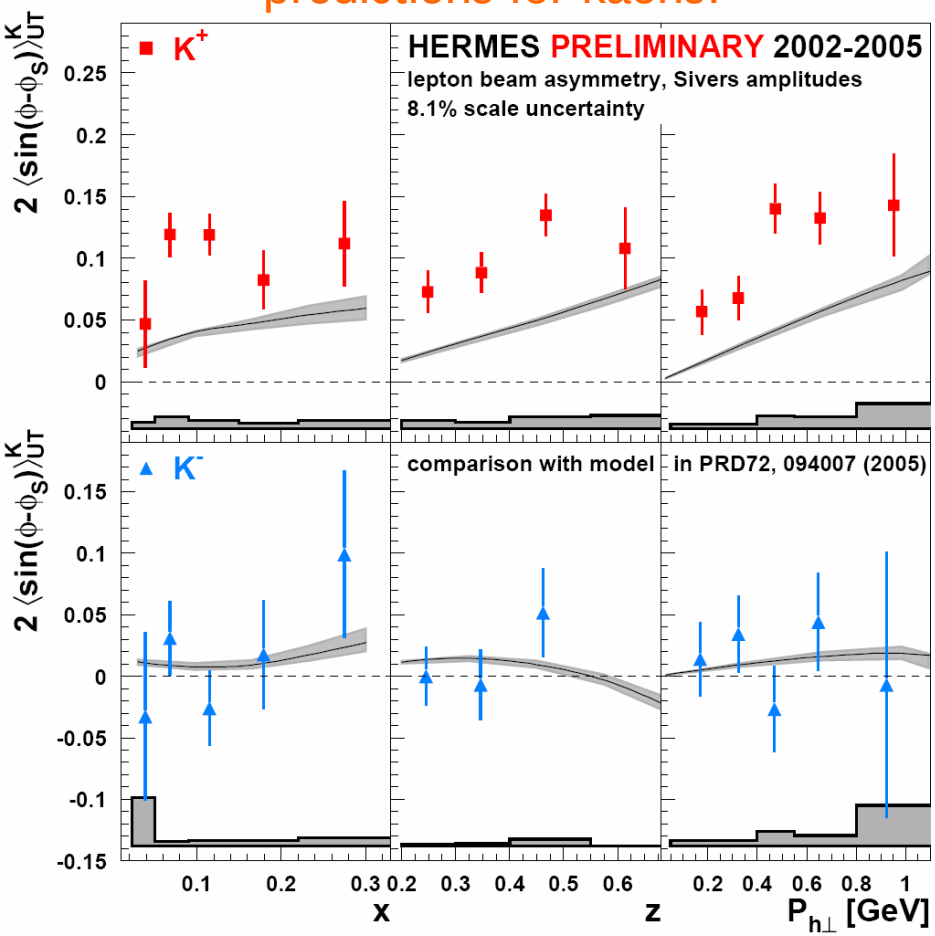
comparison to models

[Anselmino et al. PRD72(2005)]

excellent description of pion data
but: cannot constrain sea



predictions for kaons:



kaon data suggest that sea quark contribution may be significant

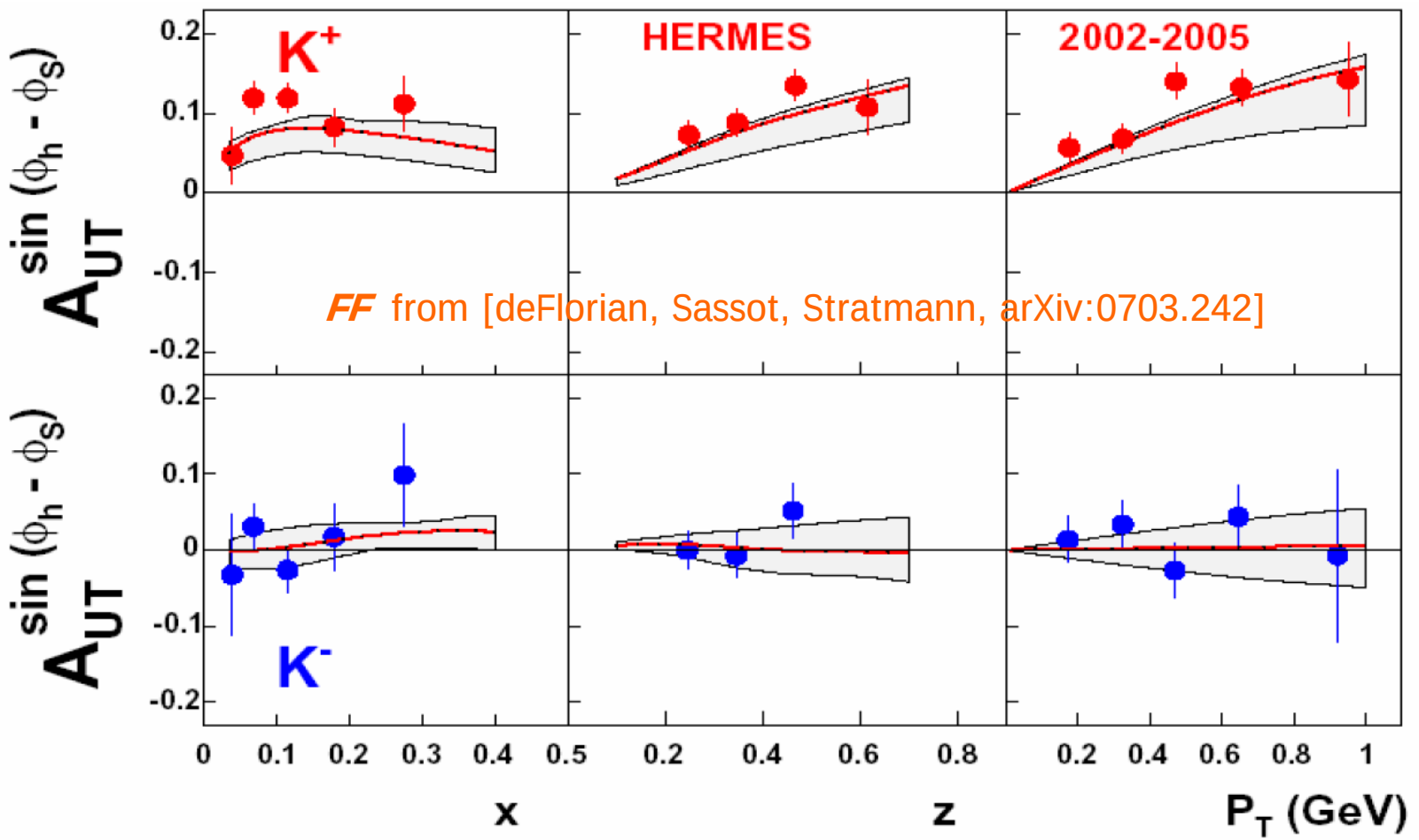
→ see talk from D'Alesio about choice of fragmentation functions

comparison to models

[Anselmino et al. PRD72(2005)]

excellent description of pion data

[M. Anselmino @PACSPIN07]

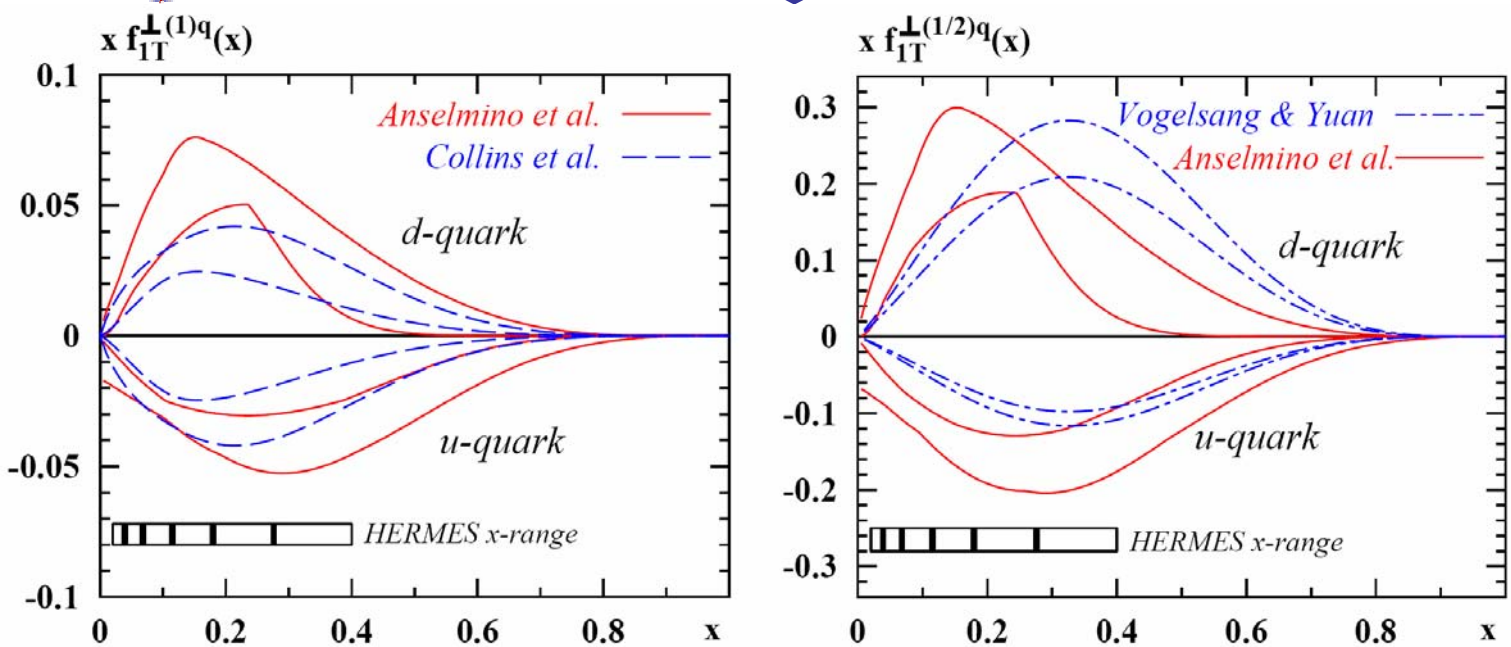


→ see talk from D'Alesio about choice of fragmentation functions

extracting the *Sivers* function

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

usual unpolarised fragmentation function



ToDo:

crucial test of pQCD:

$$(f_{1T}^{\perp q})_{DIS} \approx -(f_{1T}^{\perp q})_{DY}$$

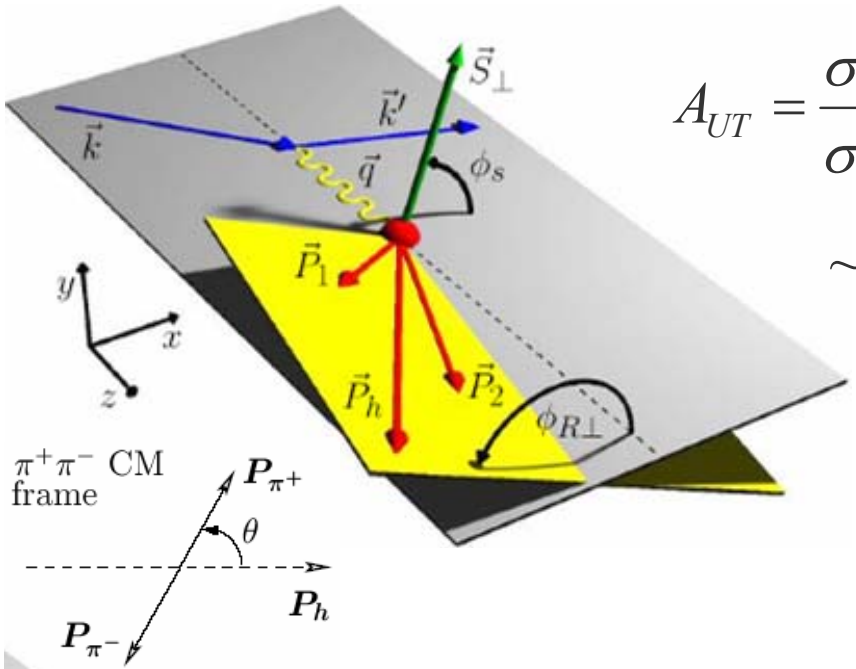
Polarized Antiproton EXperiments

@FAIR (GSI)

semi-inclusive 2-hadron production

$$e\, p^{\uparrow} \rightarrow e\, \pi^{+}\pi^{-}\, X$$

2-hadron asymmetries



$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$\sim \sin(\phi_{R\perp} + \phi_S)\sin(\theta)\, \delta q(x)\, H_1^{\sphericalangle q}(z, M_h^2)$$

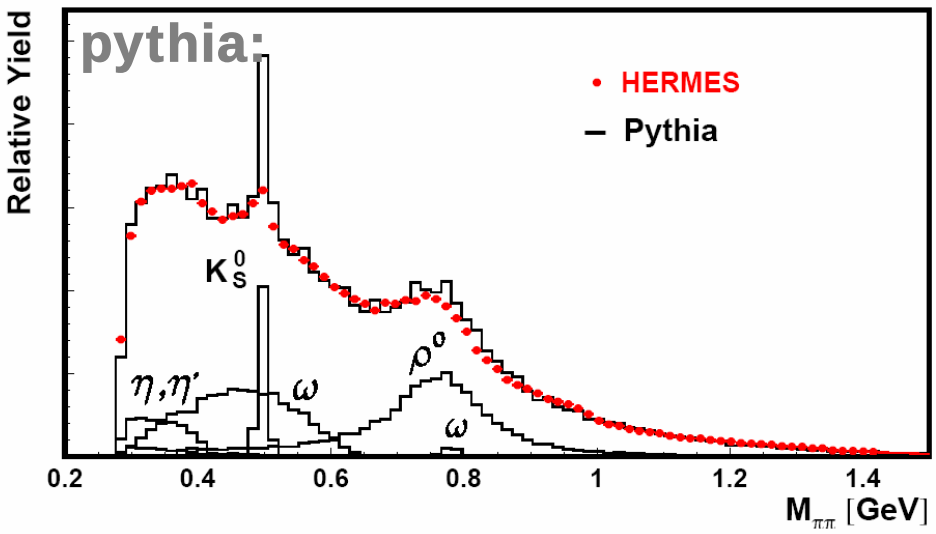
interference fragmentation function between pions in s-wave and p-wave

- only *relative* momentum of hadron pair relevant

  → integration over transverse momentum of hadron pair simplifies factorisation (collinear!) and Q^2 evolution

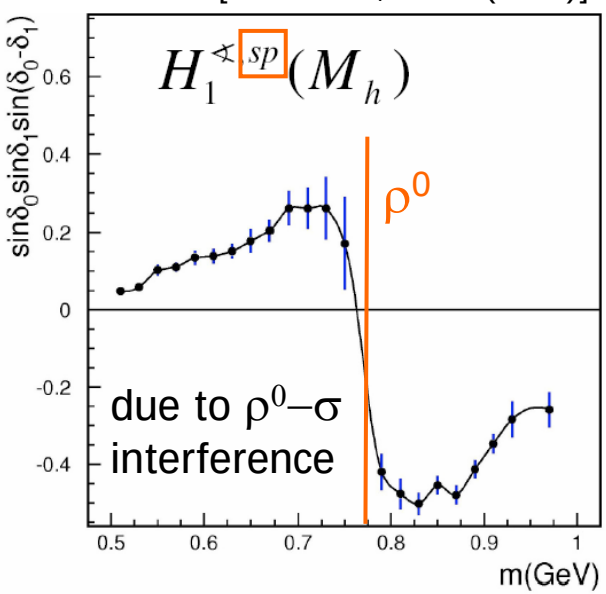
- however cross section becomes very complicated (depends on 9! variables)

models for 2-hadron asymmetries

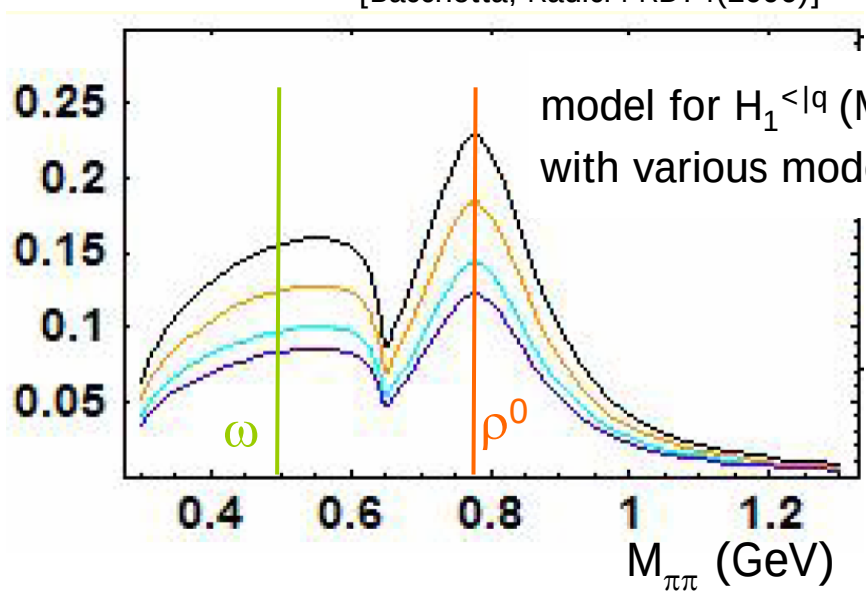


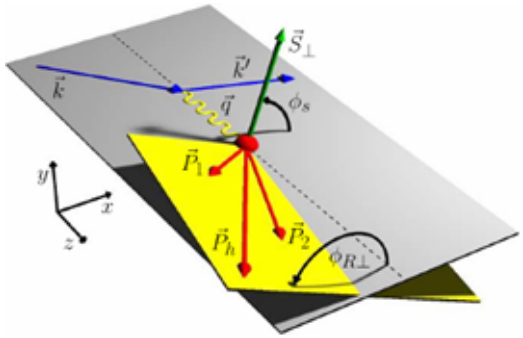
$$H_1^{\sphericalangle}(z, M_{\pi\pi}^2, \cos\theta) = H_1^{\sphericalangle, sp}(z, M_{\pi\pi}^2) + \cos\theta\, H_1^{\sphericalangle, pp}(z, M_{\pi\pi}^2)$$

[Jaffe et all, PRL80(1998)]



[Bacchetta, Radici PRD74(2006)]





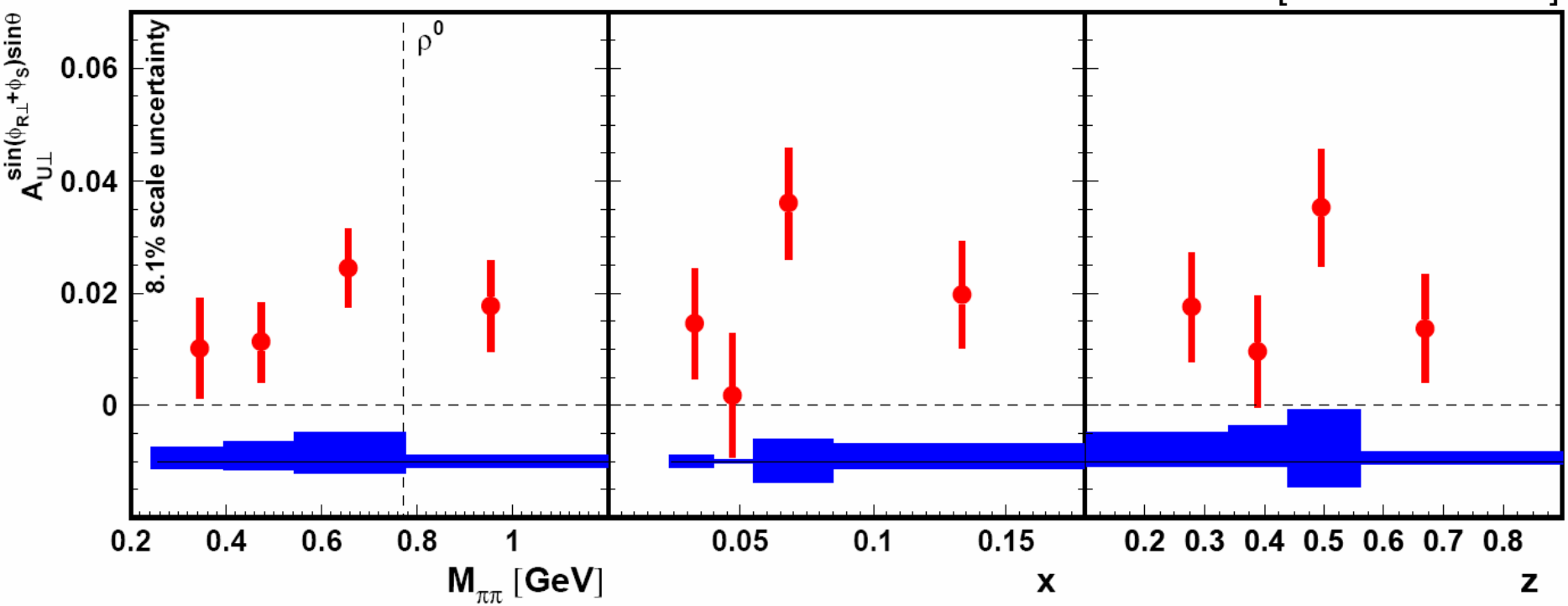
2-hadron asymmetries

$$\delta q(x)\, H_1^{\sphericalangle q}(z, M_{\pi\pi})$$

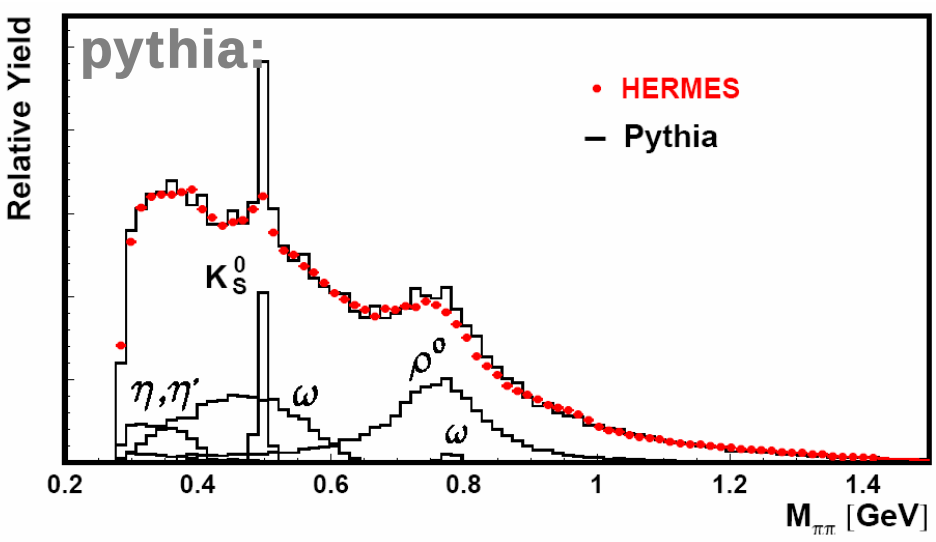
- BOTH: *transversity* and *interference fragmention function* are **non-zero** !

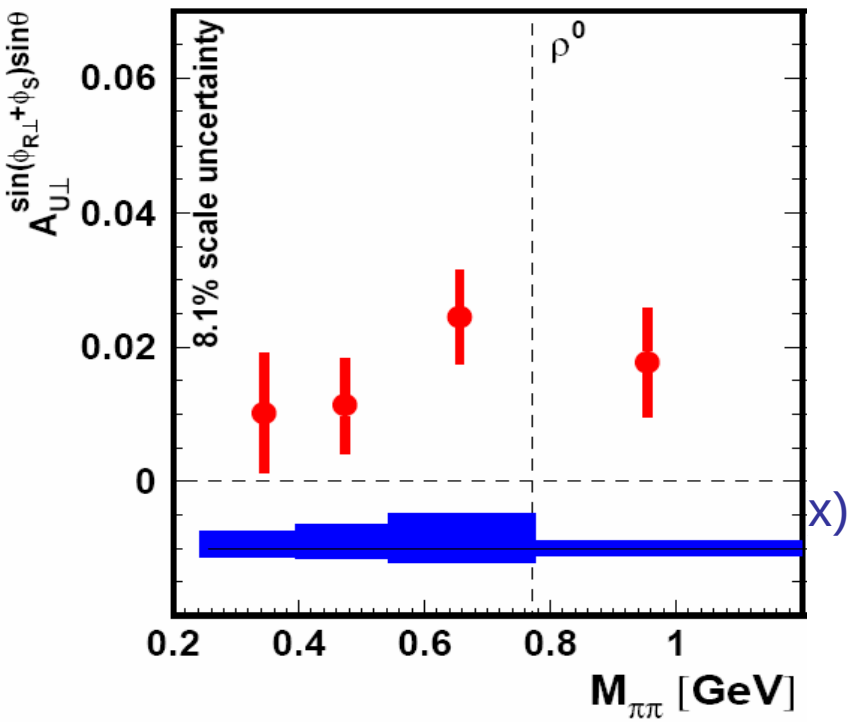
hermes $e\, p^{\uparrow} \rightarrow e\, \pi^+\pi^-\, X$

[arXiv:0803.2367]



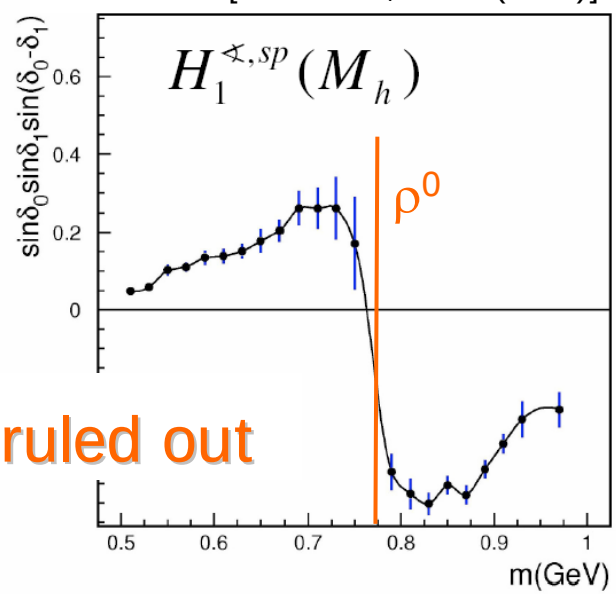
models for 2-hadron asymmetries



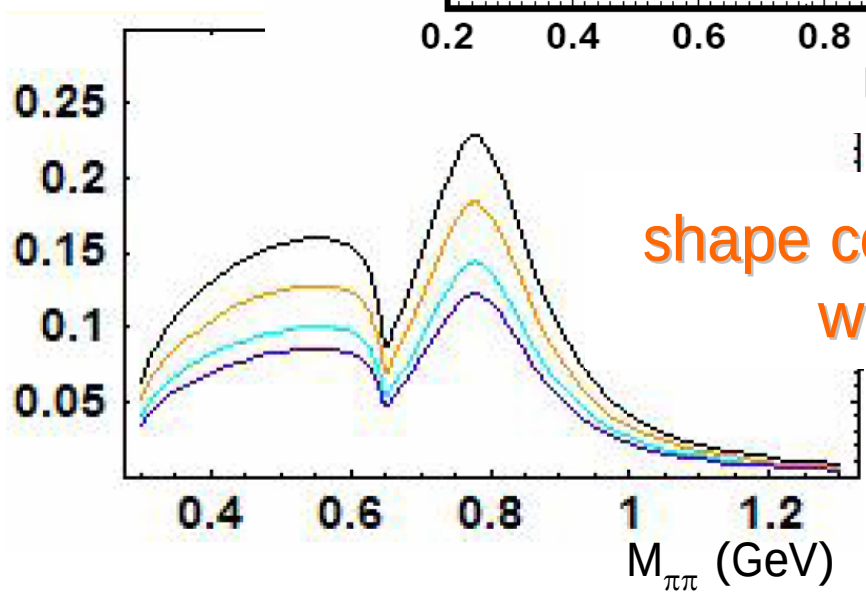


x)

[Jaffe et all, PRL80(1998)]

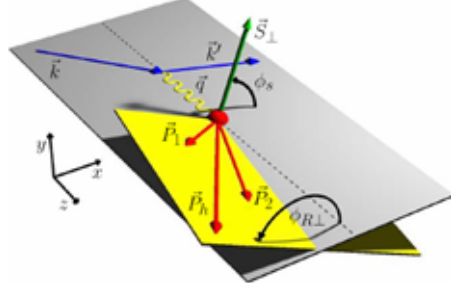


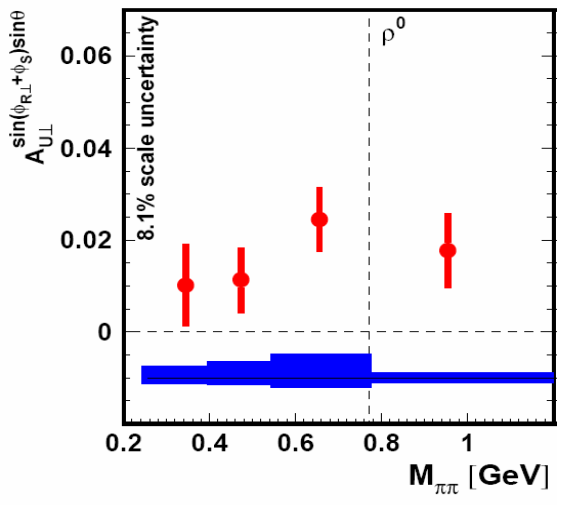
ruled out



shape compares well

2-hadron asymmetries





$$\sim \delta q(x) H_1^{\sphericalangle q}(z, M_{\pi\pi})$$

- first evidence for non-zero *interference FF*
- BELLE plans to measure it ! ☺
- this kind of interference effect is a very promising way to access δq @RHIC

→ δq(x) from SIDIS + pp + e^+e^-

where do we stand ?

- precision of data for identified hadrons adequate for quantitative extraction of flavour dependence of both *transversity* and *Sivers* fct

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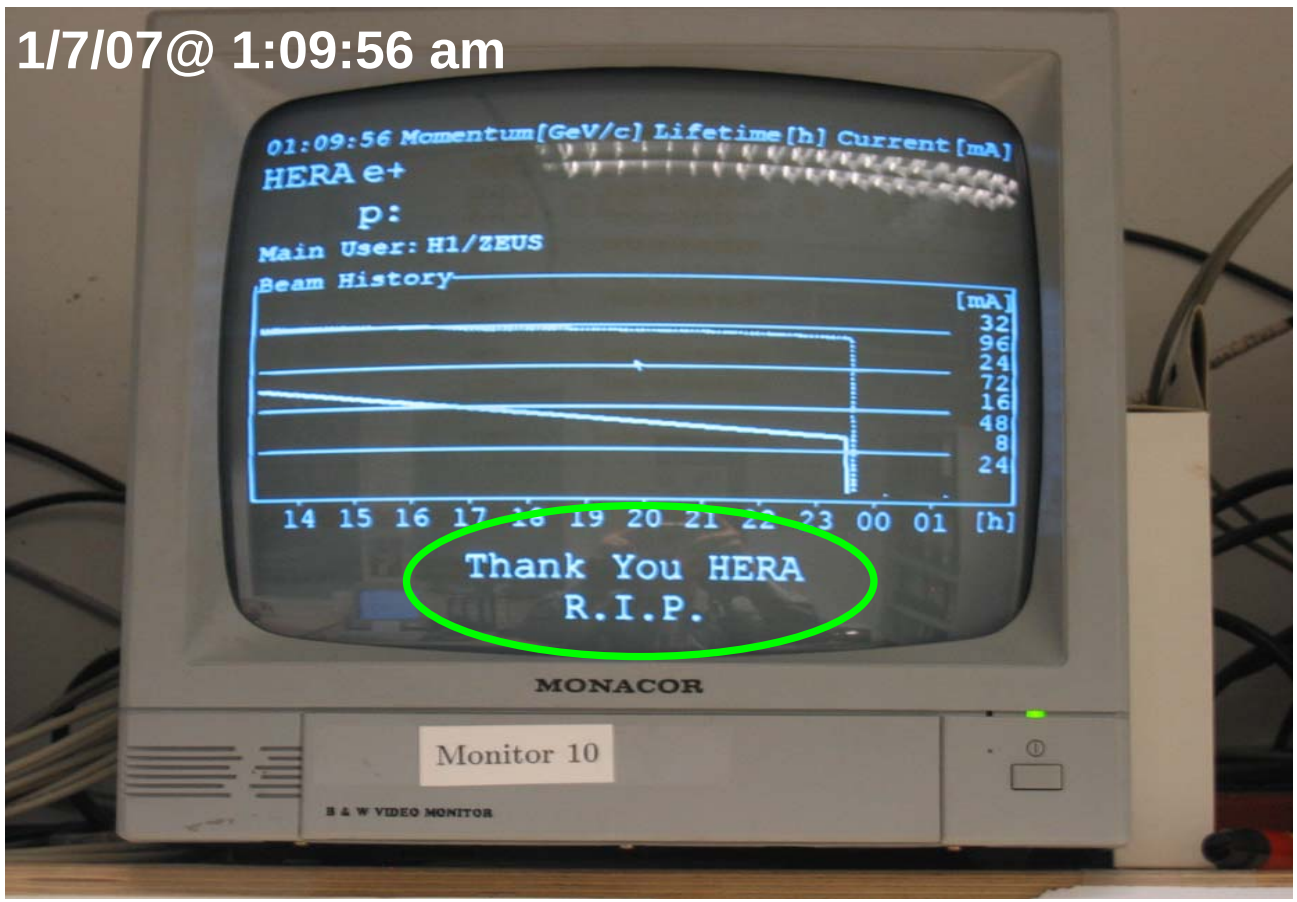
more to come:



where do we stand ?

- precision of data for identified hadrons adequate for quantitative extraction of flavour dependence of both *transversity* and *Sivers* fct

more to come:

- P_T-weighted Collins and Sivers asymmetries
  - → model-independent interpretation of asymmetries
  - → requires control of acceptance effects (more @transversity08)
- Boer-Mulders fct. via $\langle\cos(2\phi)\rangle$, $\langle k_T\rangle$ via Cahn-effect $\langle\cos\phi\rangle$
  - → requires control of acceptance effects (more @transversity08)
- $\langle\cos(\phi-\phi_S)\rangle_{LT}$: access to tw-2 fct. $g_{1T}^{\perp}$; other A_{UT} moments
- inclusive pion photoproduction A_N ("E704 effect")

stay tuned !