TRANSVERSITY 2011

Third International Workshop on

TRANSVERSE POLARIZATION PHENOMENA IN HARD SCATTERING

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Veli Lošinj, Croatia

ECSAC

EUROPEAN CENTRE FOR SCIENCE ARTS AND CULTURE

SIDIS measurements of transverse and longitudinal spin azimuthal asymmetries expected at leading twist

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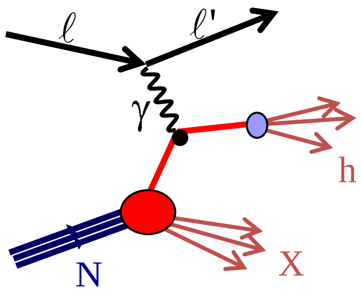
Outline

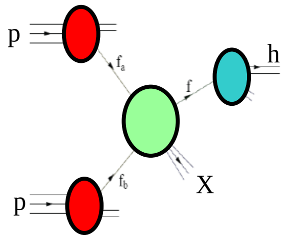
- Introduction : SIDIS and spin asymmetries
- The experiments
- Results on TMD PDFs
  - Transversity
  - Sivers
  - Pretzelosity
  - Worm gears
- Conclusions

Study of transverse momentum dependent PDF and FF



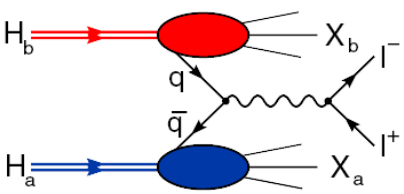
SIDIS off polarised targets *(→H.Avakian)*

DESY (HERMES) → *A.Rostomyan, G.Schnell*
CERN (COMPASS) → *F.Bradamante, C.Braun, G.Sbrizzai*
JLab → *M. Aghasyan, V. Burkert*
*future: **eRHIC, EIC, ENC**→ V. Litvinenko, F.Maas*



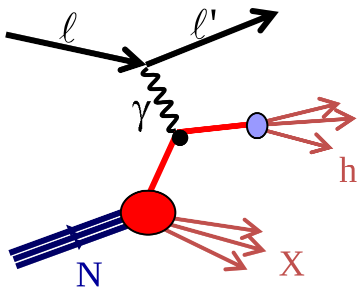
hard polarised pp scattering

RHIC / BNL
→ *A.Vossen, J. Koster, N.Poljak*



and projects for **(polarised) Drell-Yan:**
CERN (COMPASS),FNAL, JParc, RHIC, JINR, IHEP, GSI
→ *O.Denisov ,W.Lorenzon, L.Bland, P.Reimer,A.Kritsch*

Study of transverse momentum dependent PDF and FF with SIDIS



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SIDIS:

- Knowledge of FF is needed
- TMD effects are not mixed, as in hadroproduction, but generate different azimuthal asymmetries, which can be separately explored → different asymmetries can be extracted from the same data
- Allow flavor separation analyses, measuring on different type of hadrons and with different targets

SIDIS cross section

$$
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =
\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}
$$

$$
+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}
$$

$$
+\,S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]
$$

$$
+\,S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]
$$

$$
+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)
$$

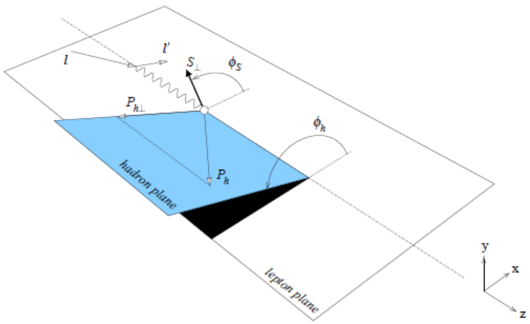
$$
+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}
$$

$$
+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]
$$

$$
+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}
$$

$$
+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
$$

several structure functions, depending on different combinations of azimuthal angles



SIDIS cross section at leading twist

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\Big]$$

$$+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\Big]$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

wormgear $h_{1L}^{\perp}\otimes H_1^{\perp}$ (→ $F_{UL}^{\sin 2\phi_h}$)

Sivers $f_{1T}^{\perp}\otimes D_1$ (→ $F_{UT,T}^{\sin(\phi_h-\phi_S)}$)

transversity $h_1\otimes H_1^{\perp}$ (→ $F_{UT}^{\sin(\phi_h+\phi_S)}$)

pretzelosity $h_{1T}^{\perp}\otimes H_1^{\perp}$ (→ $F_{UT}^{\sin(3\phi_h-\phi_S)}$)

wormgear $g_{1T}\otimes D_1$ (→ $F_{LT}^{\cos(\phi_h-\phi_S)}$)

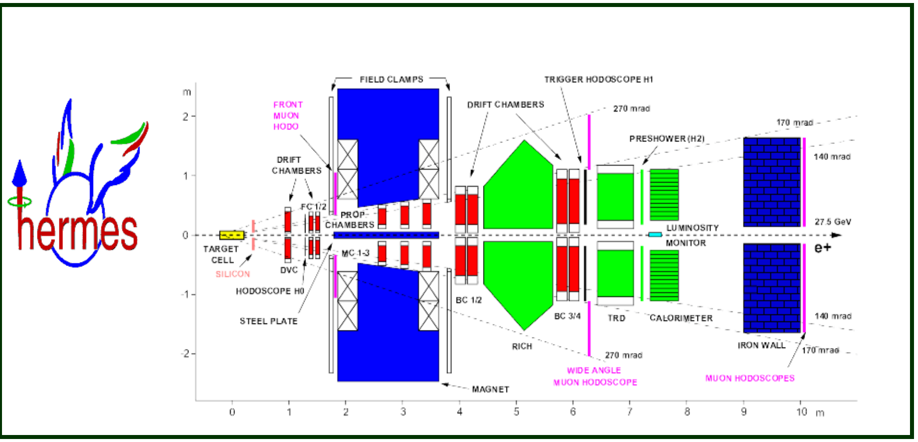
From the experimental point of view…

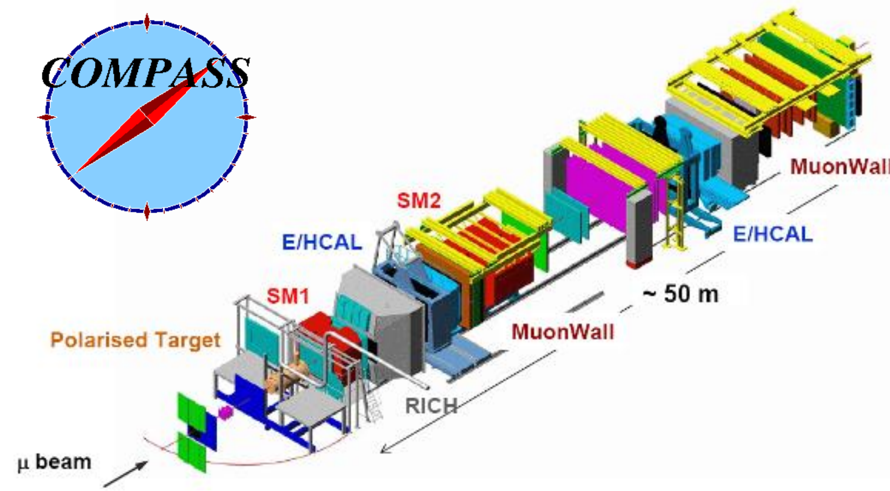
Tools needed for the measurement:
- polarized targets (beam in case of double spin asymmetries)
- large acceptance spectrometer with full particle identification : identification of scattered lepton and produced hadrons
- good coverage in azimuthal angle acceptance

For a global interpretation of the measurements:
-different target materials
-cover large kinematical ranges
-measure on different hadrons

→ complementarity between different experiments is important

The experiments





polarized (<60%) e+/e- beam of 27 GeV, both helicity states

Gaseous target, direct access to hydrogen/deuterium → dilution factor~1

Transverse meas: p, Longitudinal: p,d

P_T~ 70-85%

fast spin-flip of target → same acceptance for the different polarization states

polarized (-80%) μ+ of 160 GeV

Solid state target, 120 cm long

^{6}LiD (d) P_T ~ 50% ; f ~ 0.40 both L and T

NH_3 (p) P_T ~ 80% ; f ~ 0.15 both L and T

nearby cells are oppositely polarised to take data simultaneously on the two orientation of the target→ Spin reversal in order of the hours/days

The experiments

JLab E06-010

e- beam at ~6 GeV/c

40cm 3He gas target

transversely polarised, different orientations possible

P_T~55% (n) f ~ 0.1-0.3

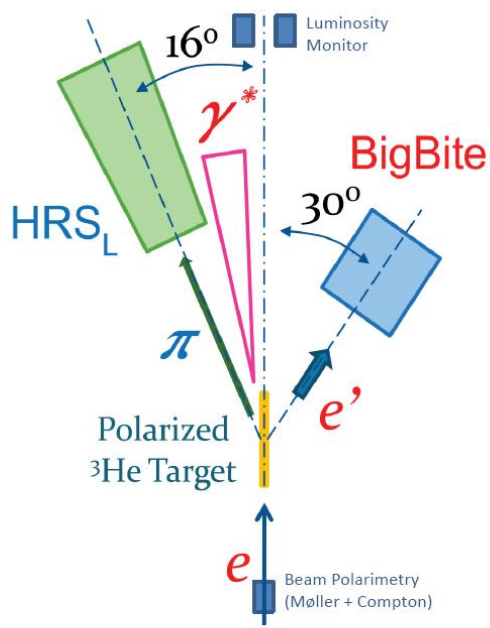
Spin flip every 20 minutes

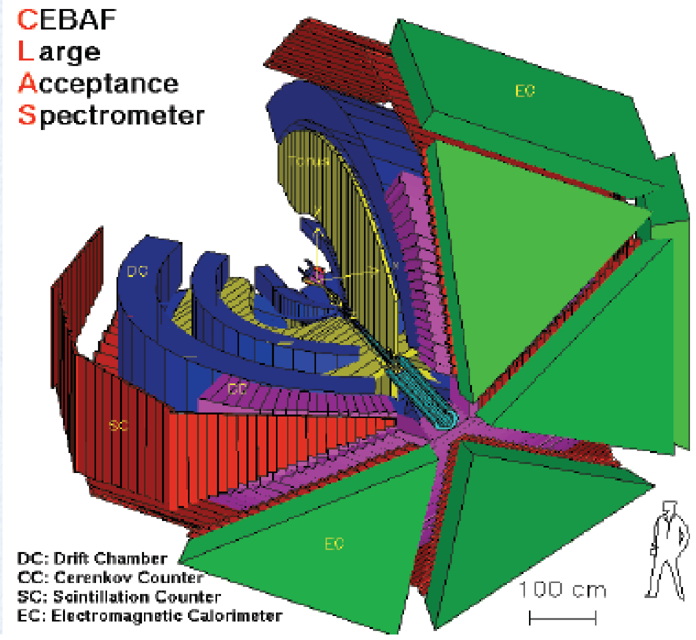
JLab CLAS

e- beam at ~6 GeV/c

NH_3 longitudinal polarization

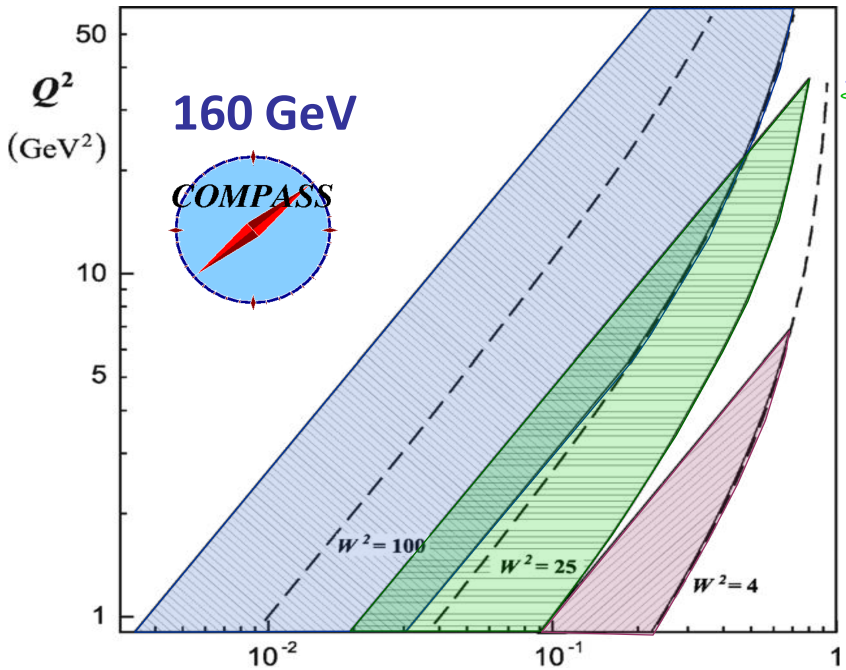
P_T ~75%, ; f ~ 0.15





Phase space of different experiments

Strong dependence of x, Q2 and W, depending on the lepton beam energy.



hermes

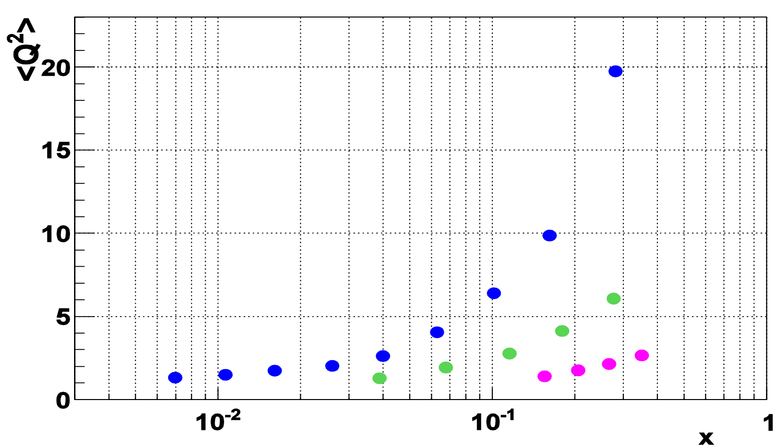
27.5 GeV

0.004 < x < 0.3, $25 < W^2 < 200 GeV^2$

0.023 < x < 0.4, $10 < W^2 < 50$

0.14 < x < 0.34, $4 < W^2 < 10$
(0.48)

JLab 6 GeV



Phase space determined also by cuts

- $Q^2 > 1(GeV/c)^2$
- y (0.1<y<0.9/0.95)
- low W to avoid resonance regions
- cut on momenta imposed by PID
- relative energy z of each hadron:
  - lower cut to avoid fragmentation region, usually z>0.2 (*depending on W)*
  - higher cut (z< 0.7, 0.85)

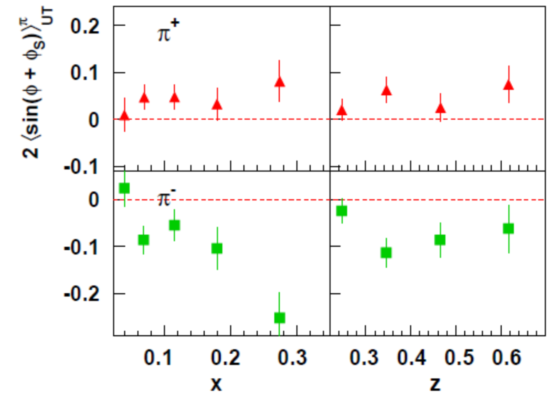
Results

Collins asymmetries

2005 First informations

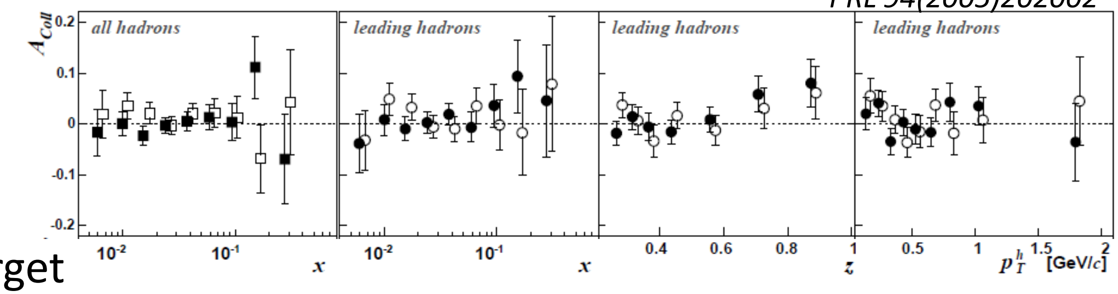
Sizeable asymmetries on proton target
→First evidence that transversity PDF and Collins FF are different from zero

PRL 94 (2005) 012002



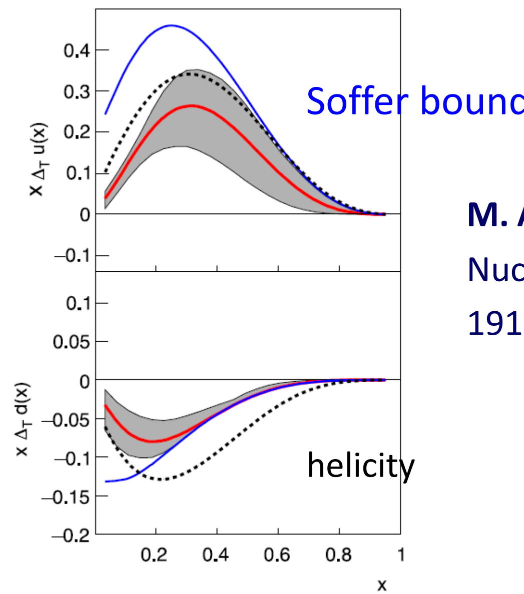
Asymmetries on deuteron target compatible with zero

PRL 94(2005)202002



→ Cancellation between u and d contributions due to the isoscalar target

These data, together with Belle e+e- data are well described with a global fit
→first extraction of the Collins FFs and the transversity PDFs



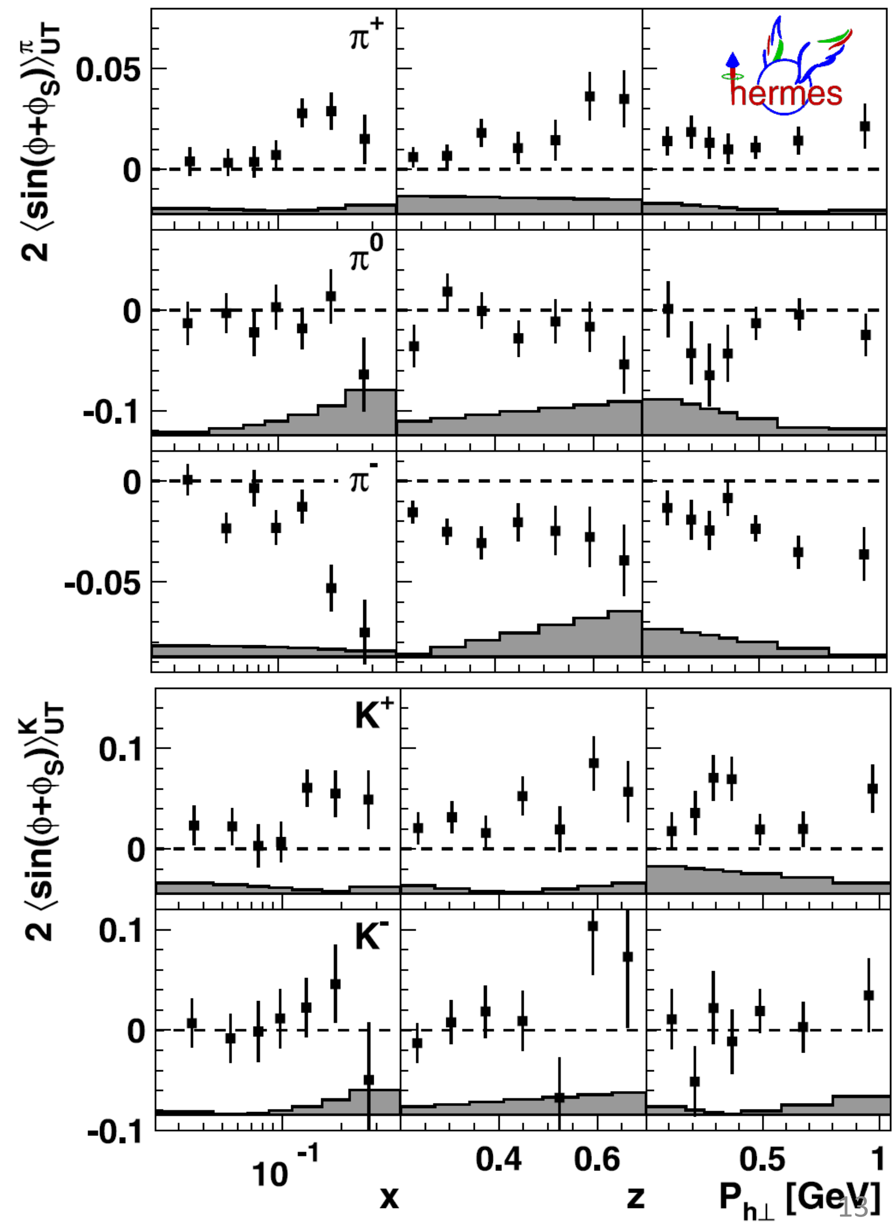
M. Anselmino et al.,
Nucl.Phys.Proc.Suppl. 191 (2009) 98

Collins asymmetries, results on proton

PLB 693 (2010) 11

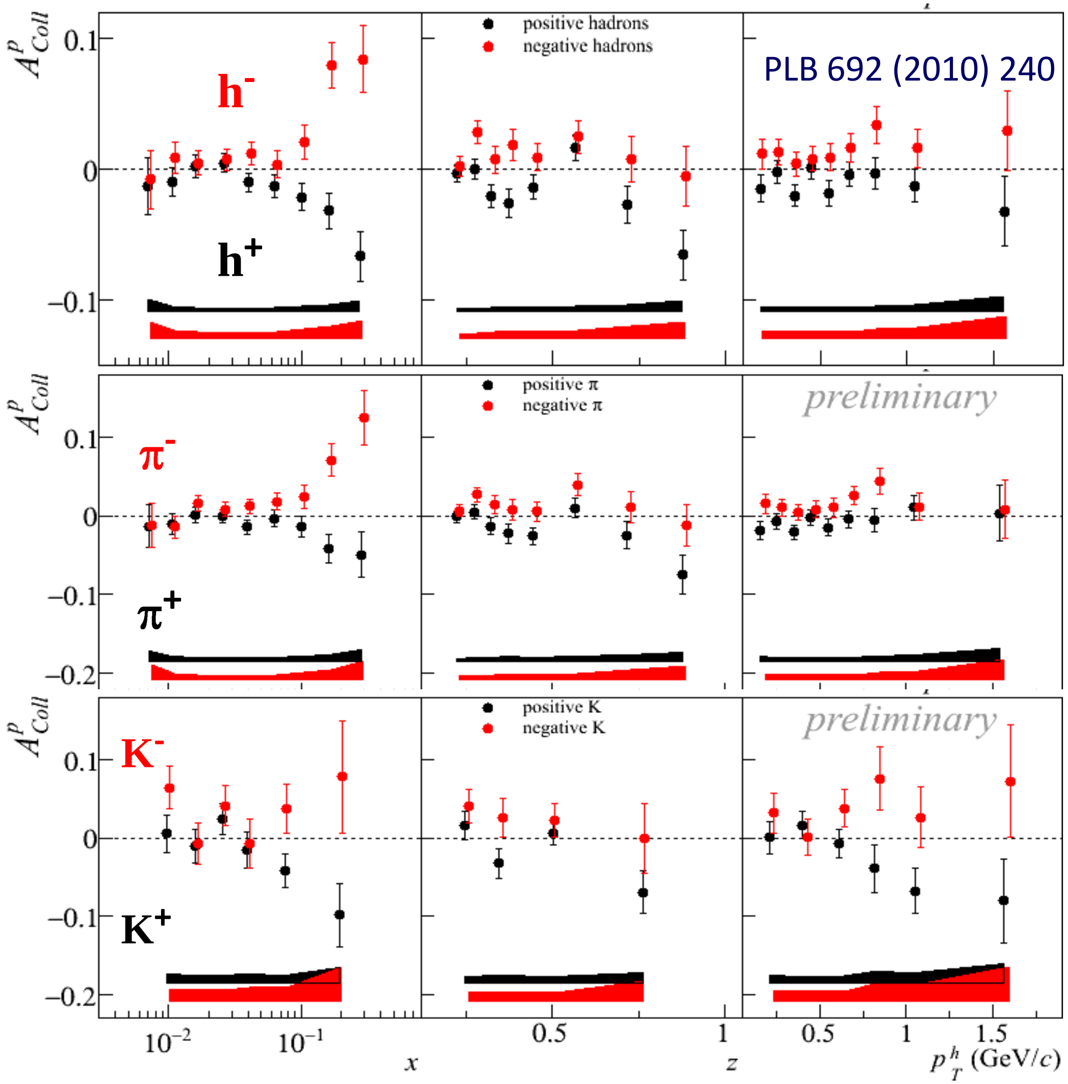
final HERMES results

- Increase signal with x, valence region
- Increase also with z
- clear signal for π^+ and π^- x>0.1 opposite sign
  - Dunf~-Dfav
- K^+ signal larger than π^+: role of sea quarks?



Collins asymmetries, results on proton

COMPASS results from 2007 proton run

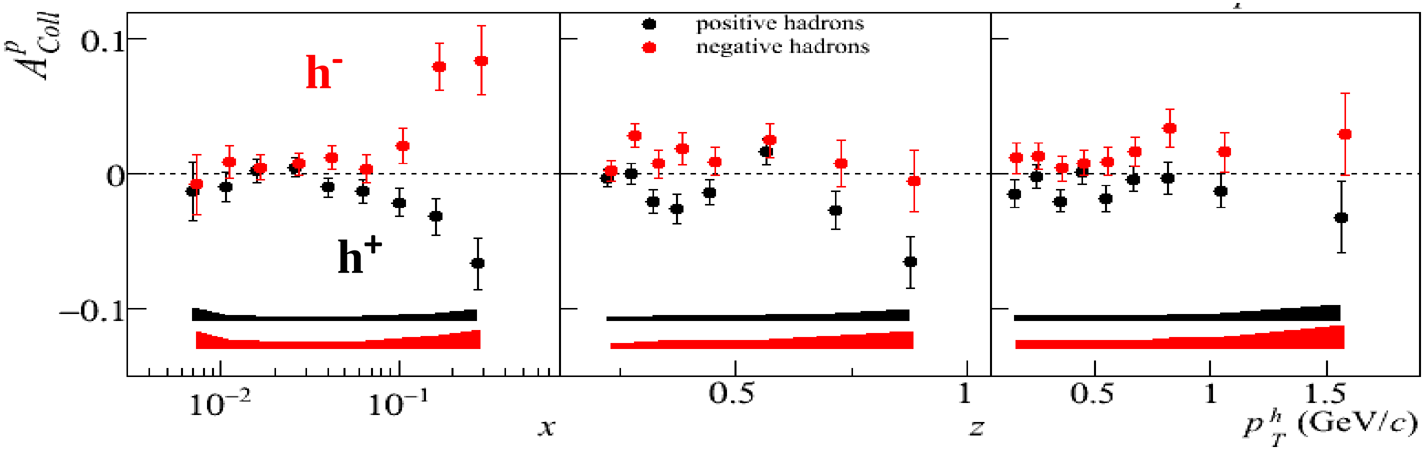


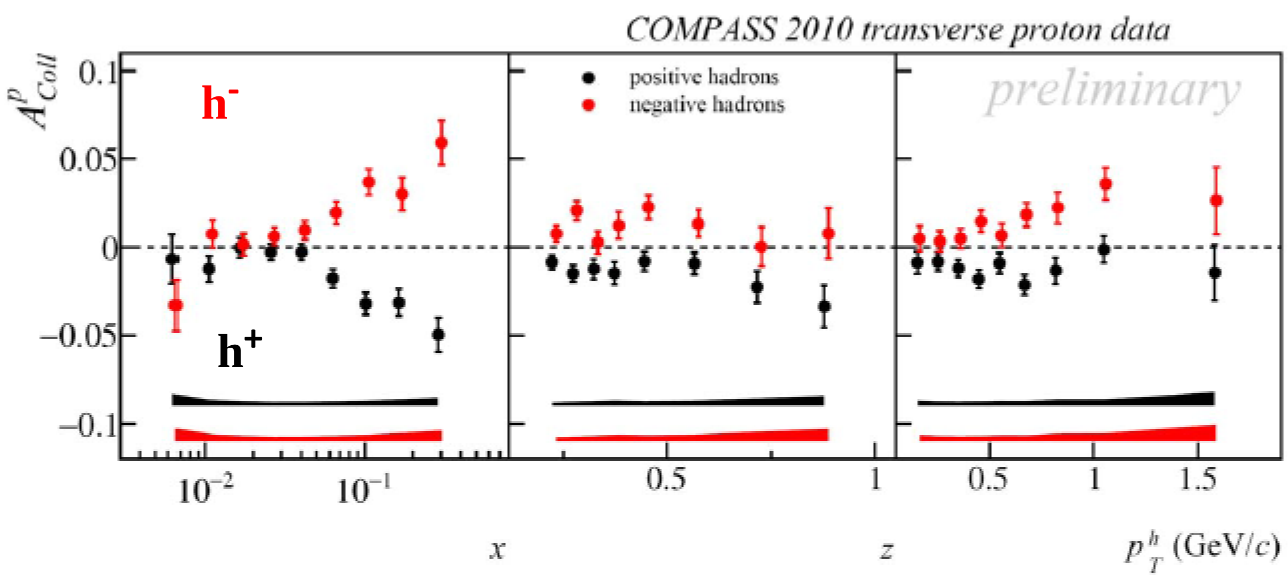
- at small x, region not covered by HERMES asymmetries compatible with zero
- Strong signal in the valence region of opposite sign for π+ and π- agreement with HERMES
- Non trivial result: Q2 COMPASS larger of HERMES's of a factor 2-3 in the last x bins →low Q2 dependence,

K+ negative trend in the valence region
K-positive in average

Collins asymmetries, results on proton

PLB 692 (2010) 240





New:

Results from 2010 run :

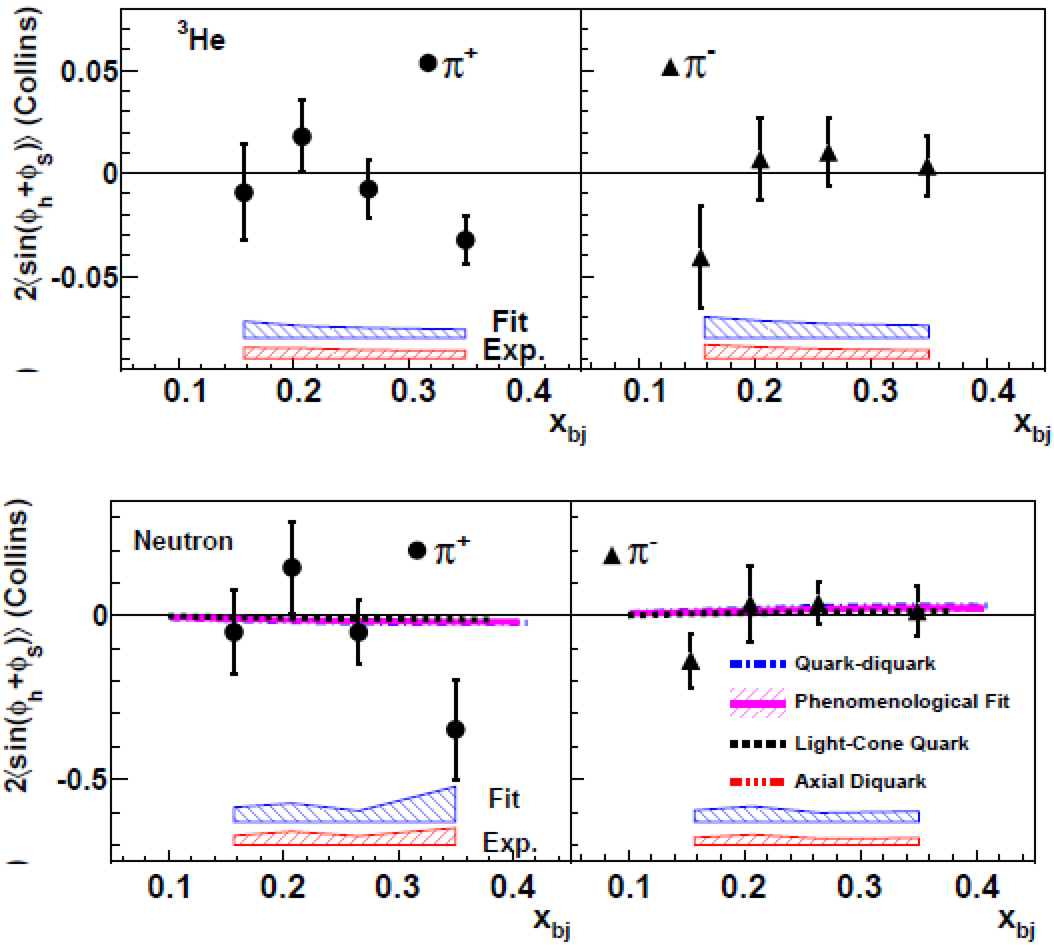
confirm the 2007 results with higher precision (factor ~2)

Collins asymmetries, results on neutron

Neutron helps to constrain PDF for d quark, together with proton and deuteron data

JLAB E06-010 Collaboration

Phys.Rev.Lett.107:072003,2011.



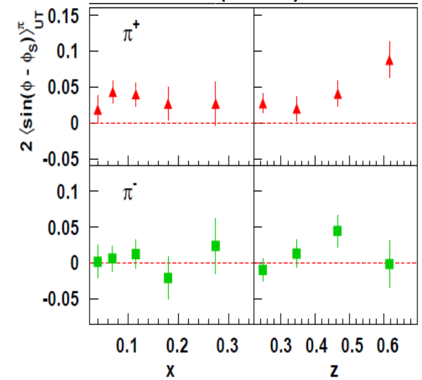
Consistent with zero
expect π+ at x~0.34

Agreement with expectation
from models and fit

$$A^{C/S}_{^3\mathrm{He}} = P_n \cdot (1-f_p) \cdot A^{C/S}_n + P_p f_p \cdot A^{C/S}_p$$

Sivers asymmetries

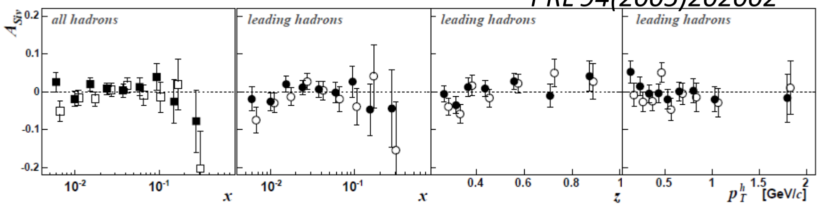
PRL 94 (2005) 012002



2005 first information

- **first strong signal seen by HERMES for π^+ on protons**
- **no signal seen by COMPASS for h^+ and h^- on deuterons**

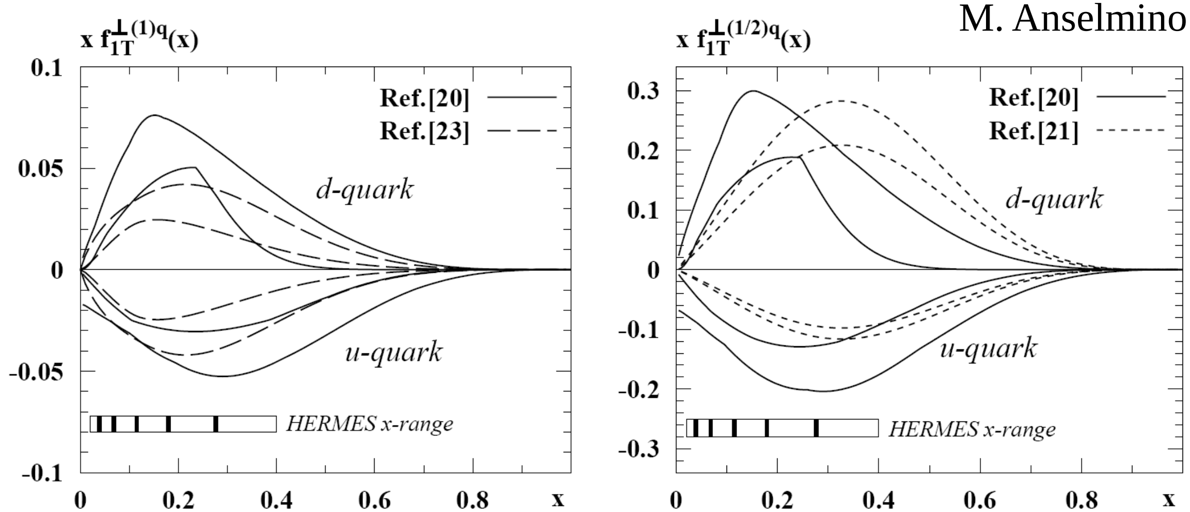
PRL 94(2005)202002



→ first extractions of the Sivers function from HERMES p (and COMPASS d) data

good description of the experimental results

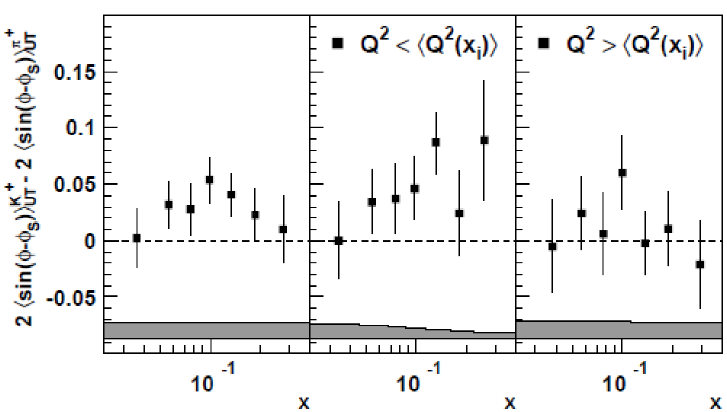
M. Anselmino et al., Transversity2005

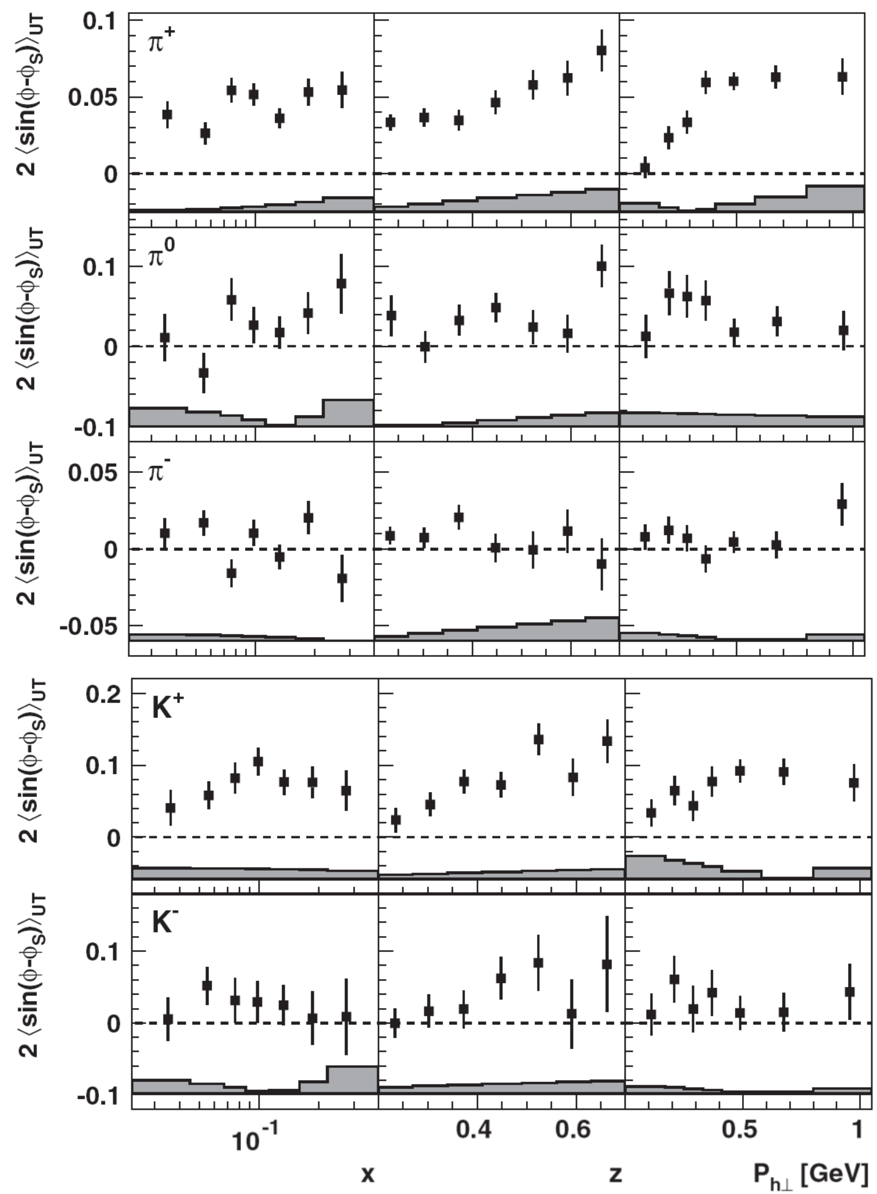


Sivers asymmetries, results on proton

final HERMES results

- **large signal for π^+ and K^+ over all the measured x range**
- **increasing with z**
- **linear behavior at small pt, saturation for $P_T^h > 0.4$ GeV/c**
- **difference between K^+ and π^+:**
  important role of sea quarks?
  larger at lower Q^2
  higher twist effects
  in K production?

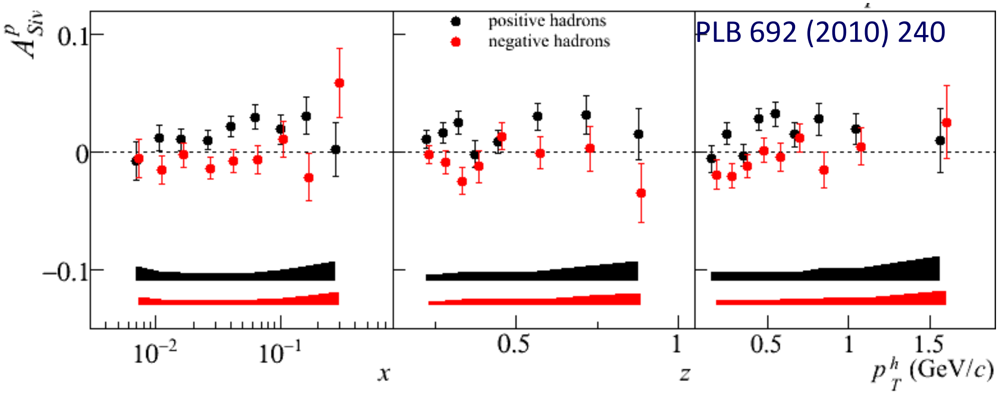




PRL **103**, 152002 (2009)

Sivers asymmetries, results on proton

COMPASS results from 2007 data

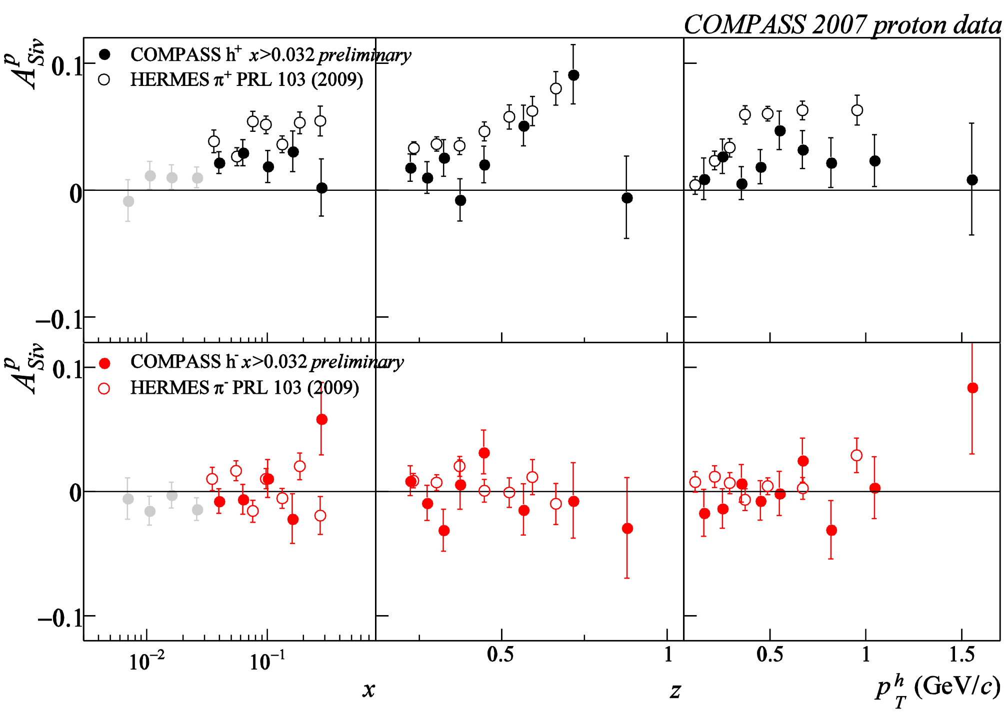


evidence for a positive signal for h^+, which extends to small x, in the region not measured before

(syst error on h+: scale factor of +-0.01)

K+ positive in average

K- compatible with 0



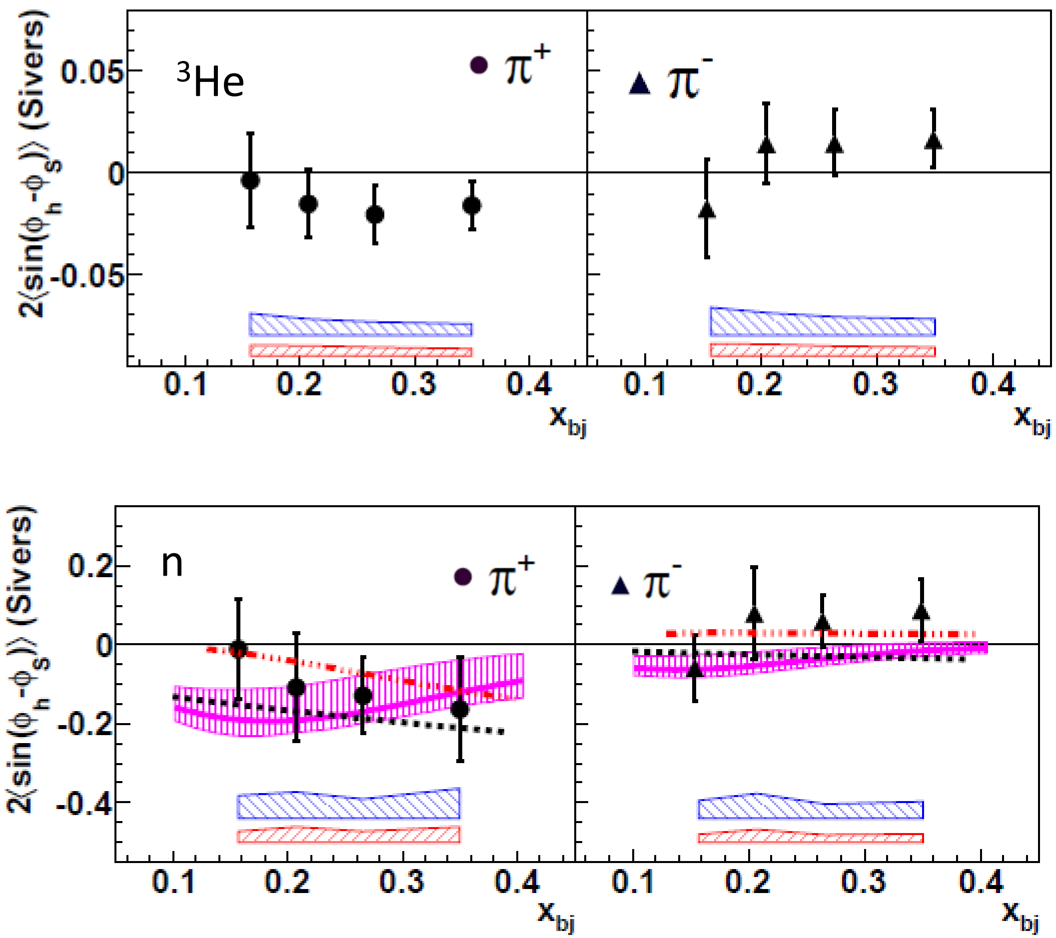
COMPASS results in the overlap region smaller by a factor ~ 2 wrt HERMES

NEW :
2007 results confirmed by the 2010 run
with improved statistical precision (factor ~2.5)

Sivers asymmetries, results on neutron

JLAB E06-010 Collaboration

Phys.Rev.Lett.107:072003,2011.



π^- consistent with zero

π^+ favor negative values

Agreement with global fit and Light cone model

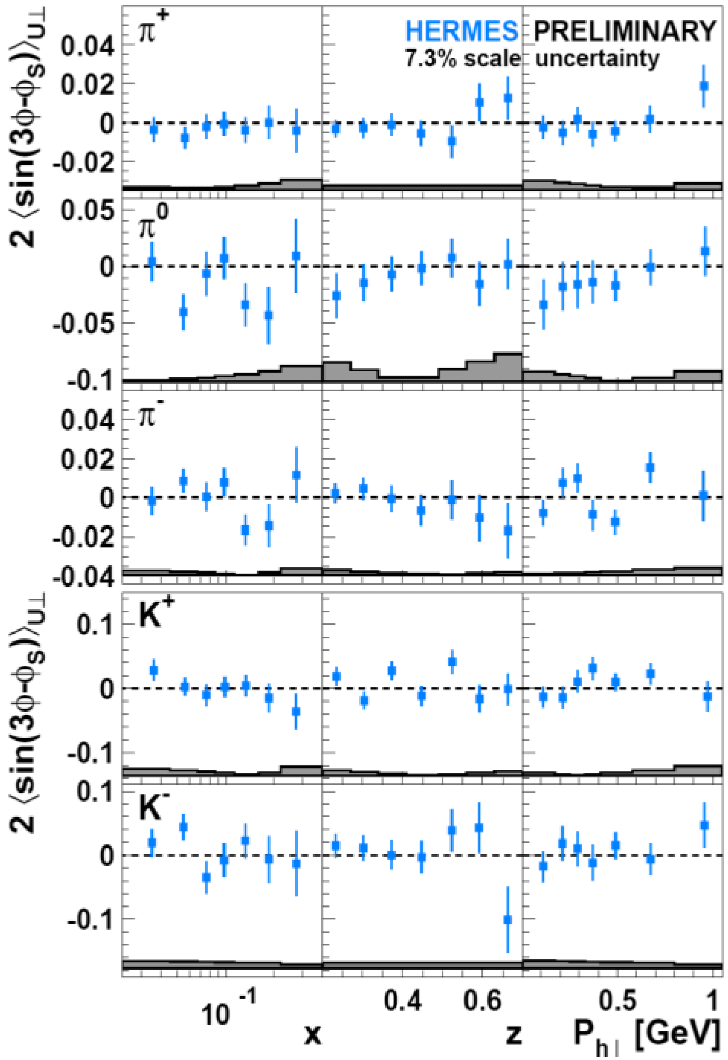
$$A_{^3\mathrm{He}}^{C/S} = P_n \cdot (1 - f_p) \cdot A_n^{C/S} + P_p f_p \cdot A_p^{C/S}$$

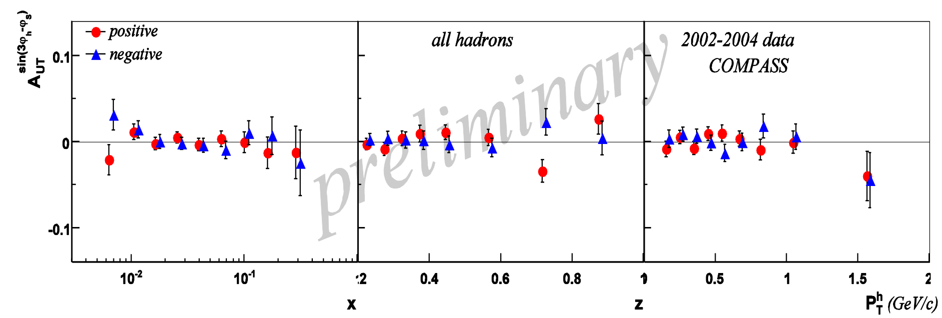
$A_{UT}\sin(3\Phi_h-\Phi_S)$ asymmetry

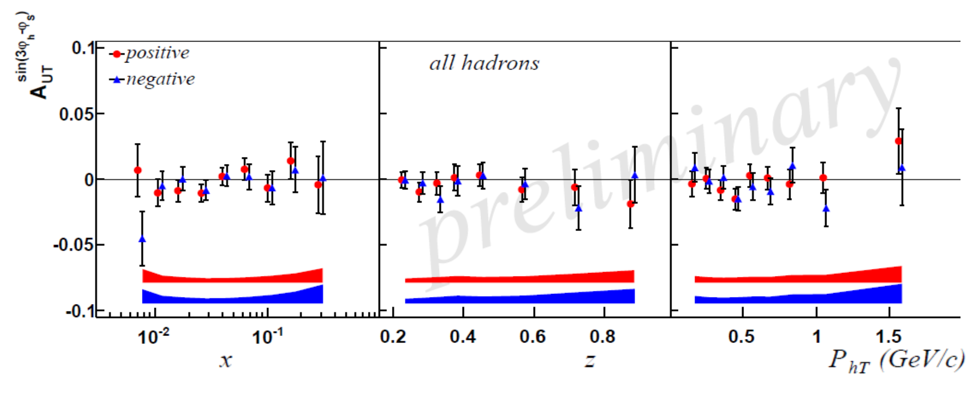
Leading twist signal from pretzelosity PDF times Collins FF

PANIC2011 hermes p target

SPIN2010 COMPASS d and p targets



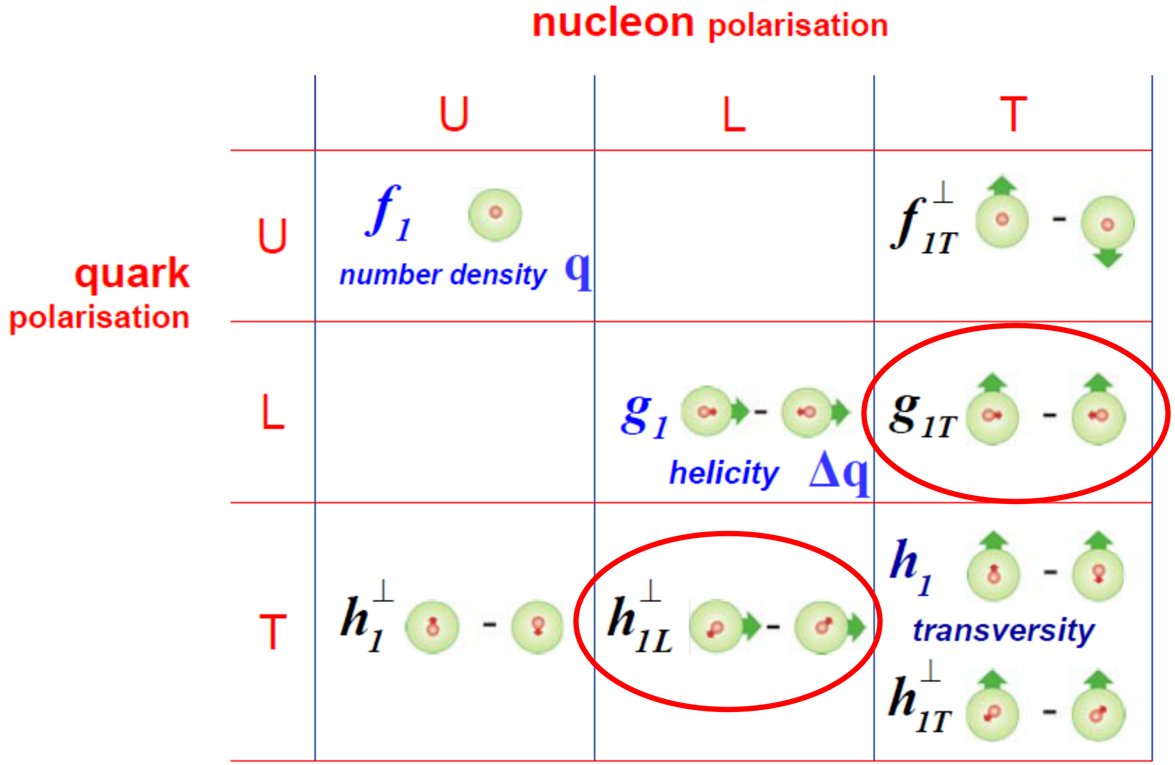




All asymmetries , on proton and deuteron, compatible with zero

- Small pretzelosity PDFs/cancellations
- suppression for P_T^3

Worm gears



Probability of finding a longitudinally polarized quark inside a transversely polarized nucleon

accessed via
double spin asymmetries,
requiring both longitudinally polarized beam and transversely polarized target,
convoluted with unpolarized FF

$A_{LT}\cos(\Phi_h-\Phi_S)$

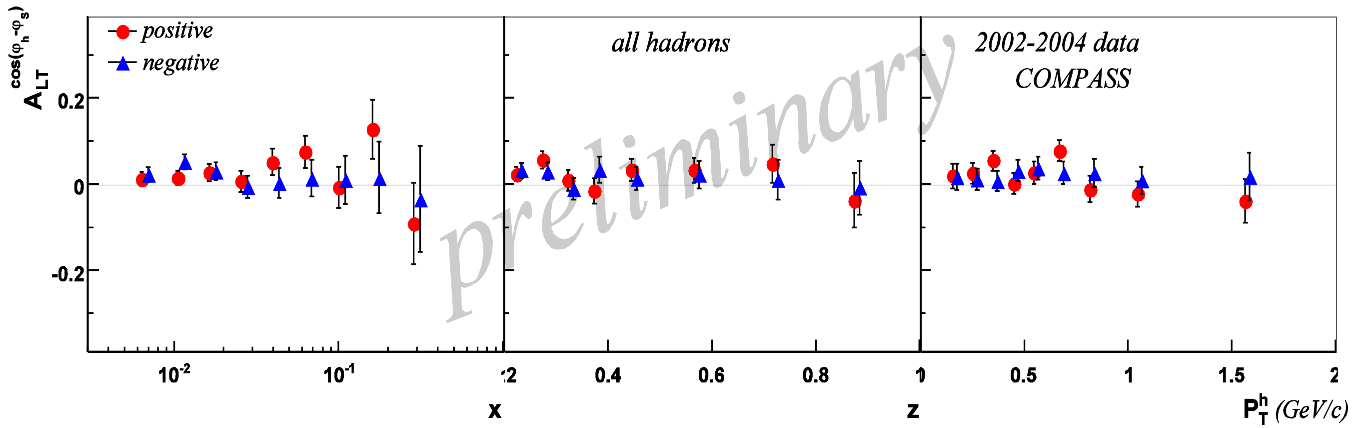
Probability of finding a transversely polarized quark inside a longitudinally polarized nucleon

Accessed via longitudinal target SSA ,
convoluted with Collins FF

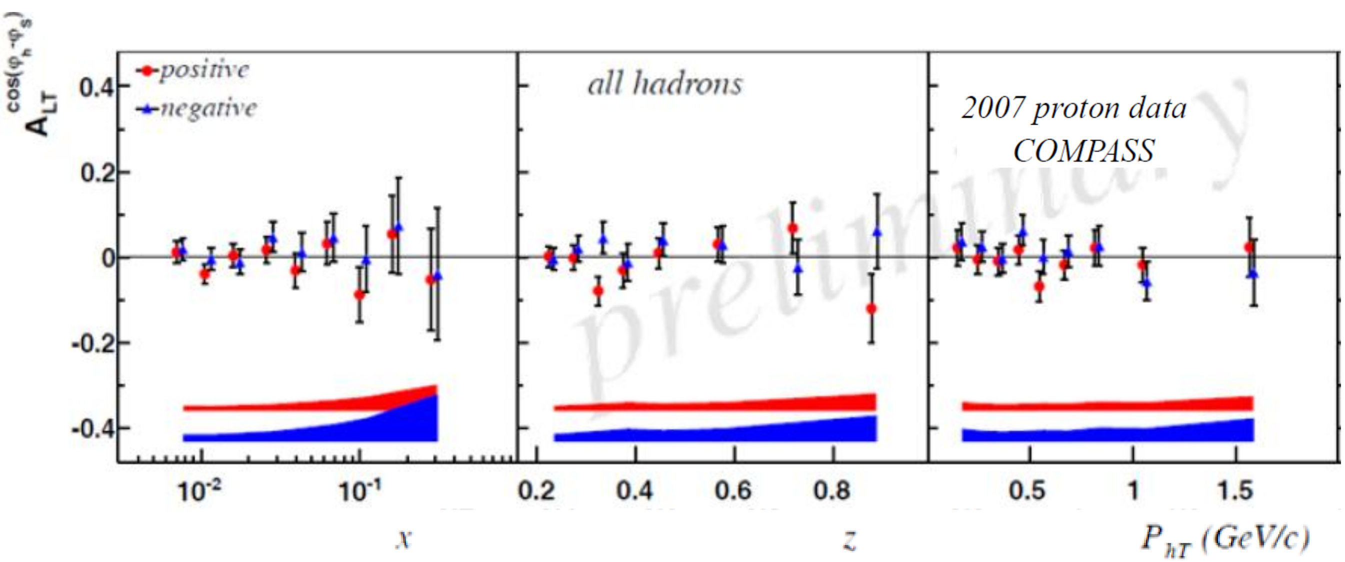
$A_{UL}\sin(2\Phi_h)$

$A_{LT}\cos(\Phi_h-\Phi_S)$ asymmetry

SPIN2010



Deuteron target

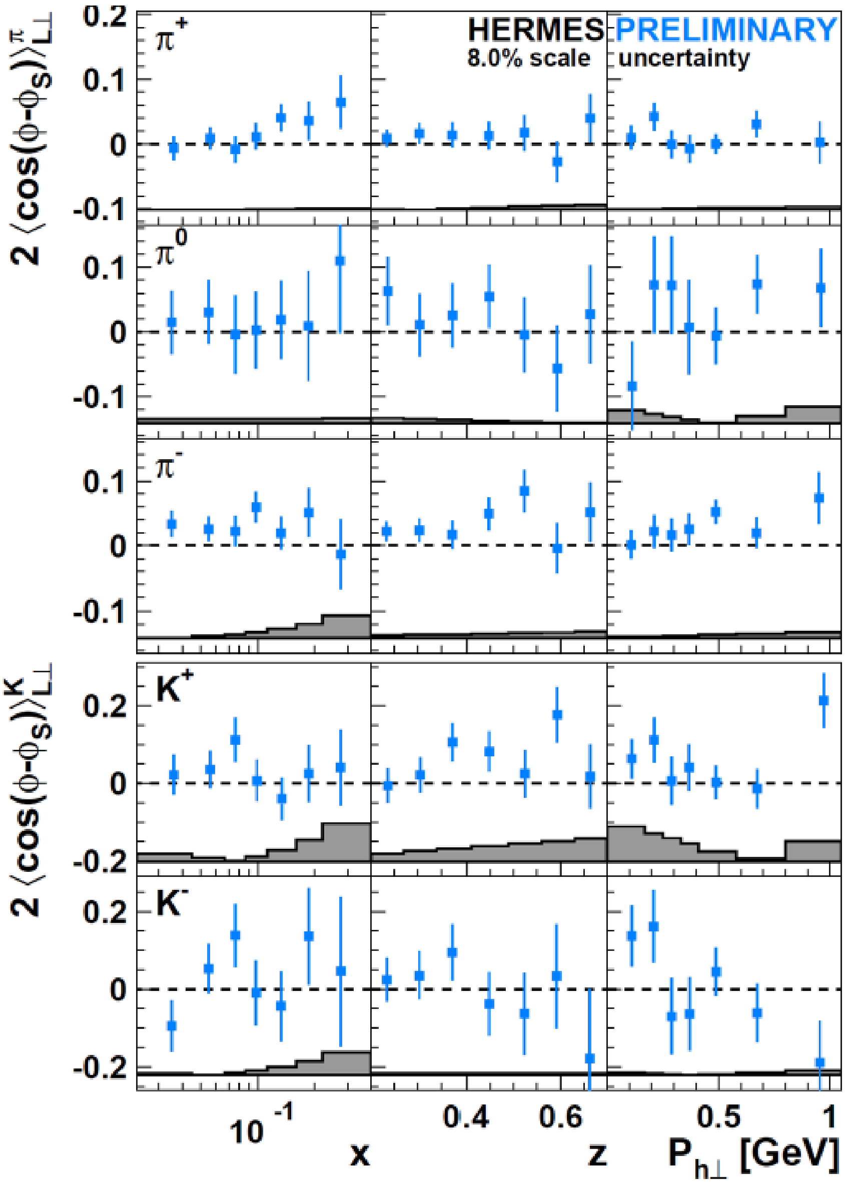


Proton target

All asymmetries compatible with zero

PANIC2011

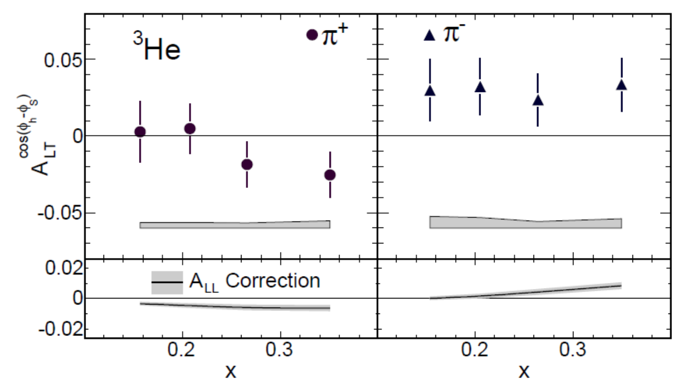
$A_{LT}\cos(\Phi_h-\Phi_S)$ asymmetry

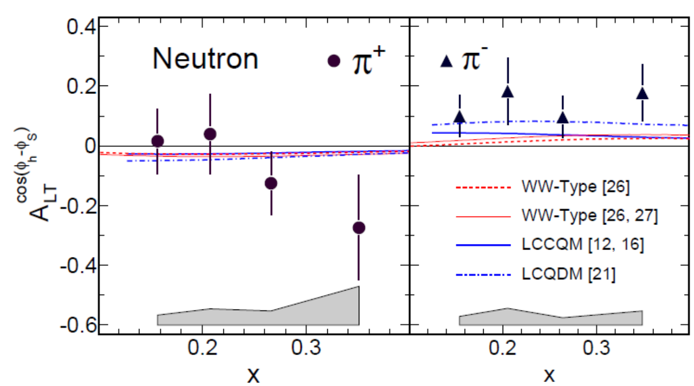


Hint for a positive signal for π^-, and π^+ high x

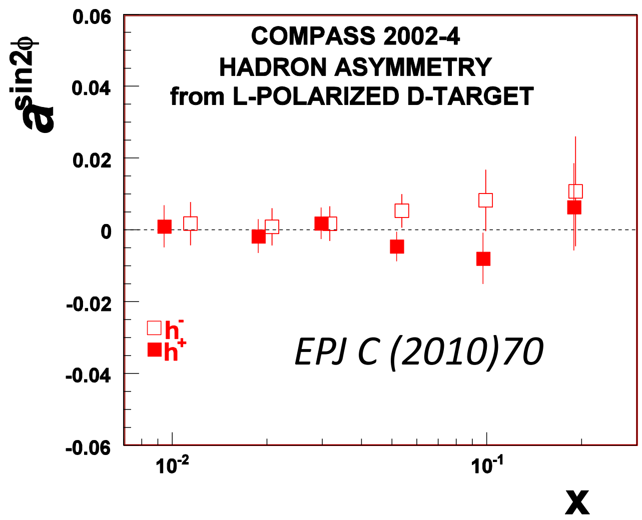
Positive signal seen for π^- also seen by E06-00, on neutron:

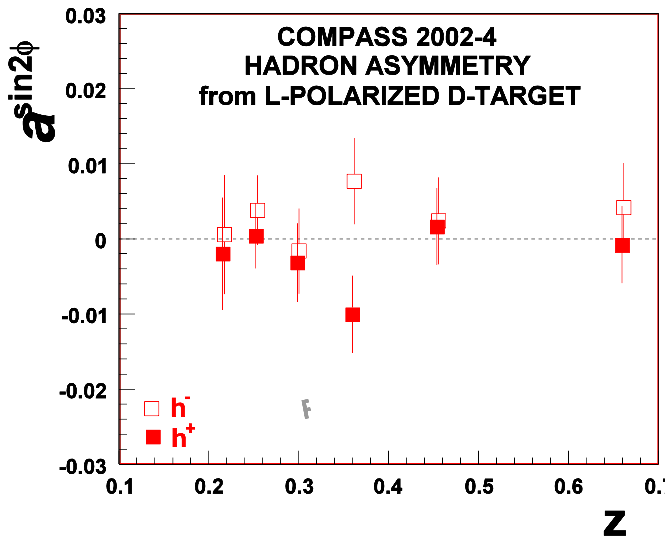
arXiv:1108.0489, submitted to PRL



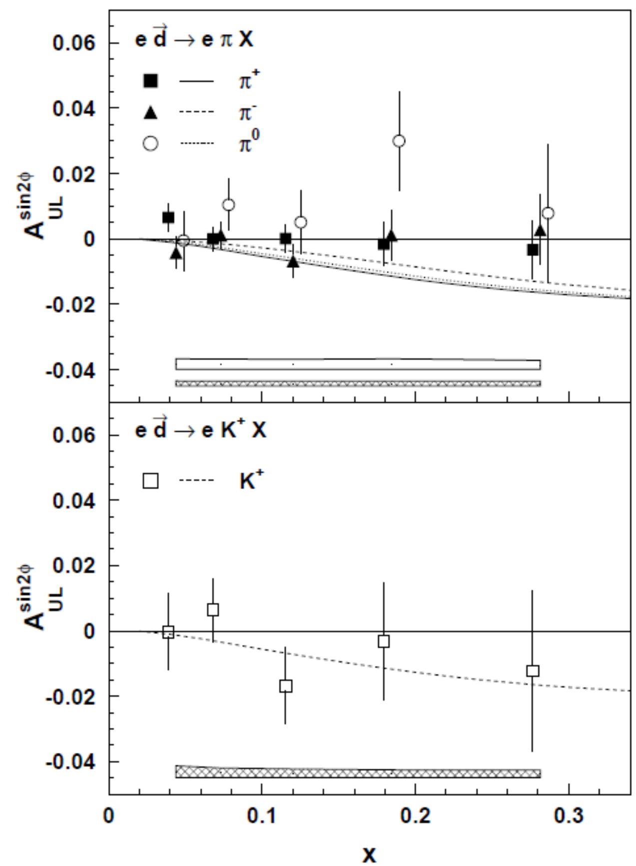


$A_{UL}\sin(2\Phi_h)$ asymmetry deuteron target



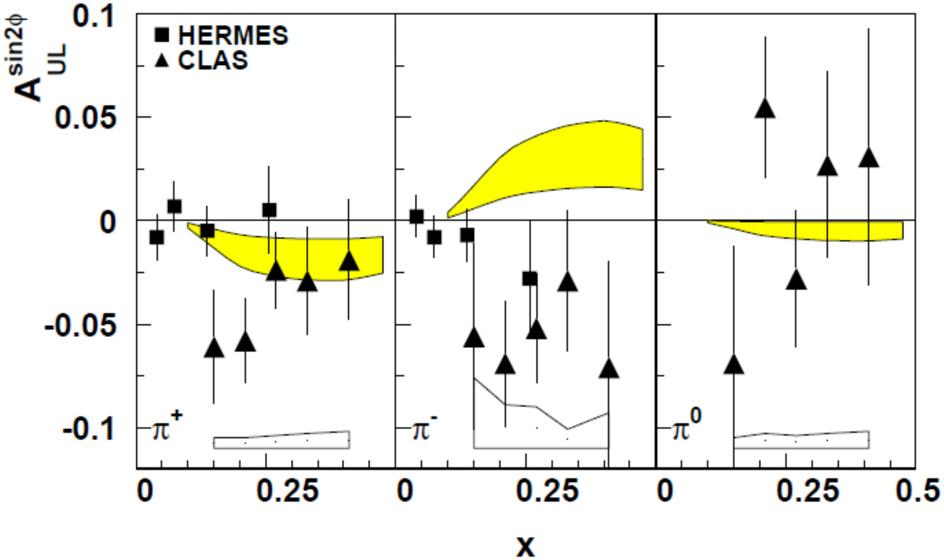


PLB 562(2003)182



All asymmetries consistent with zero

$A_{UL}\sin(2\Phi_h)$ asymmetry proton target



Hermes asymmetries
on pions
consistent with zero

CLAS: signal for π+ and π-

Large x values: u dominance
first glimpse to worm gear
knowing the ratio of Collins FF

HERMES PRL 84 4047 (2000)
CLAS PRL 105 262002 (2010)

Conclusions and outlook

- Several measurements from different SIDIS experiments, complementary on phase space and targets
- Consistent picture for Sivers and Collins asymmetries, still with room for improvement on some issues
- Information on other interesting TMDs from SSA,

  →New input for global fits…

…theoreticians have still a lot of work to do,
while waiting for further results
(COMPASS proton, JLab 6,12 GeV/c,
and on a longer time scale: ep collider)