Transverse spin and transverse momentum structure of the nucleon from the COMPASS experiment

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on behalf of the COMPASS Collaboration

CLAS12 3rd European Workshop

COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Fixed target experiment at CERN SPS
Data taking since 2002

Nucleon spin structure

SIDIS with high energy muon beams on: longitudinally and transversely polarized targets:

- **-gluon polarization**
- **-helicity PDF**
- **-transversity PDF**
- **-TMD PDFs**

this talk

Future measurements with DY:
Michela Chiosso talk

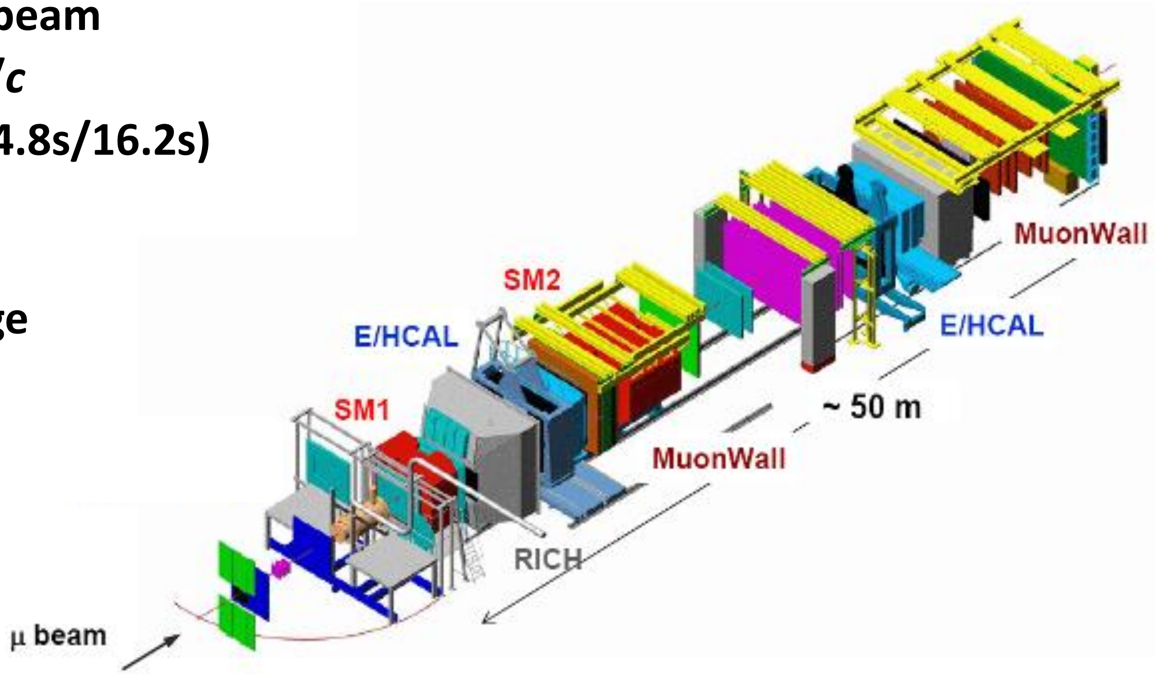
Meson and baryon spectroscopy with high energy hadron beams
Boris Grube talk yesterday

The COMPASS spectrometer

longitudinally polarised muon beam
beam momentum: 160 GeV/*c*
beam intensity: $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)

2 stage spectrometer in order to cover a large kinematic range
180 mrad angular acceptance

Muon identification
Detection and identification of hadrons for SIDIS measurements



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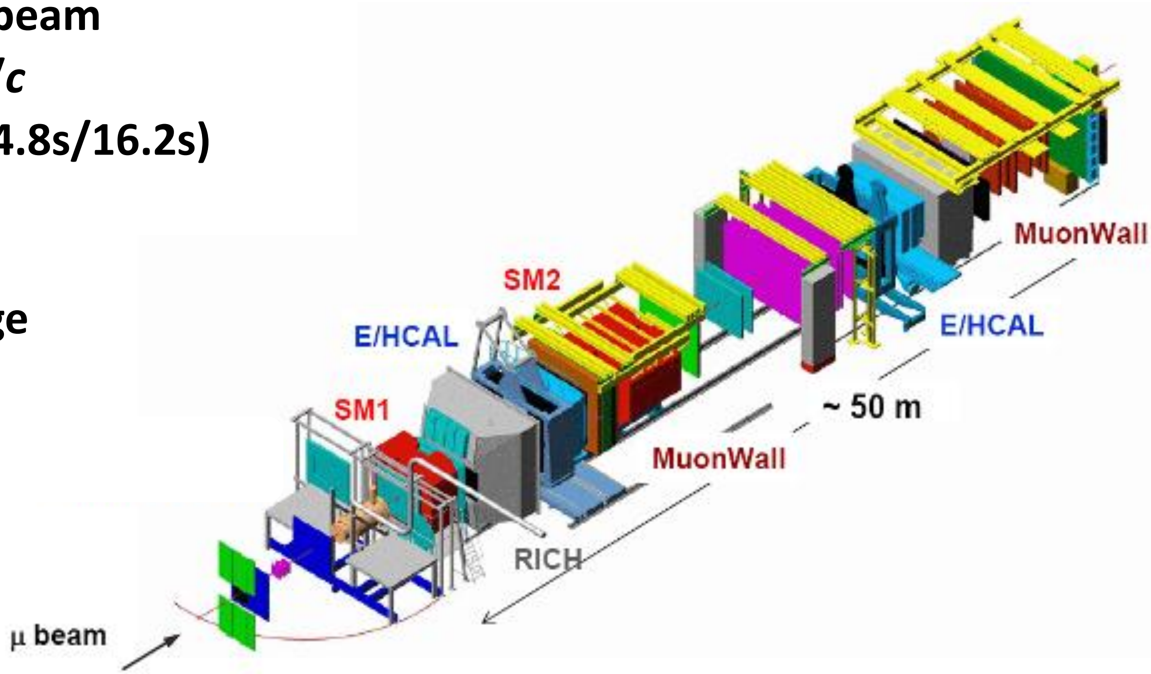

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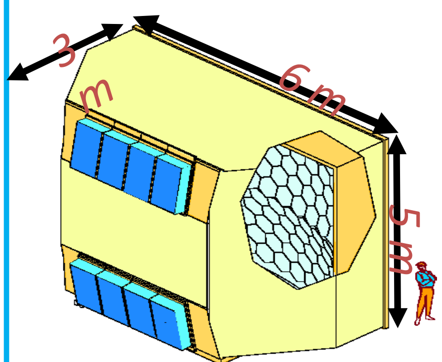
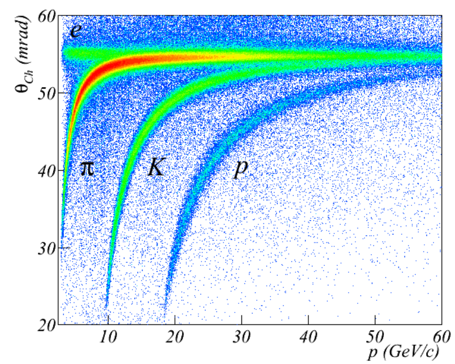


Hadron identification:

$\pi^\pm$ $K^\pm$

based on RICH-1 response (likelihood algorithm)



Cherenkov thresholds

π ~ 3 GeV/c

K ~ 9 GeV/c

p ~ 18 GeV/c

The COMPASS spectrometer

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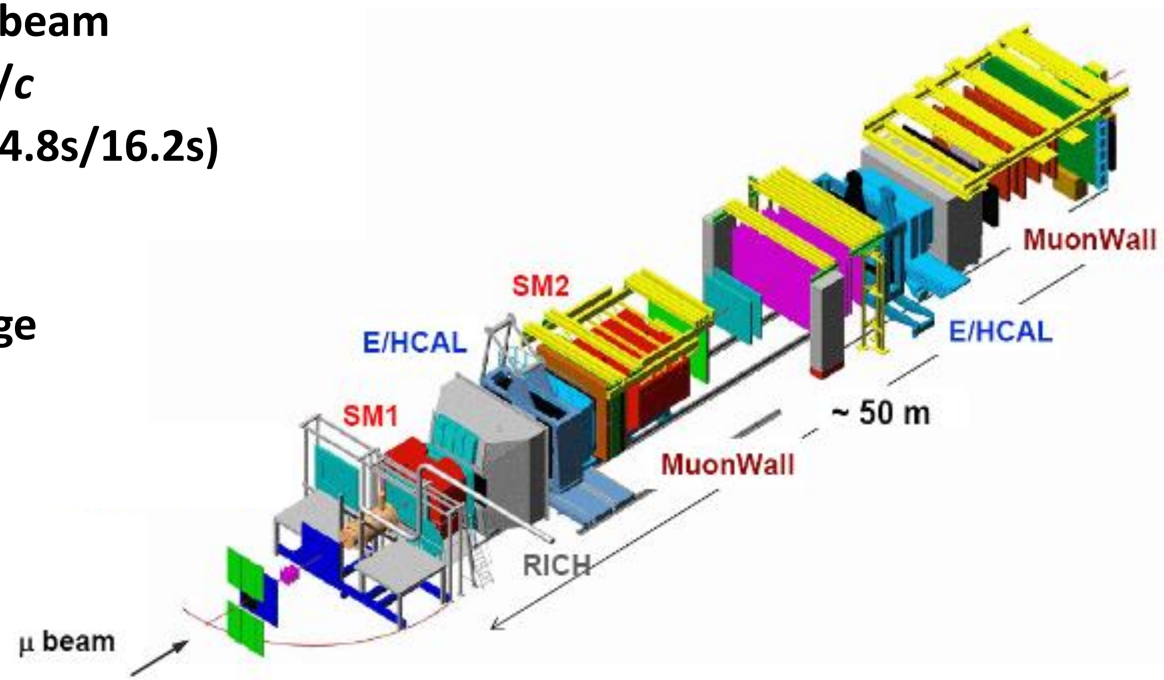
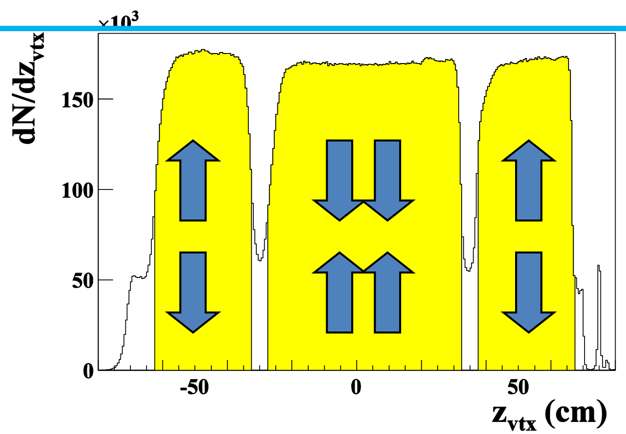


Transverse data taking
2002-4: ^{6}LiD target
p_T ~ 50% ; f ~ 0.38
2007/2010: NH_3 target
p_T ~ 90% ; f ~ 0.15



solid state target operated in frozen spin mode

2 configurations: reversed every few days

SIDIS cross section

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

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

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

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

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

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

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

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

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

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

several structure functions, depending on different combinations of azimuthal angles

Each structure function : convolution of PDF and FF

COMPASS measures all of them

SIDIS cross section: Collins and Sivers SSA

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

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$
$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$
$$+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$
$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$
$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$
$$+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

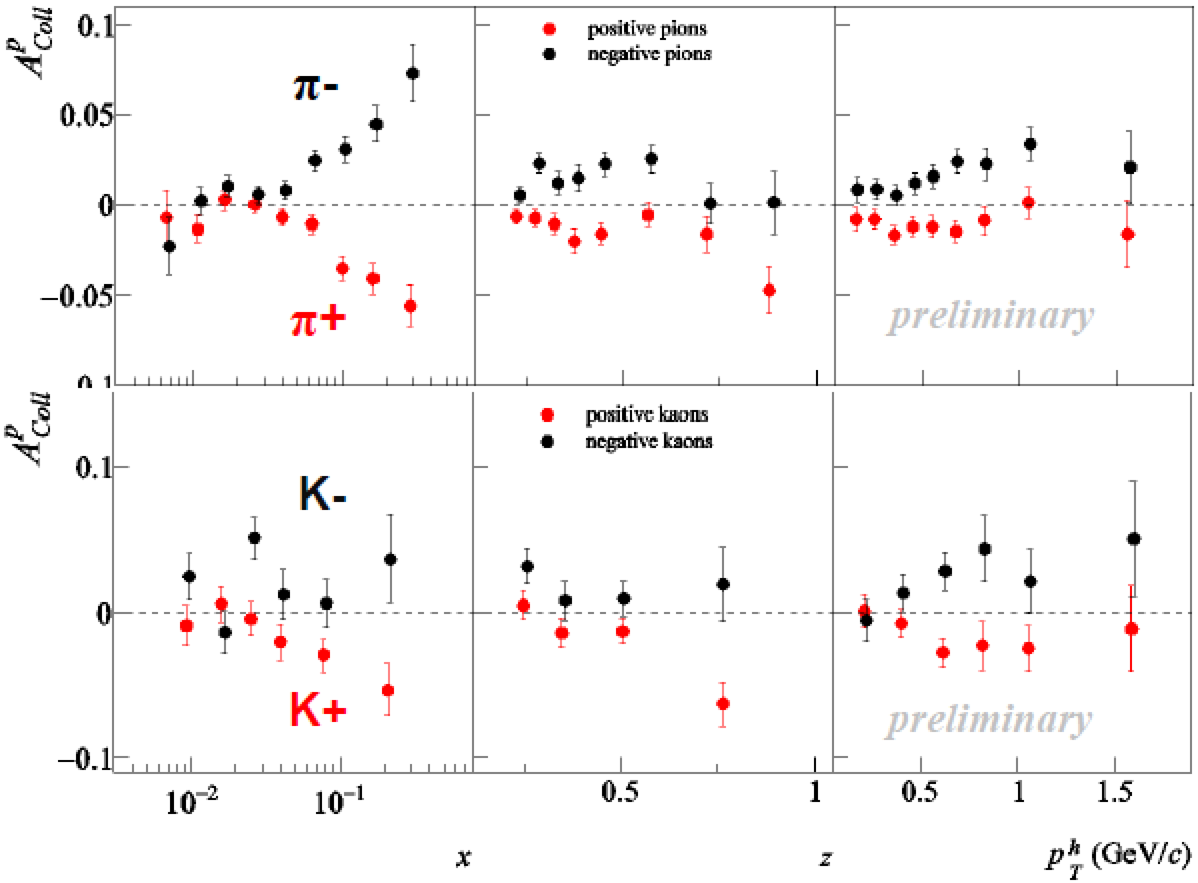
Sivers

Collins

18 structure functions,
8 transverse target dependent spin asymmetries
with different azimuthal dependences

Collins asymmetries, results on proton

Results from 2007 and 2010 data taking



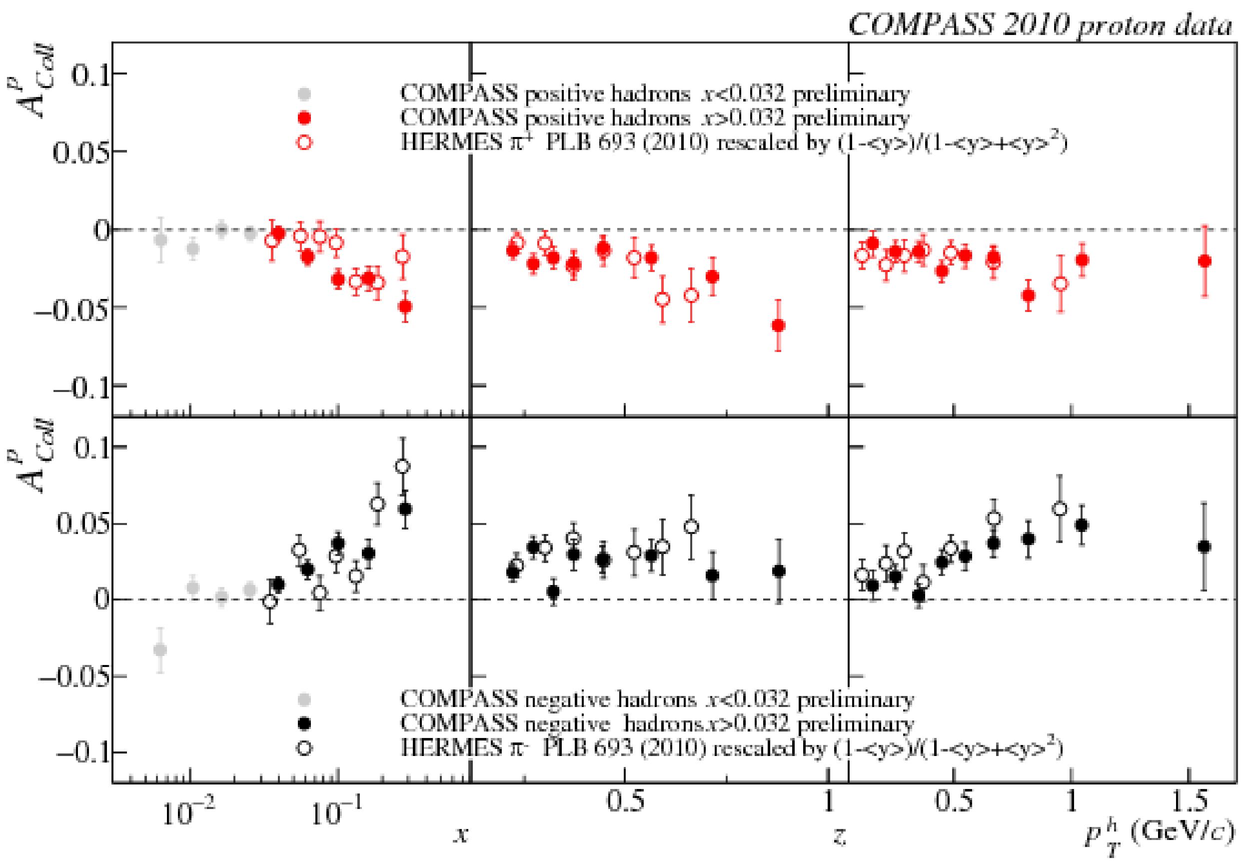
syst error ~ 0.6 stat error

- at small x asymmetries compatible with zero
- Strong signal in the valence region of opposite sign for π+ and π-
- opposite sign
  - Dunf~-Dfav

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

Collins asymmetries, results on proton

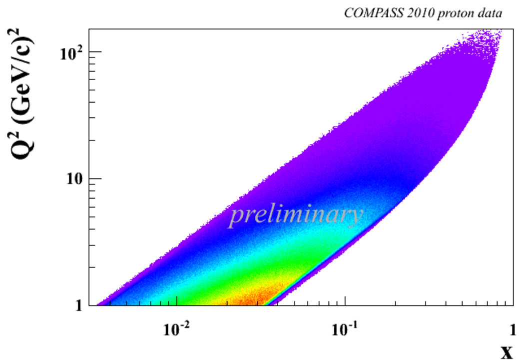
Comparison between HERMES and COMPASS,
limiting COMPASS range to the x>0.032 region, overlap with HERMES



Good agreement :

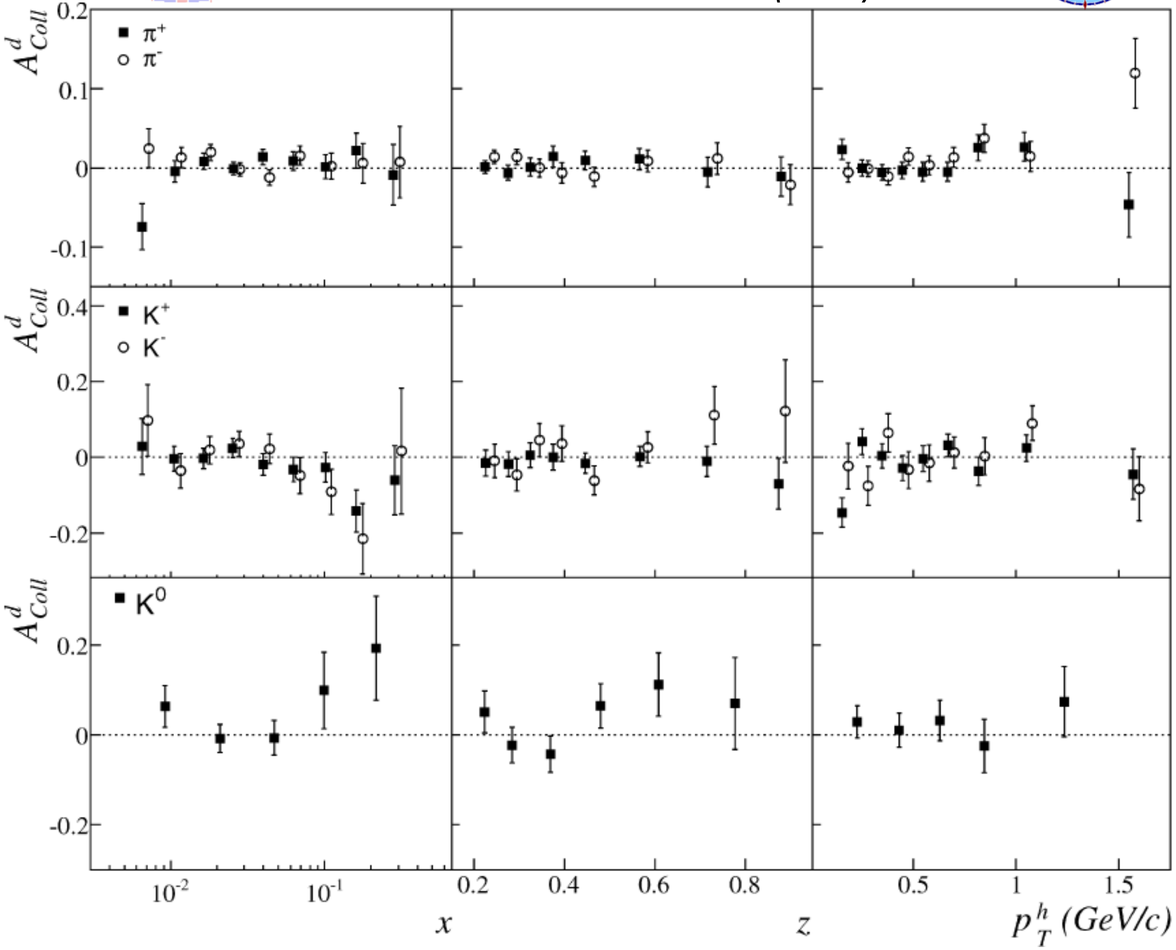
- Non trivial result:

Q^2 COMPASS larger of HERMES's of a factor 2-3 in the last x bins
→weak Q^2 dependence of the Collins effect



Collins asymmetries, results on deuterium

PLB 673(2009)127-135



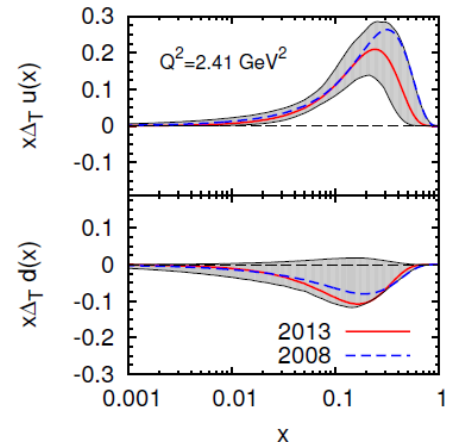
systematic error below 30% of the statistical one

Asymmetries on deuteron target compatible with zero

Some small effects expected even if $H^1_{unf} \sim -H^1_{fav}$

→ cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$

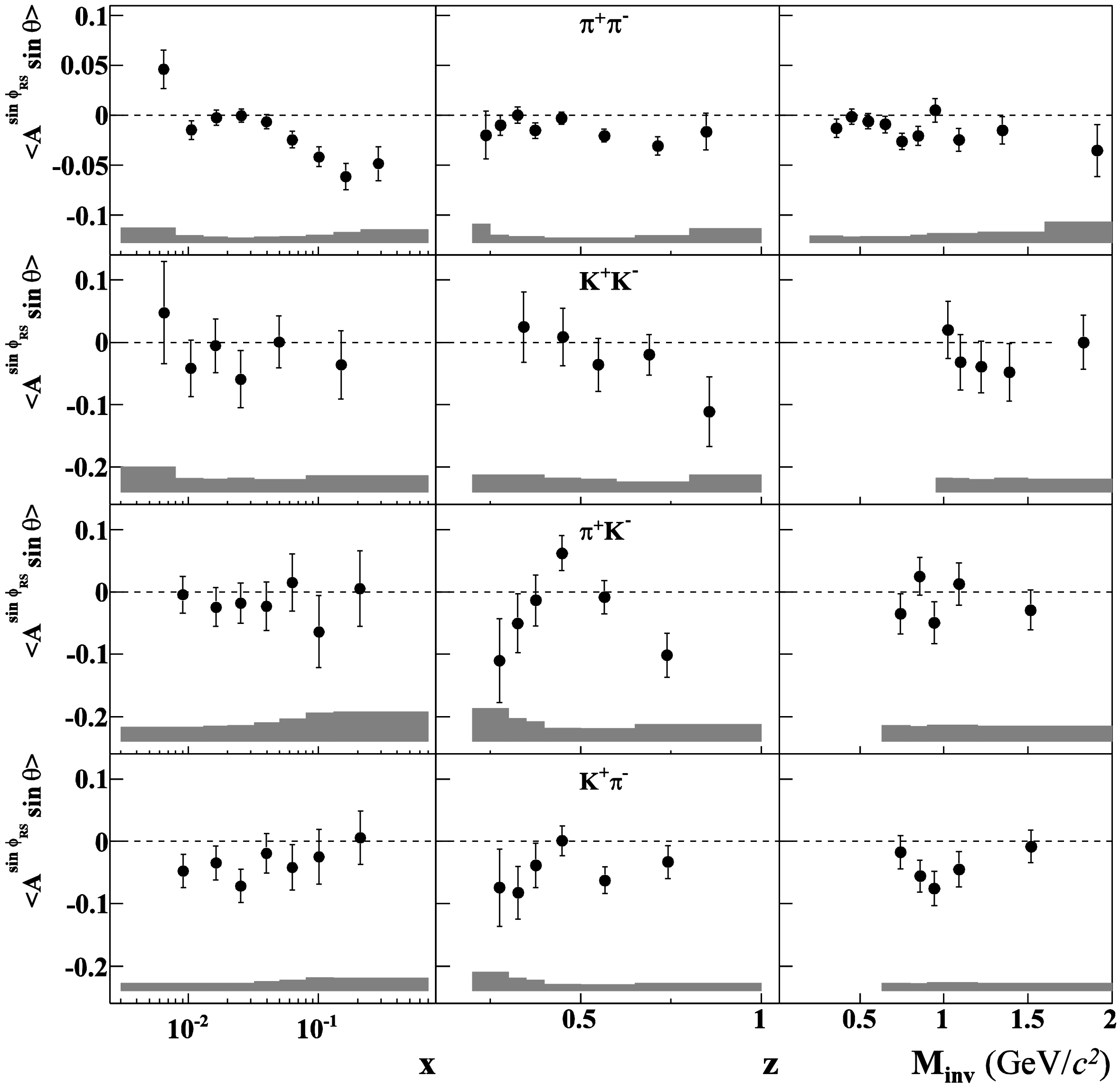
handle on $\Delta_T d(x)$



fit by Torino group (arxiv 1303.3822)

Hadron pair asymmetries, results on proton

Results from 2007 and 2010 data taking



Another way to access transversity

Recent results from all the proton data, all identified pair combinations.

$\pi^+\pi^-$ pair: trend very similar to the Collins asymmetries:
at small x asymmetries, compatible with zero,
large signal in the valence region

Other combinations $\pi^+\pi^-$ $K^+\pi^-$ π^+K^- : no clear trends visible.

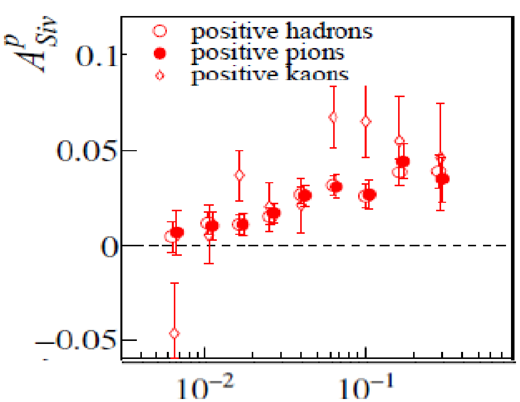
COMPASS measured also very small asymmetries on deuterium

Sivers asymmetries, results on proton

- 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

K^+ positive in average
K^- compatible with 0

- difference between K^+ and π^+: **important** role of sea quarks?



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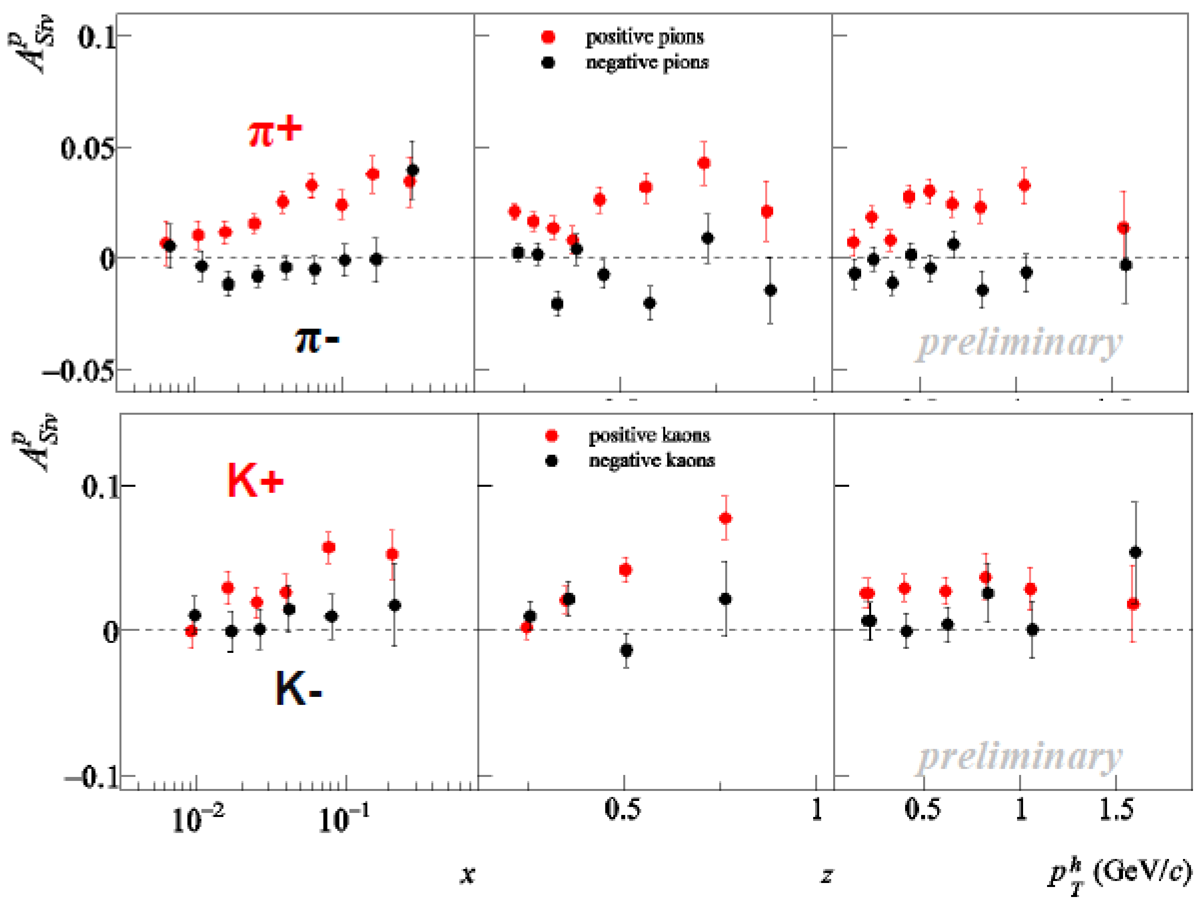
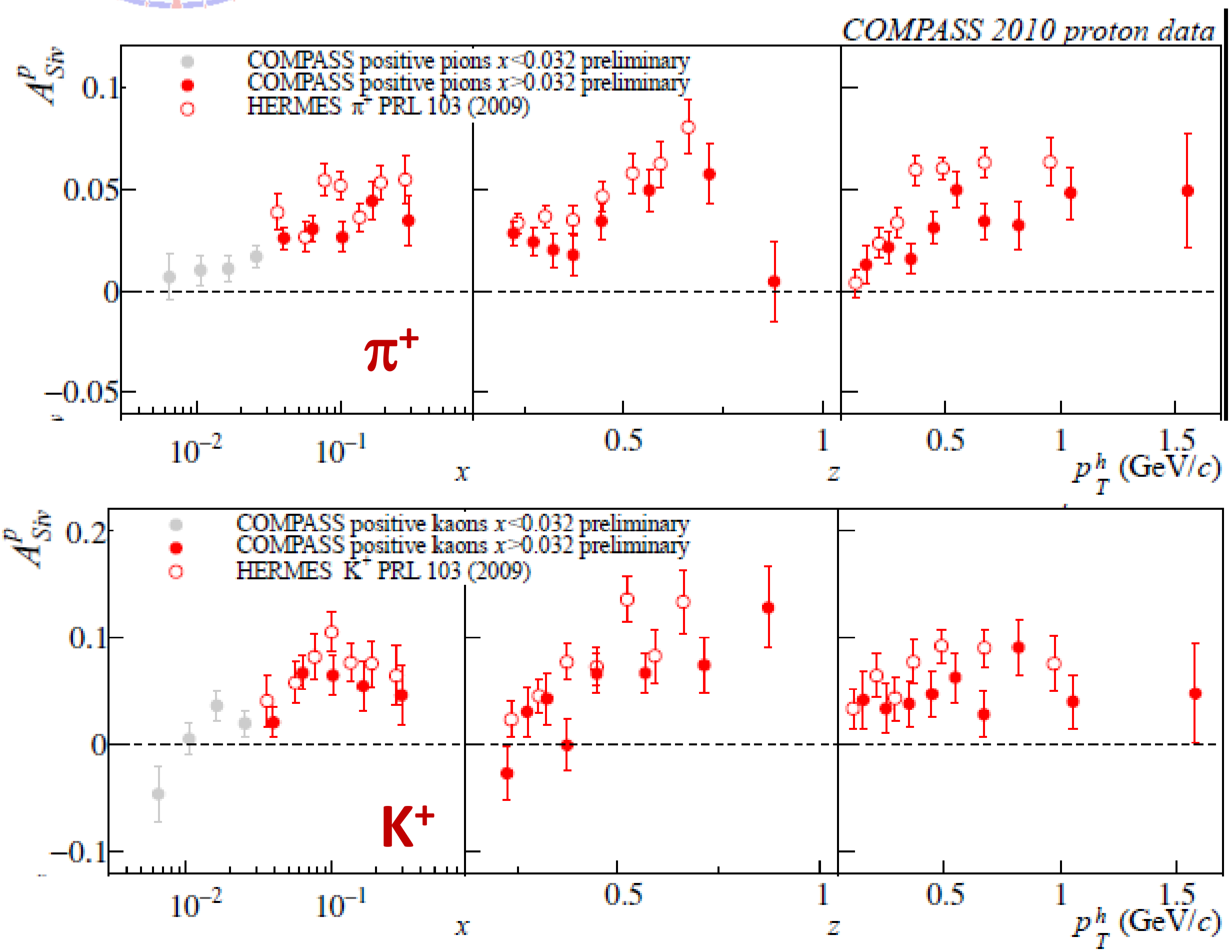


syst error ~ 0.6 stat error

Sivers asymmetries, results on proton

Comparison between HERMES and COMPASS, limiting COMPASS range to the x>0.032 region, overlap with HERMES



HERMES π^+ and K^+ asymmetries larger than COMPASS

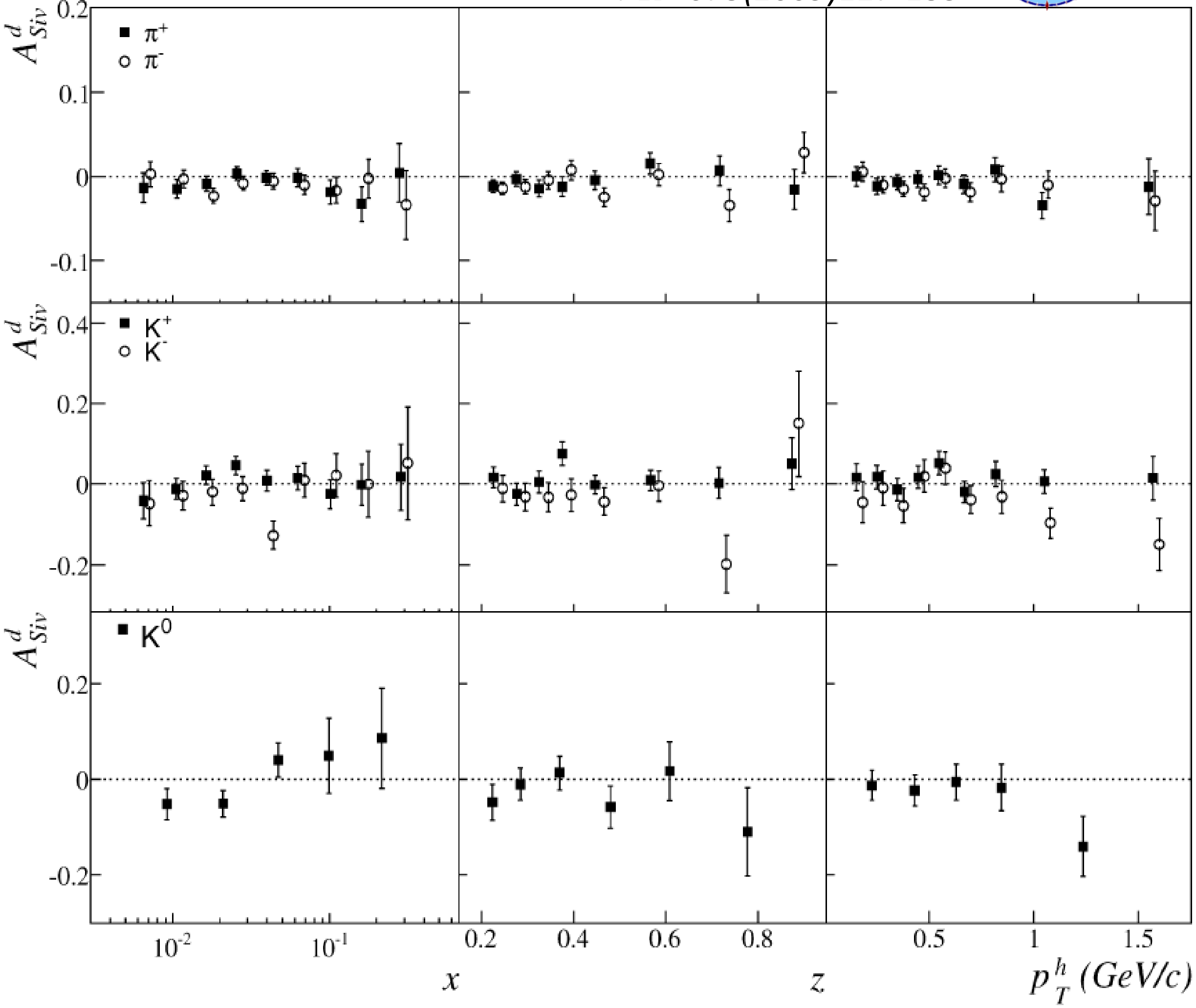
Q^2 COMPASS larger of HERMES's of a factor 2-3 in the last x bins
→Q^2 dependence of the Sivers effect plays a role

TMD Q^2 evolution has been worked out and added in global fits very recently

S. M. Aybat, A. Prokudin, T. C. Rogers PRL 108 (2012) 242003
M. Anselmino, M. Boglione, S. Melis PRD 86 (2012) 014028

Sivers asymmetries, results on deuterium

PLB 673(2009)127-135



Asymmetries on deuteron target compatible with zero

→ cancellation between $\Delta_T u$ (x) and $\Delta_T d$ (x)

handle on $\Delta_T d$ (x)

systematic error below 30% of the statistical one

SIDIS cross section other leading twist terms

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

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

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

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

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

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

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

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

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

wormgear $h_{1L}^{\perp}\otimes H_1^{\perp}$

All asymmetries on d compatible with zero;

pretzelosity $h_{1T}^{\perp}\otimes H_1^{\perp}$

All asymmetries on p and d, compatible with zero

wormgear $g_{1T}\otimes D_1$

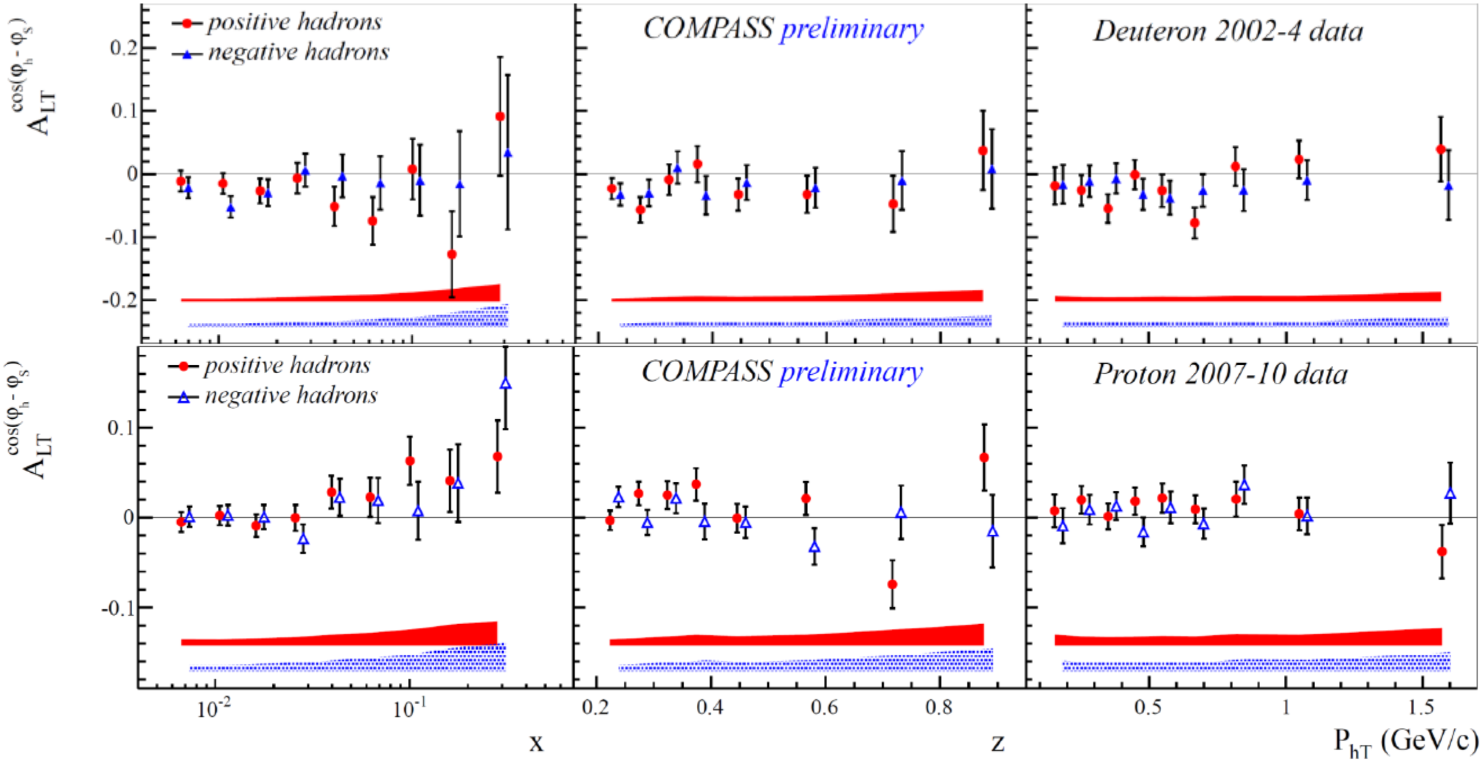
Other transverse spin asymmetries

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

wormgear

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

Double spin asymmetries, requiring both longitudinally polarized beam and transversely polarized target



Similar trend is present in HERMES preliminary results

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

SIDIS cross section: unpolarized part

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

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

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

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

3 independent modulations in the hadron azimuthal distribution

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

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

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

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

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

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

SIDIS cross section: unpolarized part

Also the azimuthal asymmetries in the unpolarized cross section give information on TMD effects.

$A_{\sin\phi_h}$ higher twist effect proportional to beam polarization
no clear interpretation in terms of PM

$$A^{UU}_{\cos\phi_h} = \frac{1}{Q} Cahn + \frac{1}{Q} BM$$

Cahn effect + Boer-Mulders DF

$$A^{UU}_{\cos 2\phi_h} = BM + \frac{1}{Q^2} Cahn$$

Boer- Mulders x Collins FF + Cahn effect

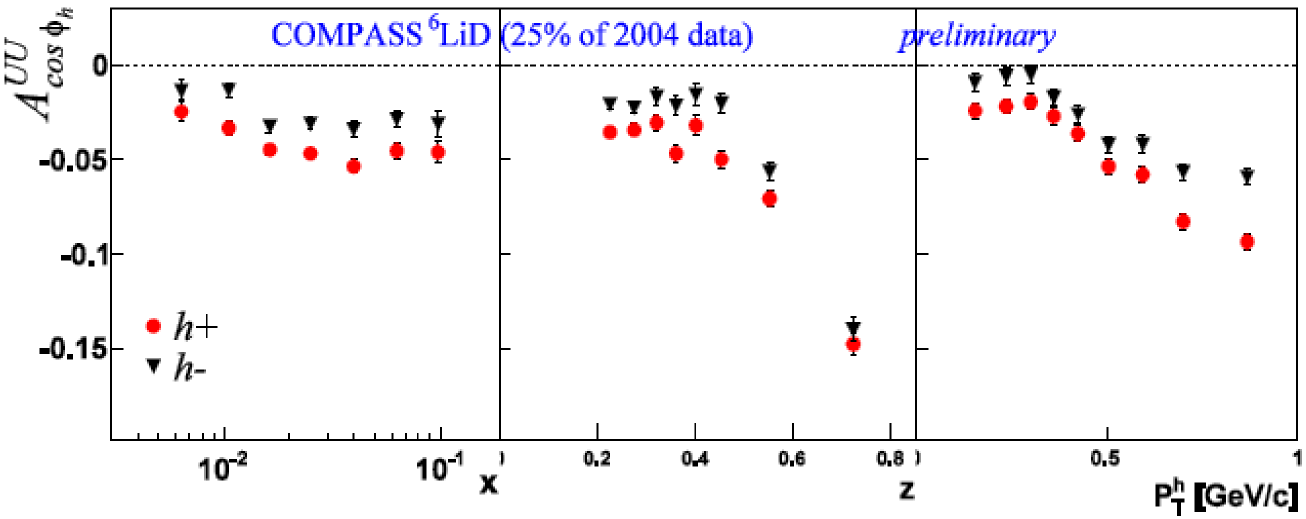
Cahn effect
kinematical effect due to quark transverse momentum

$$\frac{d\sigma}{d\phi_h} \propto 1 - 4\frac{\langle k_t^2\rangle z P_t}{Q\langle P_t^2\rangle} D_{\cos\phi_h}(y)\cos\phi_h + \dots$$

Boer-Mulders PDF
Correlation between
the **quark**
transverse momentum
and the **quark spin**
in an **unpolarized nucleon** quark

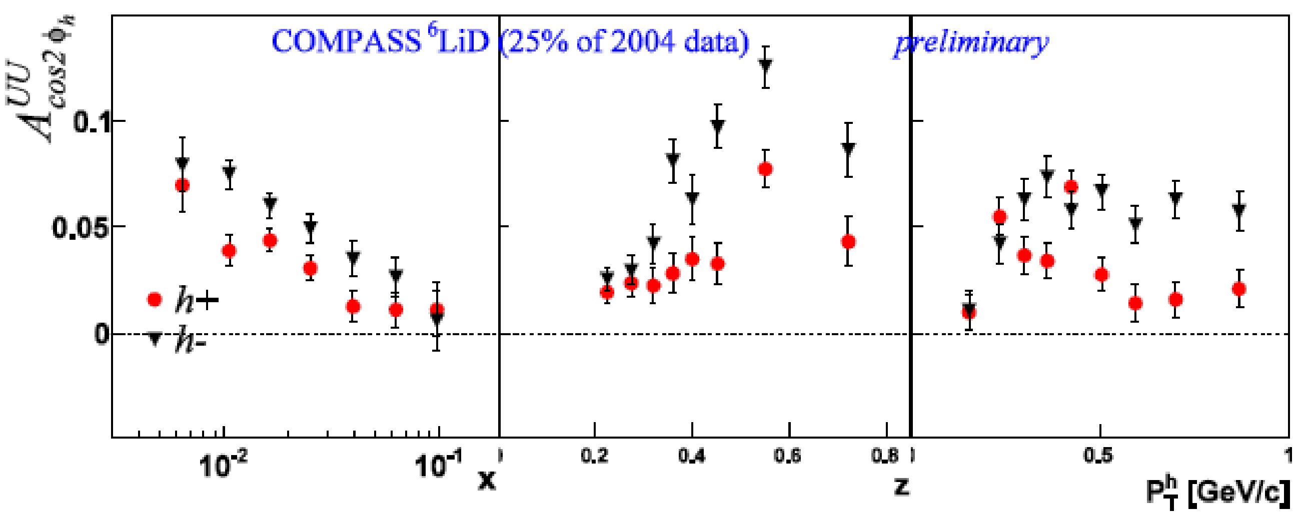
pQCD contributions expected to be important for p_T >1GeV/c

Unpolarized asymmetries, results on deuterium



cos Φ

- **Large signal over all the x range**
- **Strong z dependence, for z > 0.5**

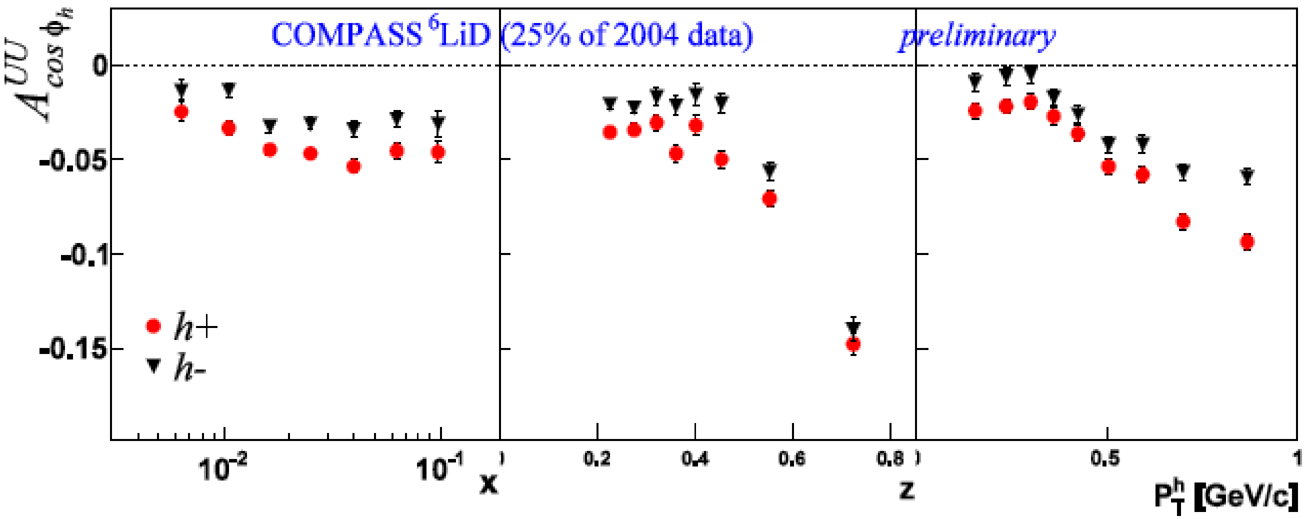


sys ≈ 2 · stat

cos 2Φ

- **Different for positive and negative hadrons**
- **Large signal at small x**
- **Strong dependence on x, z, and p_T, difficult to describe**

Unpolarized asymmetries, results on deuterium



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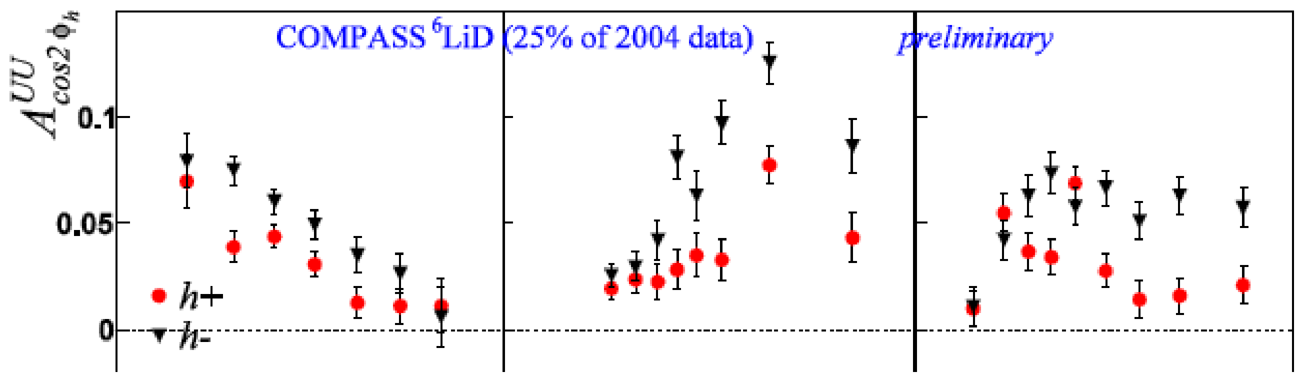

cos 2Φ
- **Different for positive and negative hadrons**
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- **Strong dependence on x, z, and p_T, difficult to describe**

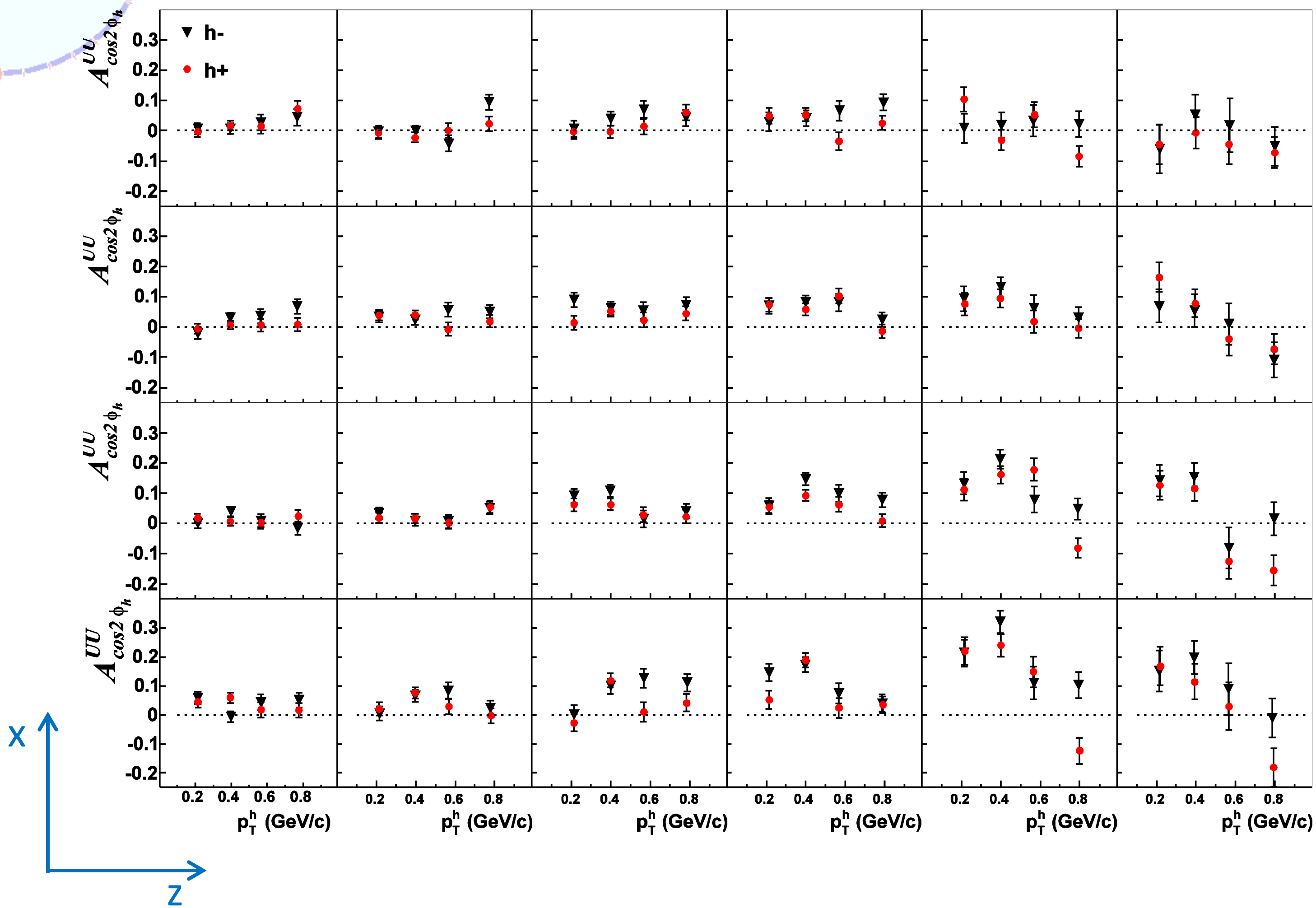
To investigate deeper the complicated and unexpected kinematical dependencies found, a multi-dimensional analysis has been done, binning simultaneously in x, z and p_T

→interesting input for theory

x	P_T^h	z
0.003 - 0.012	0.1 - 0.3	0.2 - 0.25
0.012 - 0.02	0.3 - 0.5	0.25 - 0.32
0.02 - 0.038	0.5 - 0.64	0.32 - 0.40
0.038 - 0.13	0.64 - 1.0	0.40 - 0.55
		0.55 - 0.70
		0.70 - 0.85

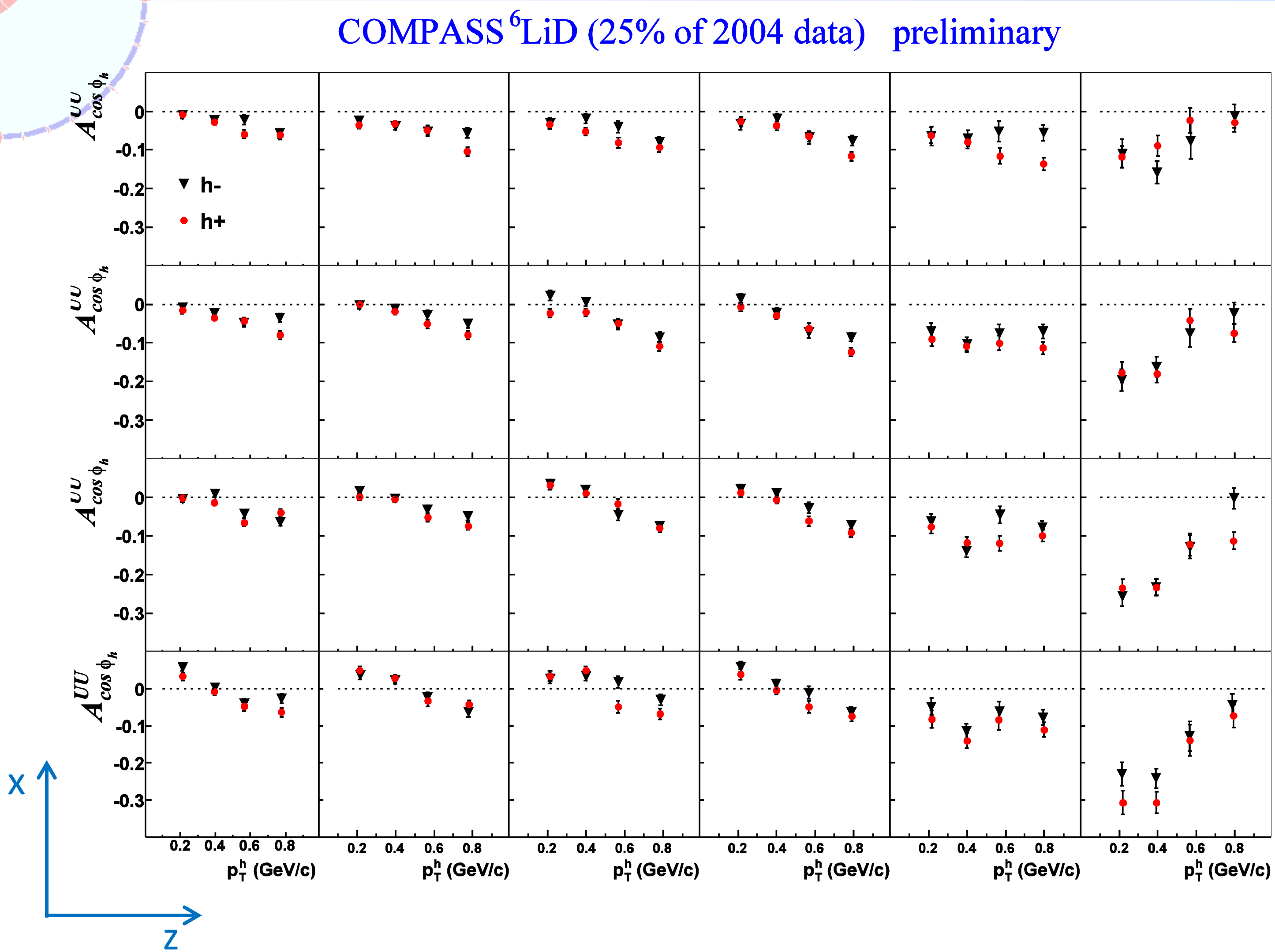
cos2Φ asymmetries multi-dimensional analysis

COMPASS ^{6}LiD (25% of 2004 data) preliminary



The p_T trend difficult to reproduce by models is there for large z and low x

cosΦ asymmetries multi-dimensional analysis



The p_T trend changes with z, and it is roughly the same over all the x range

Conclusions

COMPASS has investigated transverse spin and TMD effects via SIDIS off deuterium and proton targets.

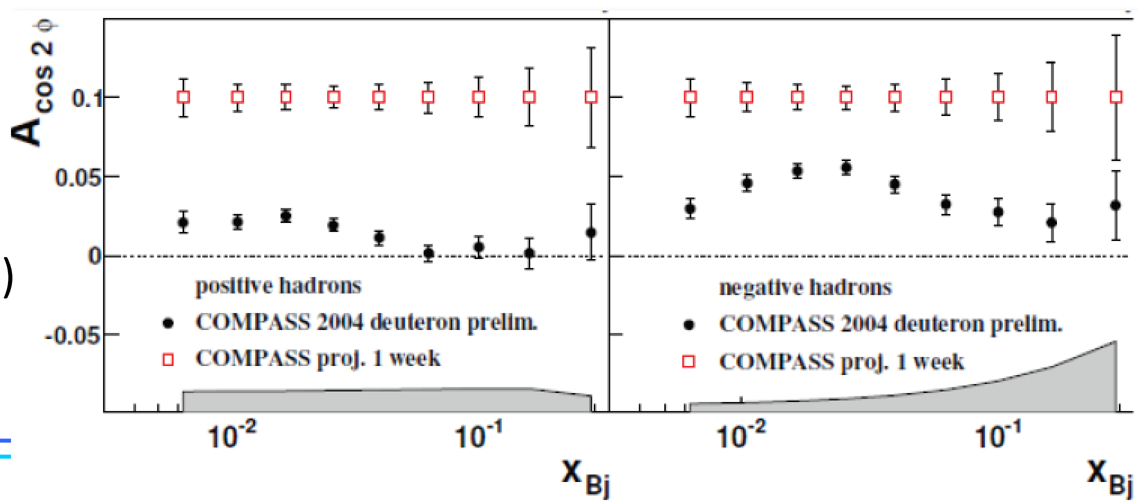
Full set of results on **Collins and Sivers asymmetries**, on pions and kaons : interesting effects on p to be investigated deeper with a multi-dimensional analysis

Results on many other channels available: other 6 transverse asymmetries , 2h asymmetries, longitudinal azimuthal spin asymmetries …

On a longer time scale, possible SIDIS measurements on p and d, with different beam energies

Unpolarized asymmetries on d different from zero, showing complex and interesting behavior in the kinematical variables.

New measurement on unpolarized hydrogen target in parallel to DVCS run at COMPASS II (2016-2017)



backup

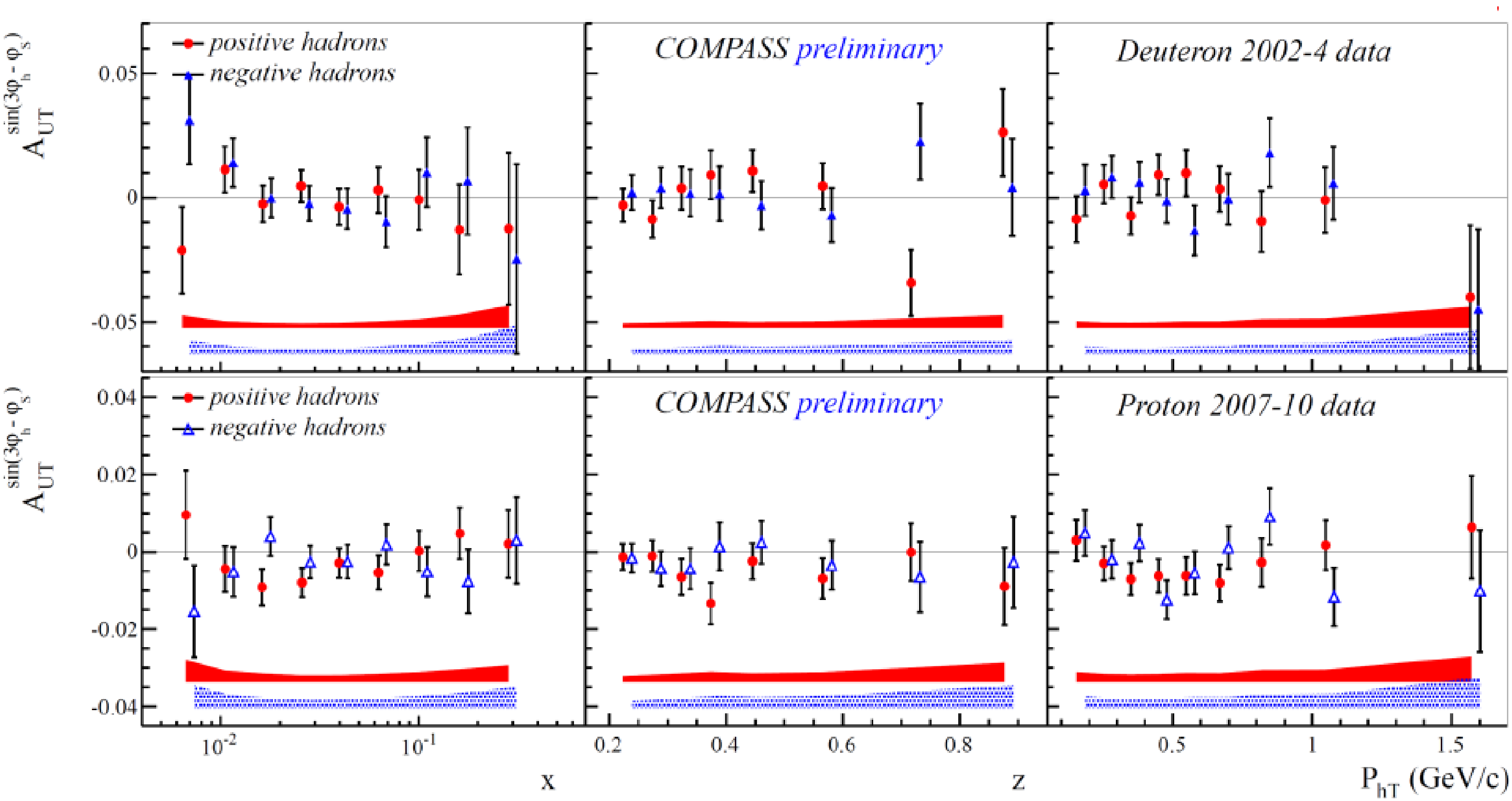
Other transverse spin asymmetries

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

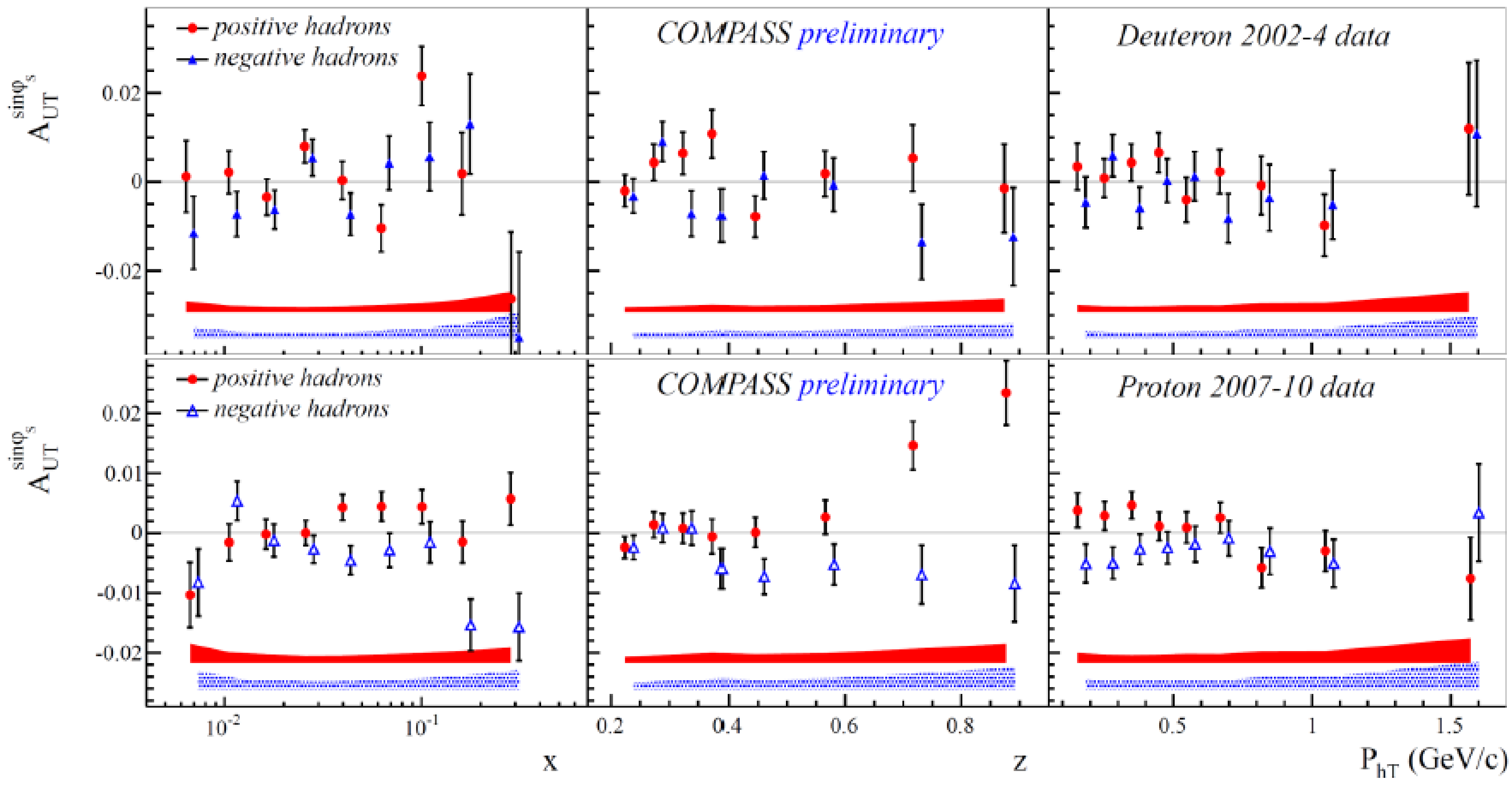
“pretzelosity” ⊗ Collins FF

All asymmetries, on proton and deuteron, compatible with zero

- Small pretzelosity PDFs/cancellations
- Suppressed by a factor of P_T^2 wrt Collins and Sivers

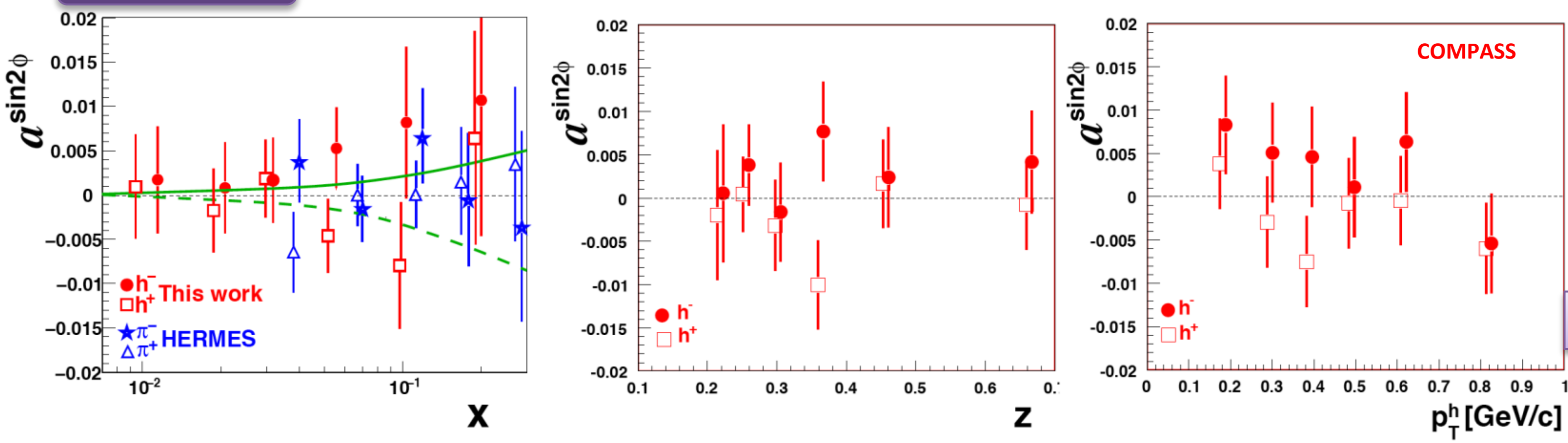


Other transverse spin asymmetries

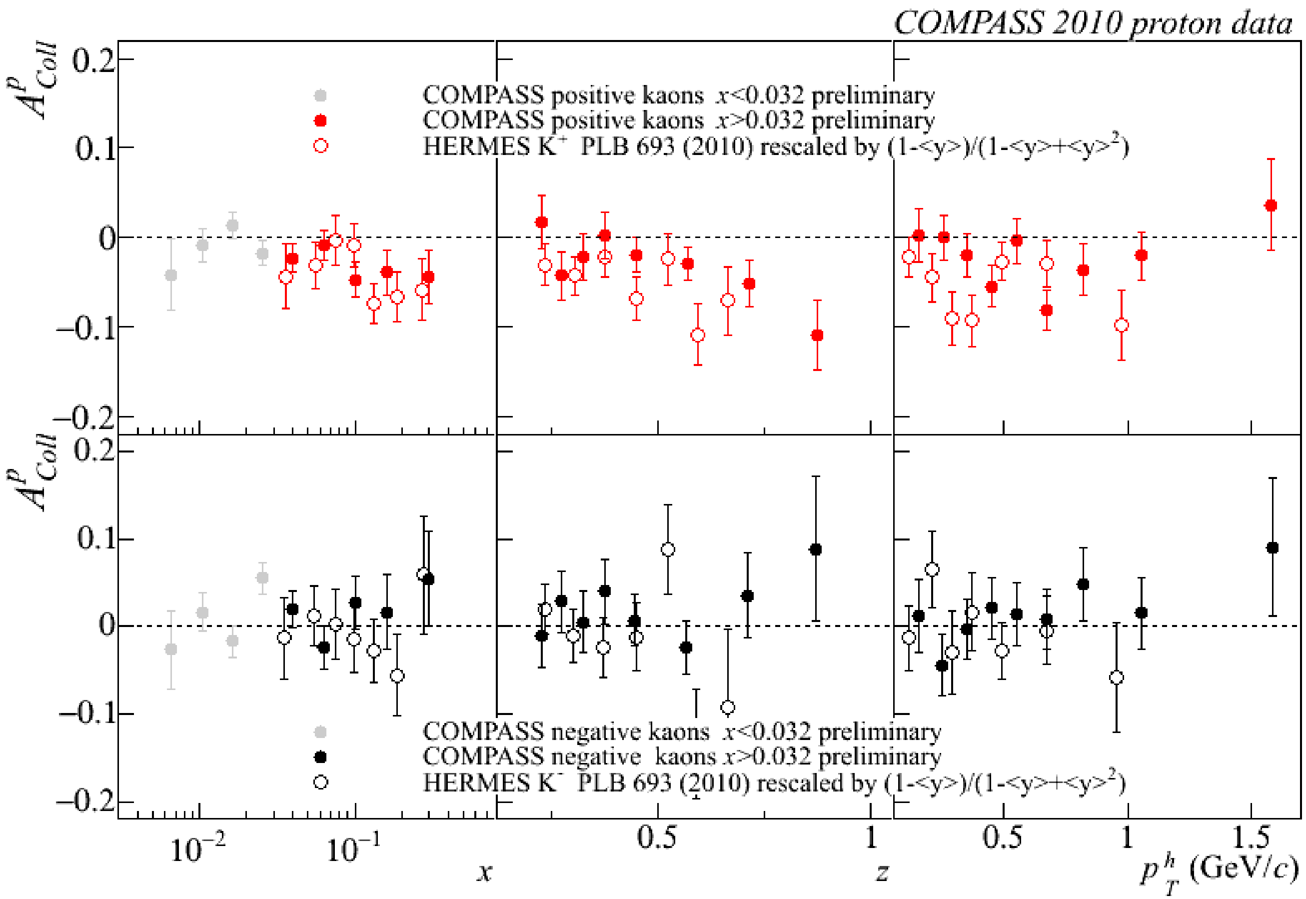


$$A_{UT}^{\sin\phi_s} \propto \frac{M}{Q}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

Deuteron



arXiv: 1007.1562



COMPASS 2010 proton data
A^p_{Coll}
COMPASS positive kaons x<0.032 preliminary
COMPASS positive kaons x>0.032 preliminary
HERMES K+ PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
COMPASS negative kaons x<0.032 preliminary
COMPASS negative kaons x>0.032 preliminary
HERMES K- PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
x
z
p^h_T (GeV/c)

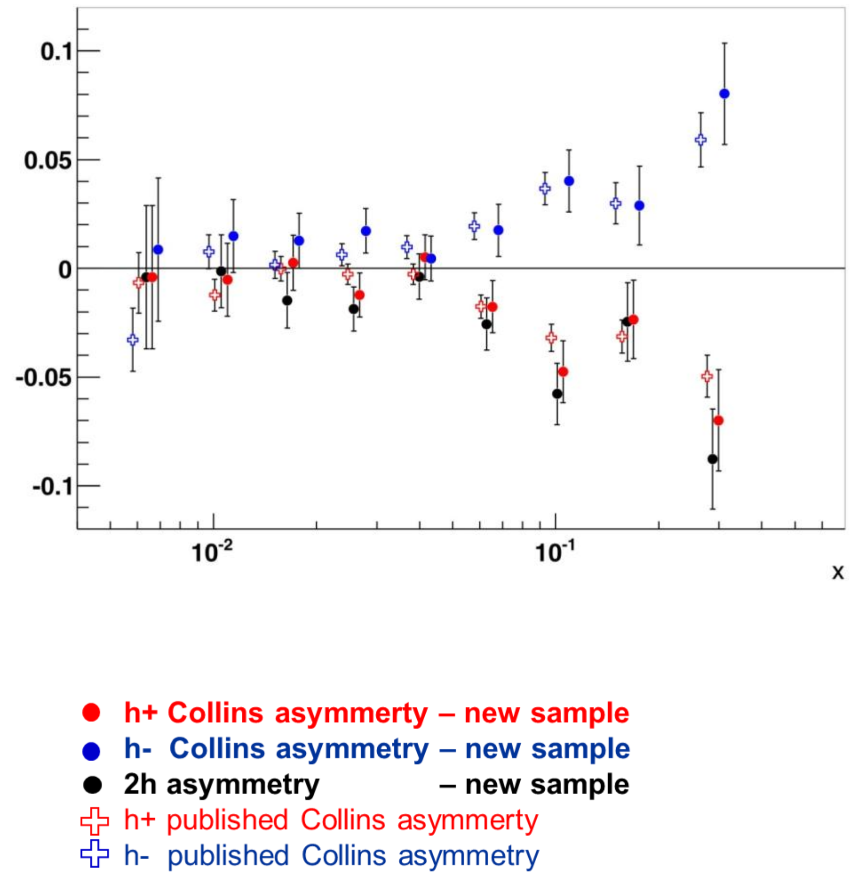
2010 data

same data selection and analysis than for published / released results

common hadron sample for Collins and 2h analysis, i.e.

- events which contain at least one positive hadron and at least one negative hadron
- for each event the number of hadrons is the number of h+h− pairs, as defined in the 2h analysis
- $p^h_T > 0.1$ GeV/c and $R_T > 0.07$ GeV/c

two sets of data, with $z_i > 0.1$ and $z_i > 0.2$



Sivers asymmetries, evolution with Q^2

TMD Q^2 evolution has been worked out and added in global fits very recently
S. M. Aybat, A. Prokudin, T. C. Rogers PRL 108 (2012) 242003
M. Anselmino, M. Boglione, S. Melis PRD 86 (2012) 014028

Fit to HERMES p and COMPASS d and p 2010 data