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

Federica Sozzi
INFN Sezione di Trieste

on behalf of the COMPASS Collaboration

Quark structure of the nucleon

At leading order, the inner structure of the nucleon can be described with three **Parton Distribution Function** (PDF):

nucleon polarisation

quark polarisation	U	L	T
U	f_1 *number density* q		
L		g_1 - *helicity* Δq	
T			h_1 - *transversity*

helicity and transversity PDF:

probability of finding a quark with a momentum fraction x and spin parallel to that of the parent nucleon...

...in a longitudinally polarised nucleon

...in a transversely polarised nucleon

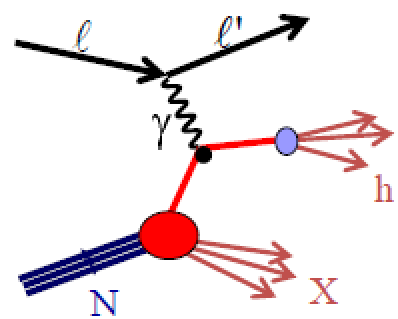
Quark structure of the nucleon

Taking into account the intrinsic parton transverse momentum, the nucleon structure description becomes more complex and needs 8 **"Transverse Momentum Dependent" PDF**.

TMDs describe the correlations between the spin and the momentum of quarks and of the parent nucleon

nucleon polarisation

quark polarisation	U	L	T
U	f_1 *number density* q		$f_{1T}^{\perp}$ Sivers
L		g_1 *helicity* Δq	g_{1T} Worm-gear
T	$h_1^{\perp}$ Boer Mulders	$h_{1L}^{\perp}$ Worm-gear	h_1 *transversity* $h_{1T}^{\perp}$ pretzelosity



One experimental way to access TMDs : SIDIS off polarised targets

SIDIS cross section

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

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

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

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

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

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

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

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

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

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

several structure functions, depending on different combinations of azimuthal angles

Each structure function : convolution of PDF and FF

COMPASS measures all of them

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Fixed target experiment
at CERN SPS
Data taking since 2002

Nucleon spin structure

with high energy muon beams
on longitudinally polarized targets:

- **-gluon polarization**
- **-helicity PDF**

Transversely polarized targets:

- **transversity PDF**
- **TMDs**

this talk

Meson and baryon spectroscopy
with high energy hadron beams

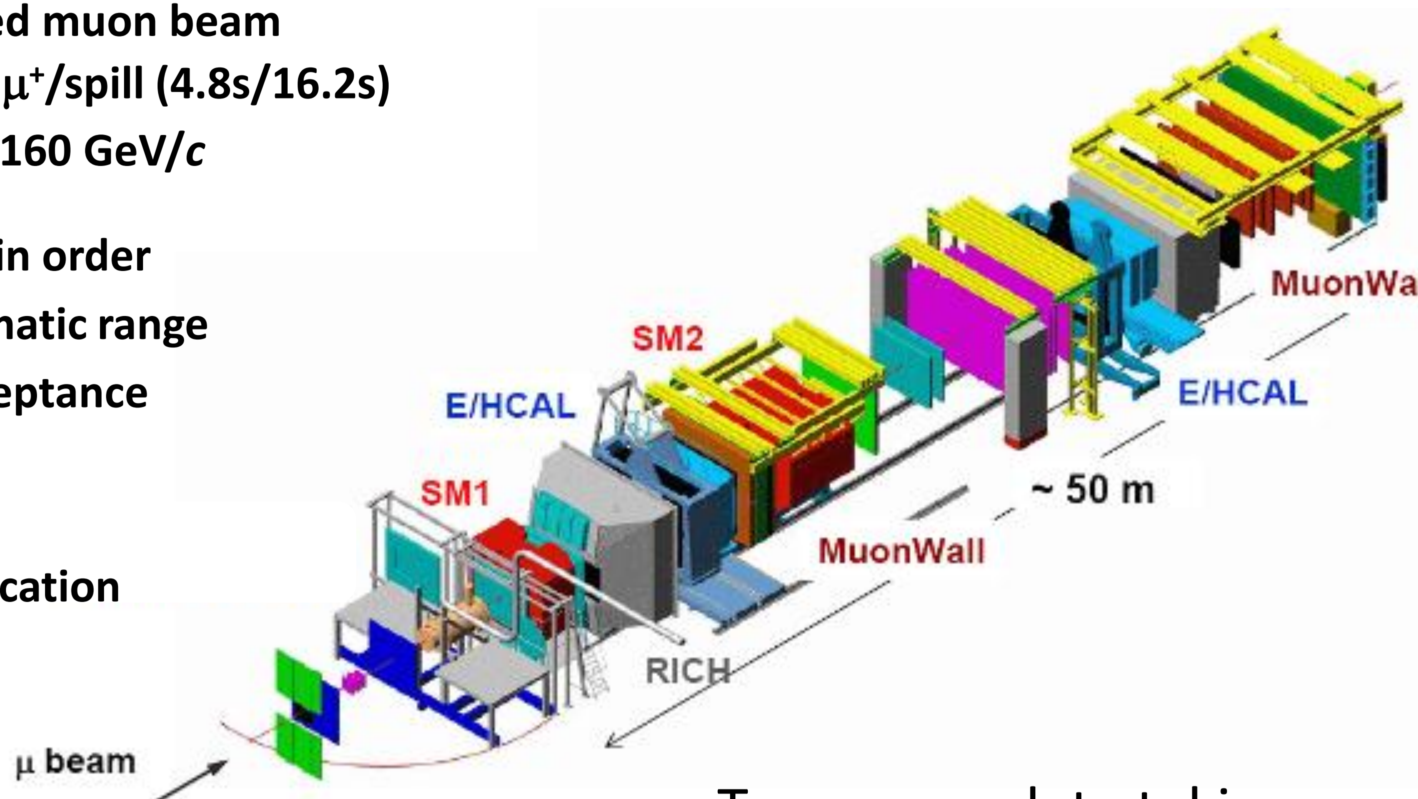
See talks by C. Marchand, C. Quintans
Poster by J. Bernhard

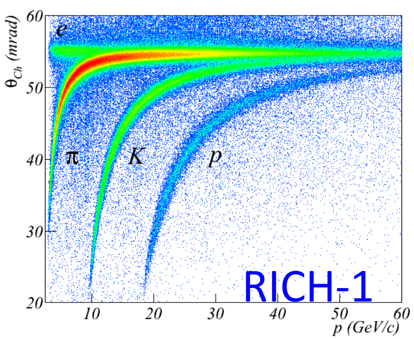
The COMPASS spectrometer

longitudinally polarised muon beam
beam intensity: 2·10[8] μ+/spill (4.8s/16.2s)
beam momentum: 160 GeV/*c*

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





π, K, p separation (from 2, 9, 17 GeV/c to ~50 GeV/c)

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

SIDIS cross section: Collins and Sivers SSA

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

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

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

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

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

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

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

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

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

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

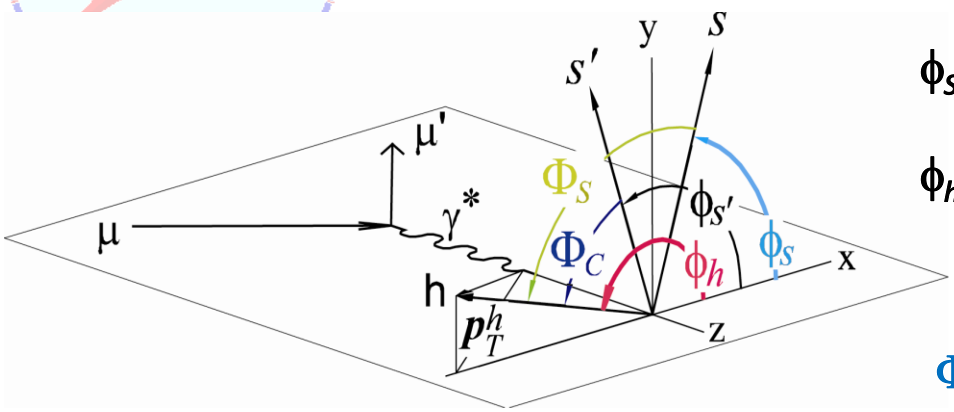
18 structure functions, 8 transverse target dependent spin asymmetries with different azimuthal dependences

Sivers

Collins

From **A. Bacchetta** et al., **JHEP 0702:093,2007**. e-Print: **hep-ph/0611265**

Azimuthal modulations: Sivers SSA



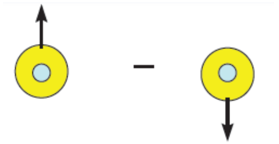
ϕ_S **azimuthal angle of spin vector of initial quark**

ϕ_h **azimuthal angle of hadron momentum**

$\Phi_S = \phi_h - \phi_S$ Sivers angle

$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

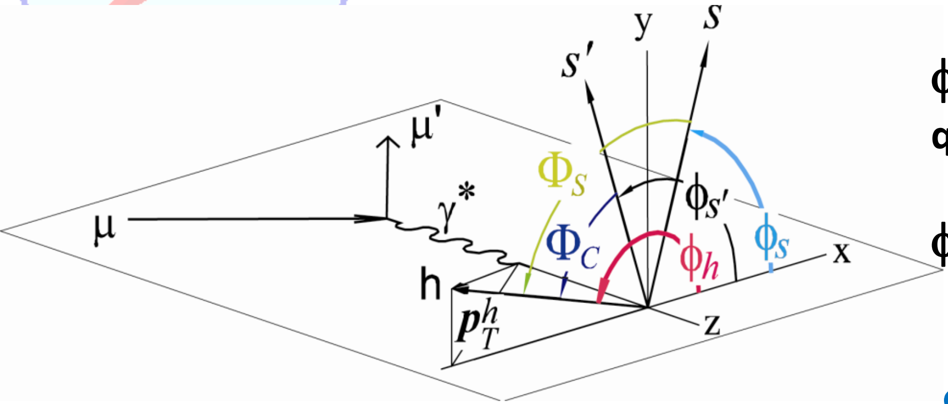
Sivers PDF ⊗ FF



Sivers PDF : correlation between the intrinsic transverse momentum of unpolarized quarks in a transversely polarized nucleon

Sensitive to orbital angular momentum

Azimuthal modulations: Collins SSA



$\phi_{S'}$ azimuthal angle of spin vector of fragmenting quark ($\phi_{S'} = \pi - \phi_S$)

ϕ_h azimuthal angle of hadron momentum

$\Phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi$ Collins angle

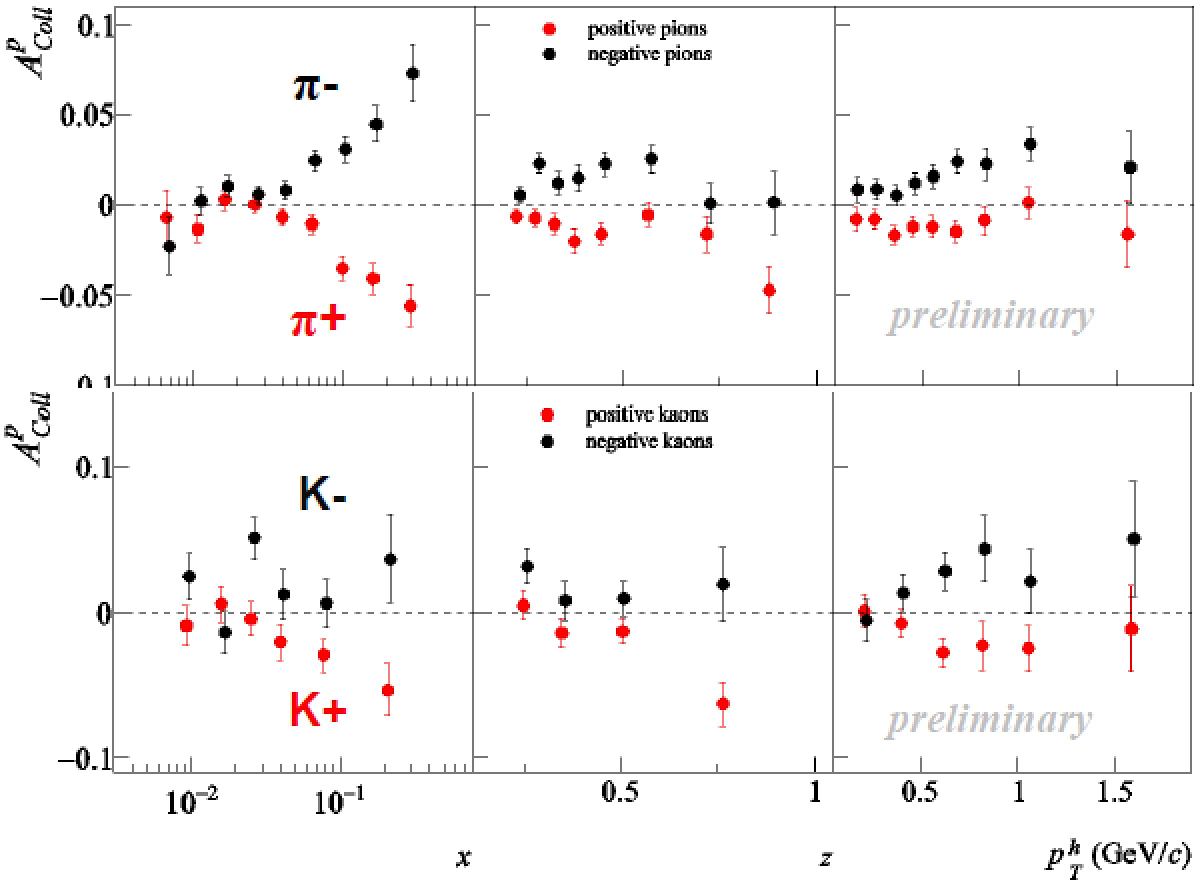
$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 \cdot h_1^q \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 \cdot f_1^q \cdot D_{1q}^h}$$

← "transversity" PDF ⊗ Collins FF

Transversity coupled to another chiral-odd function: Collins fragmentation function describing the correlation between the fragmenting quark spin and the hadron momentum

Collins asymmetries, results on proton

Results from 2007 and 2010 data taking



- at small x asymmetries compatible with zero

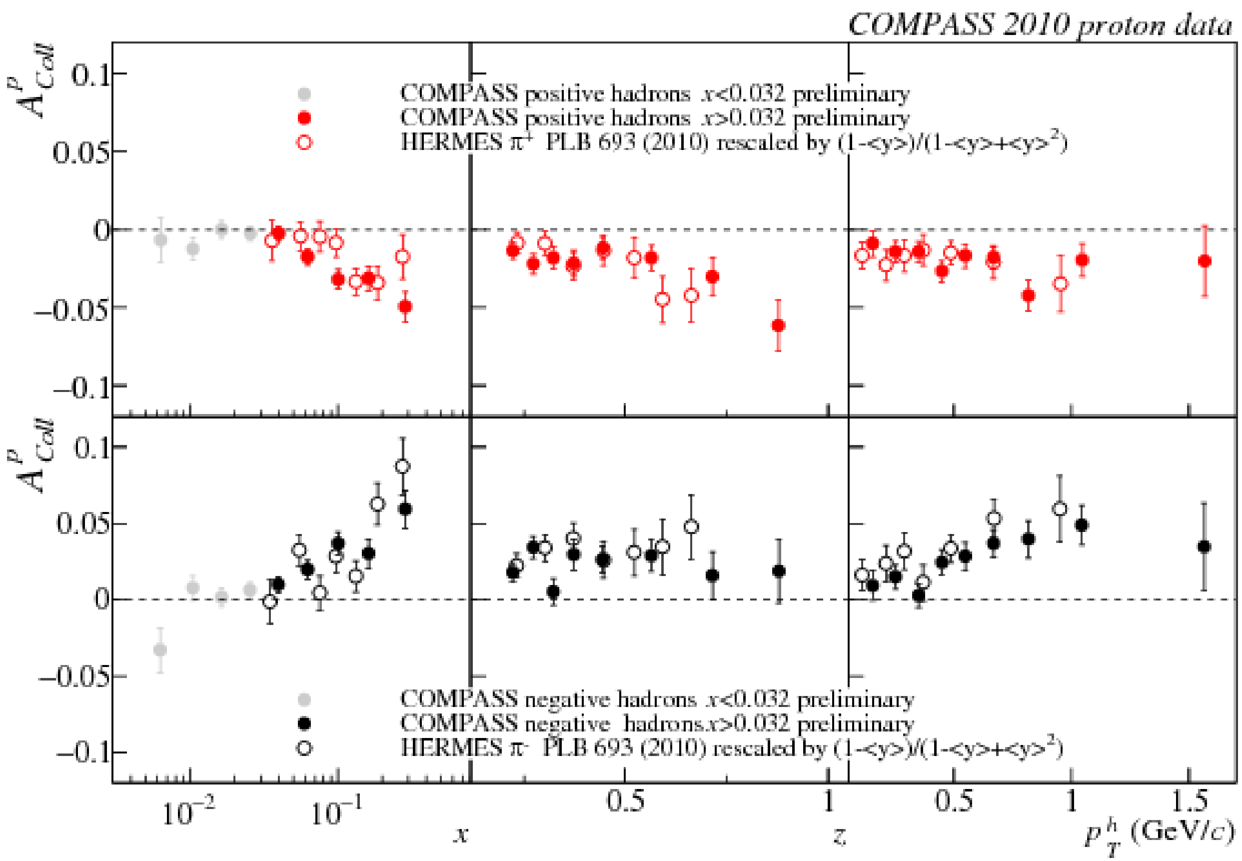
- Strong signal in the valence region of opposite sign for π+ and π-
- opposite sign
  - Dunf~-Dfav

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

syst error ~ 0.6 stat error

Collins asymmetries, results on proton

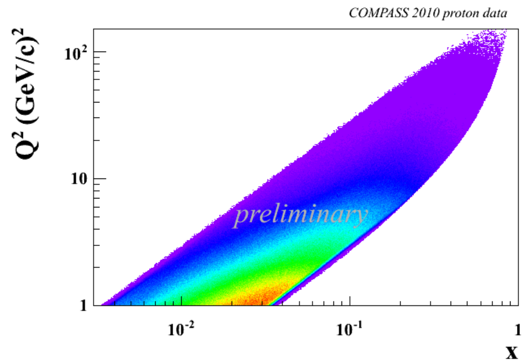
Comparison between HERMES and COMPASS,
limiting COMPASS range to the x>0.032 region, overlap with HERMES



Good agreement :

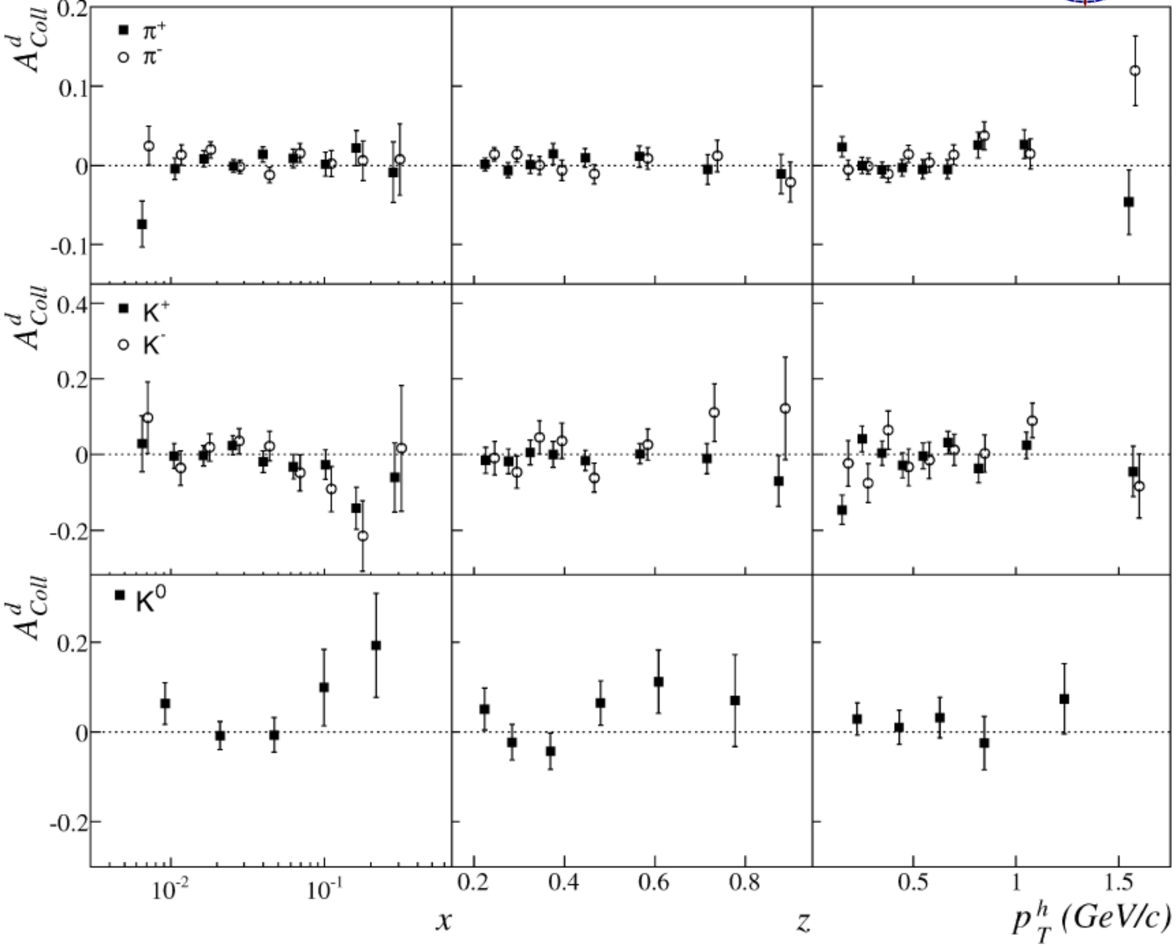
- Non trivial result:

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

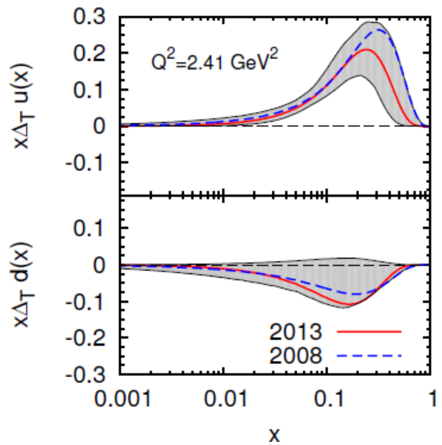


systematic error below 30% of the statistical one

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 $\Delta_T d(x)$



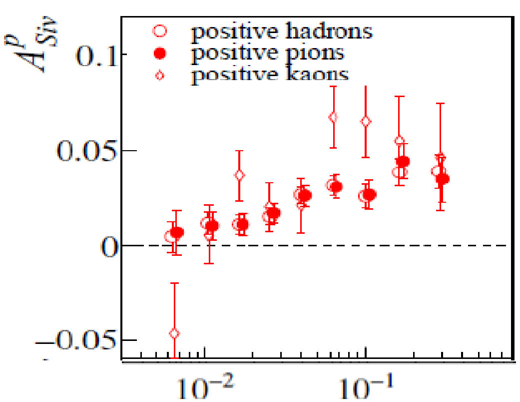
fit by Torino group (arxiv 1303.3822)

Sivers asymmetries, results on proton

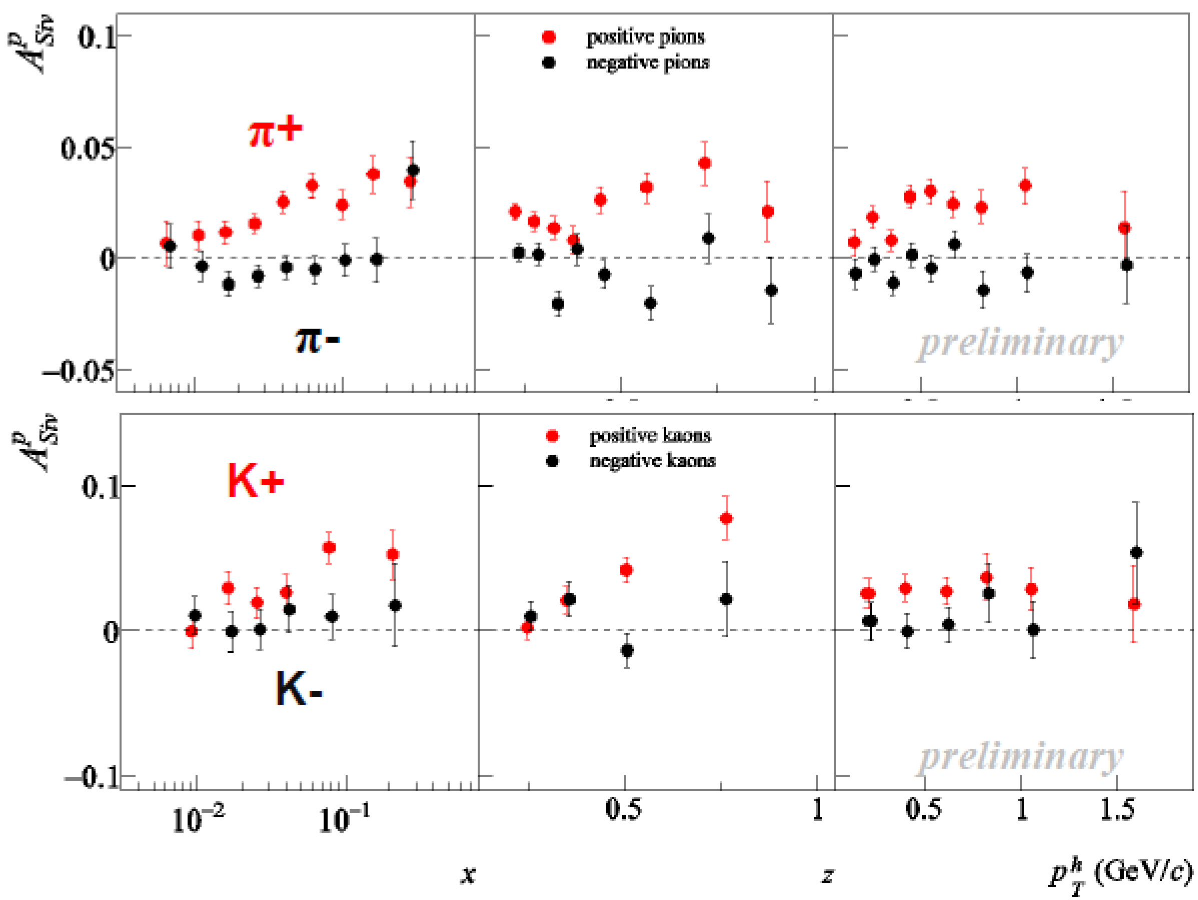
- large signal for π^+ and K^+ over all the measured x range
- increasing with z
- linear behavior at small pt, saturation for $P_T^h > 0.4$ GeV/c

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

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



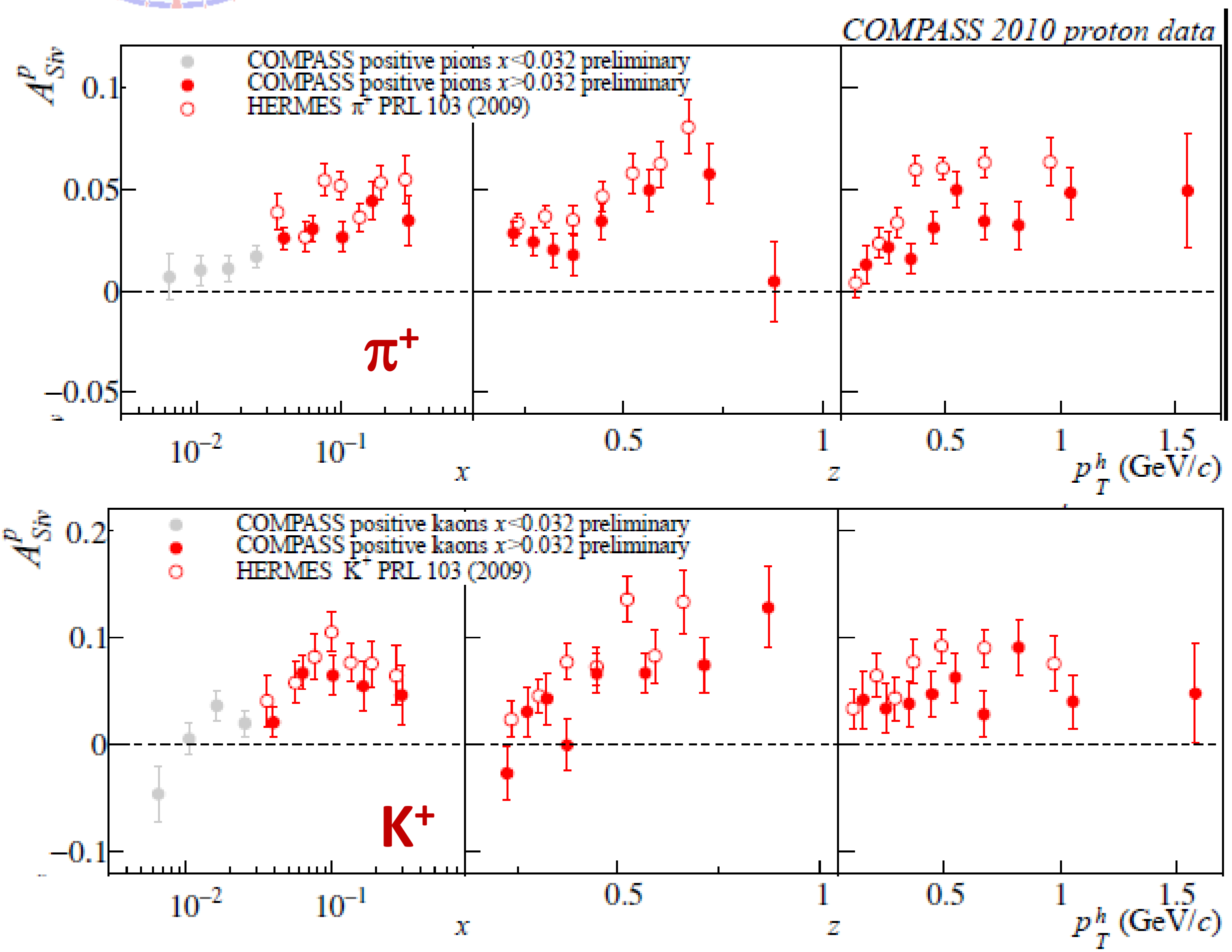
Results from 2007 and 2010 data taking



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

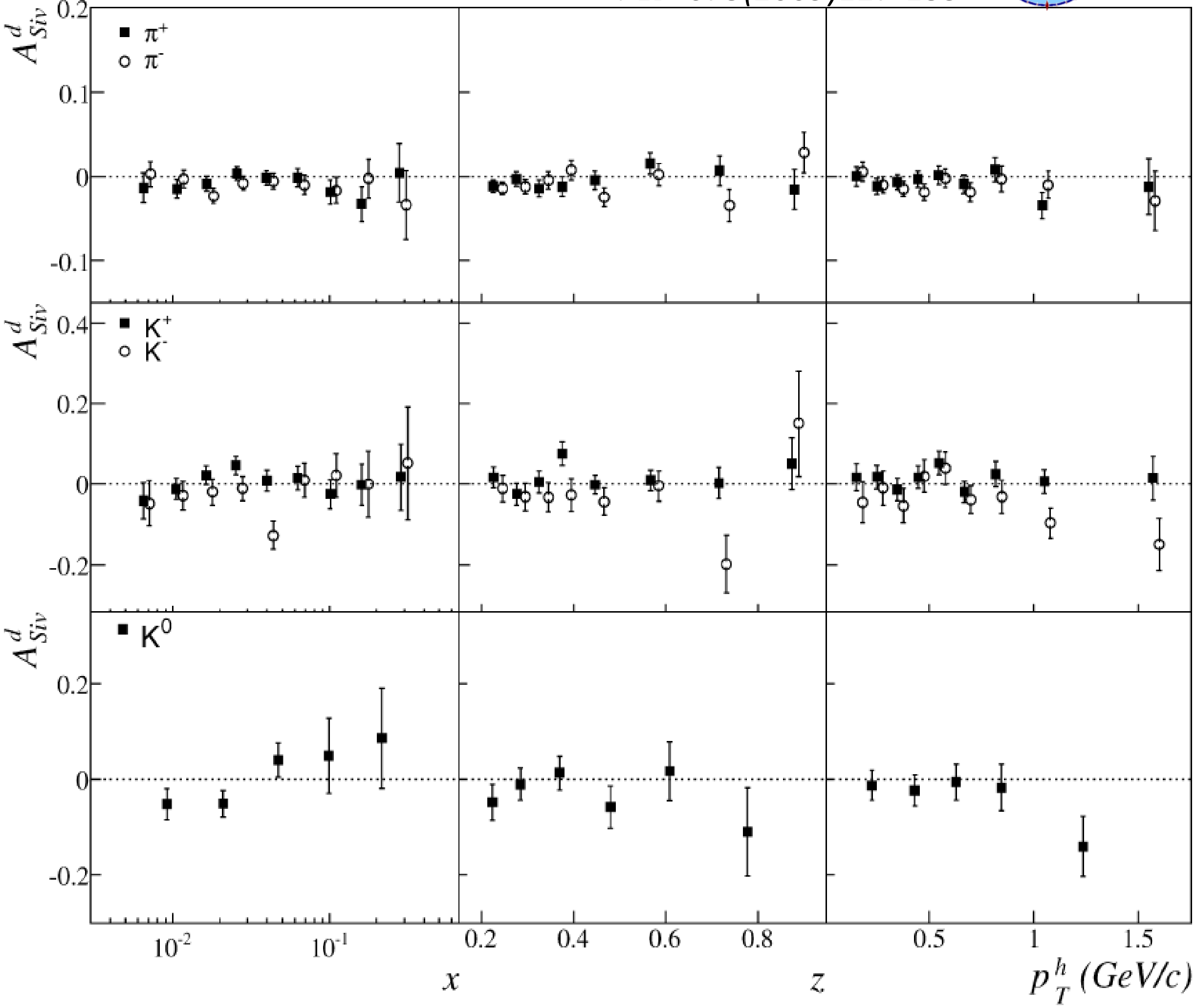
Q^2 COMPASS larger of HERMES's of a factor 2-3 in the last x bins
→Q^2 dependence of the Sivers effect plays a role

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 transverse spin asymmetries

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

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

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

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

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

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

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

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

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

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

Sivers

Collins

other twist-2 contributions

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

All asymmetries on p and d, compatible with zero

wormgear $g_{1T}\otimes D_1$

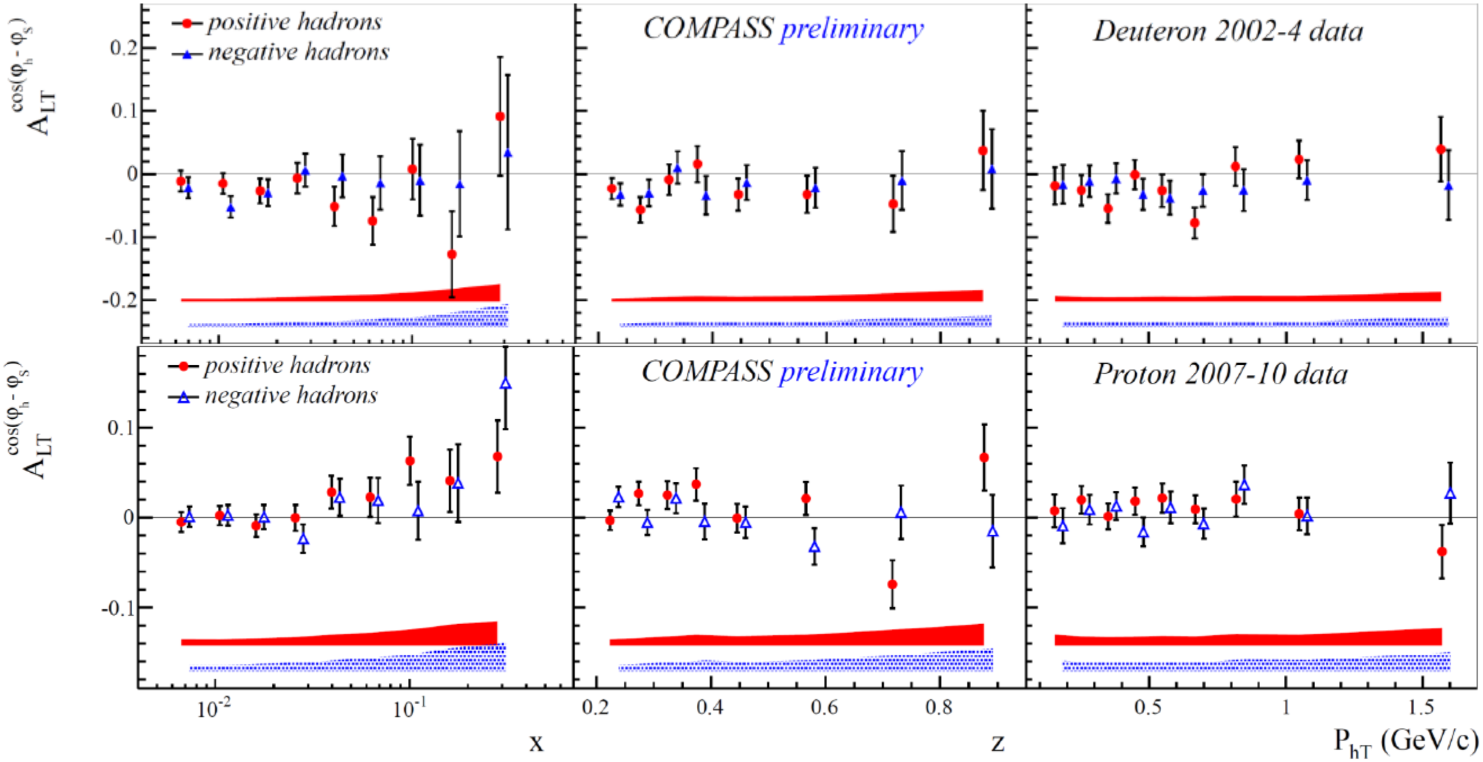
Remaining four can be interpreted as twist-3 contributions

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

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ & F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] \\
& + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
& \quad + \varepsilon\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad + \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
& + |\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S} \\
& \quad + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

3 independent modulations in the hadron azimuthal distribution

Sivers

Collins

twist-2 contribution

Remaining four can be interpreted as twist-3 contributions

From **A. Bacchetta** et al., **JHEP 0702:093,2007**. e-Print: **hep-ph/0611265**

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

$$A^{UU}_{cos2\phi_h} = BM + \frac{1}{Q^2} Cahn$$

Boer- Mulders x Collins FF + Cahn effect

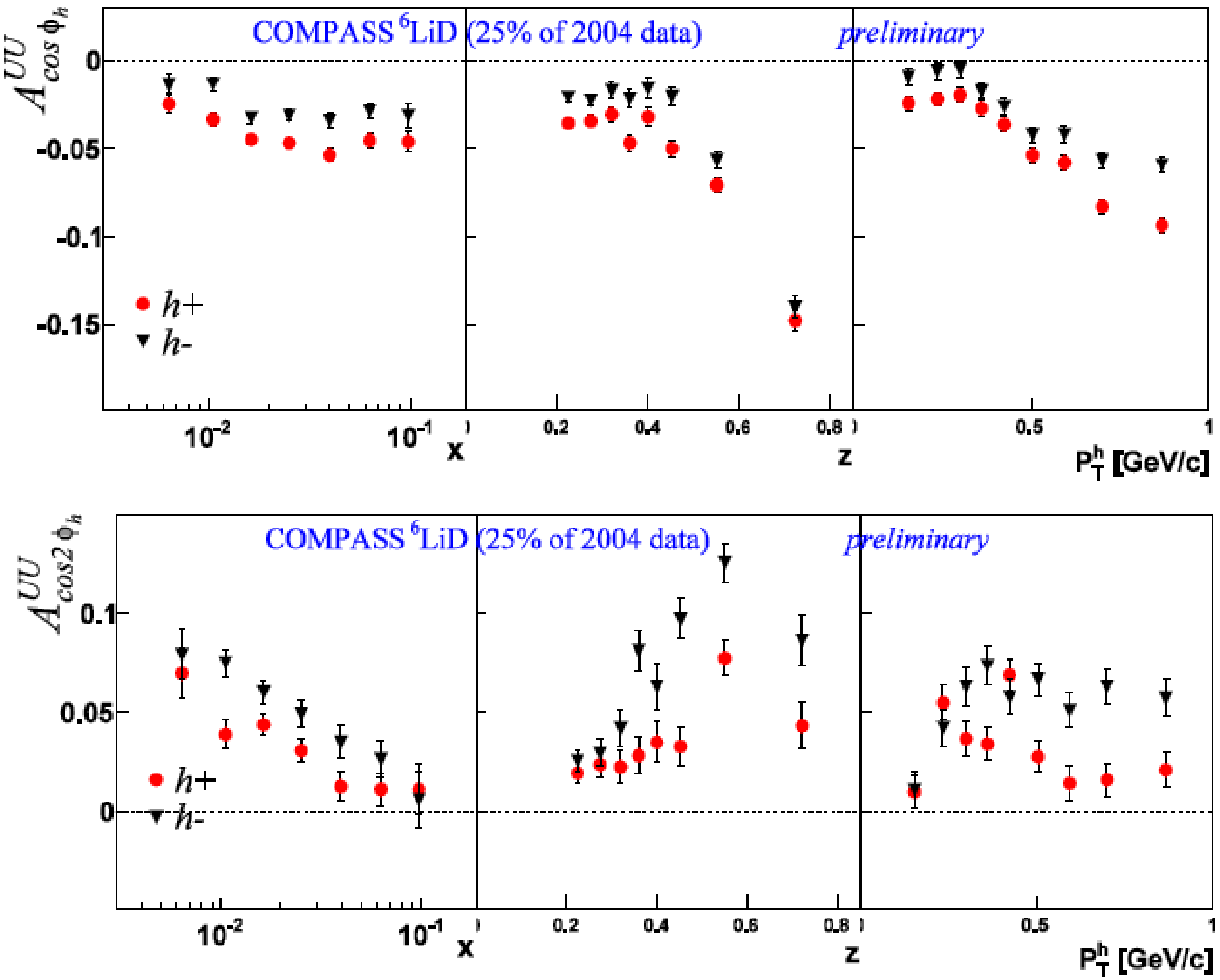
Cahn effect
kinematical effect due to quark transverse momentum

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

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

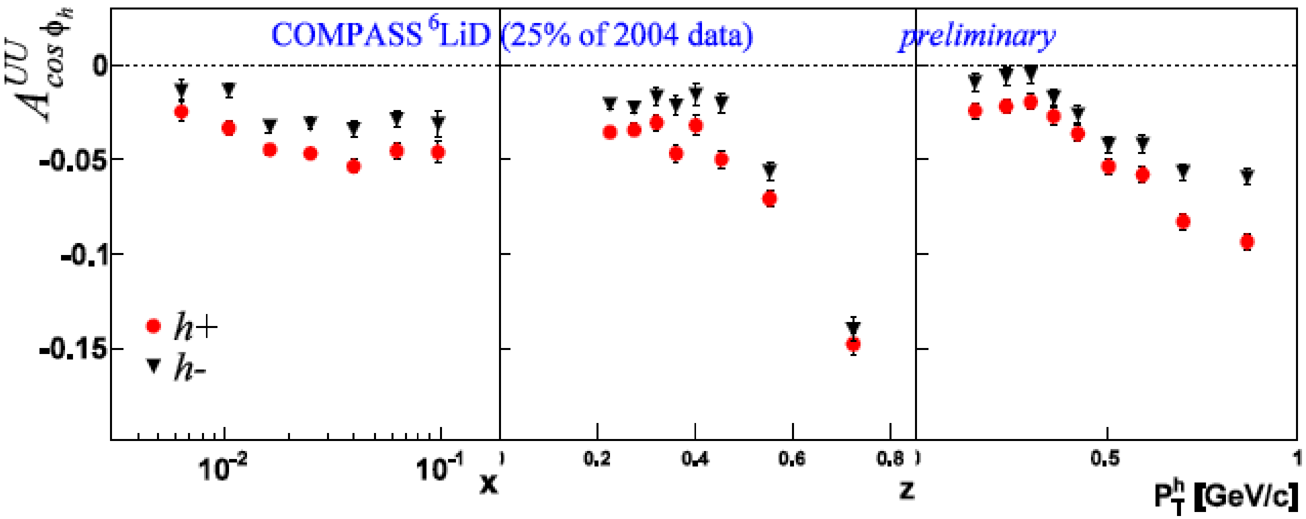


$sys \approx 2 \cdot stat$

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

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



cos Φ

- **Large signal over all the x range**
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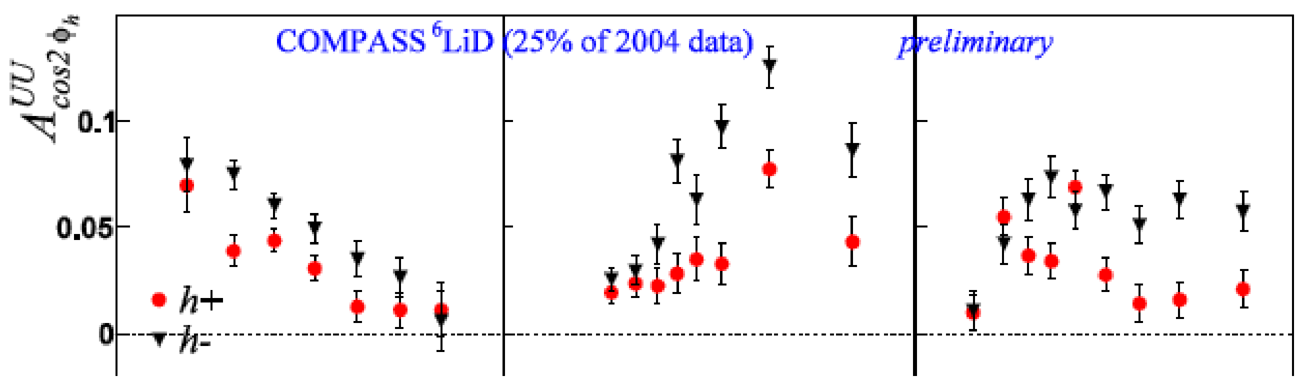


cos 2Φ

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

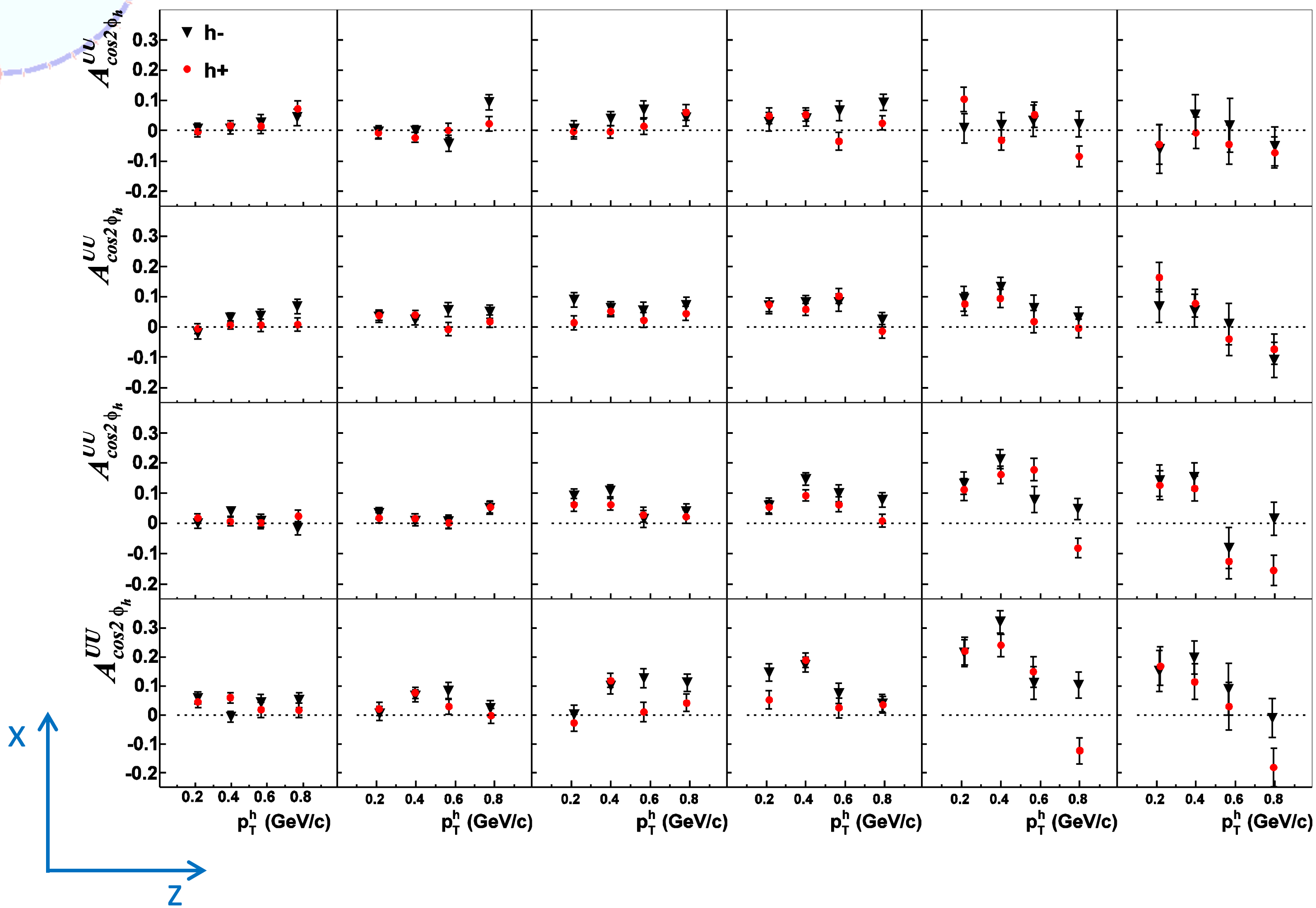
To investigate deeper the complicated and unexpected kinematical dependencies found, a multi-dimensional analysis has been done, binning simultaneously in x, z and p_T

→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

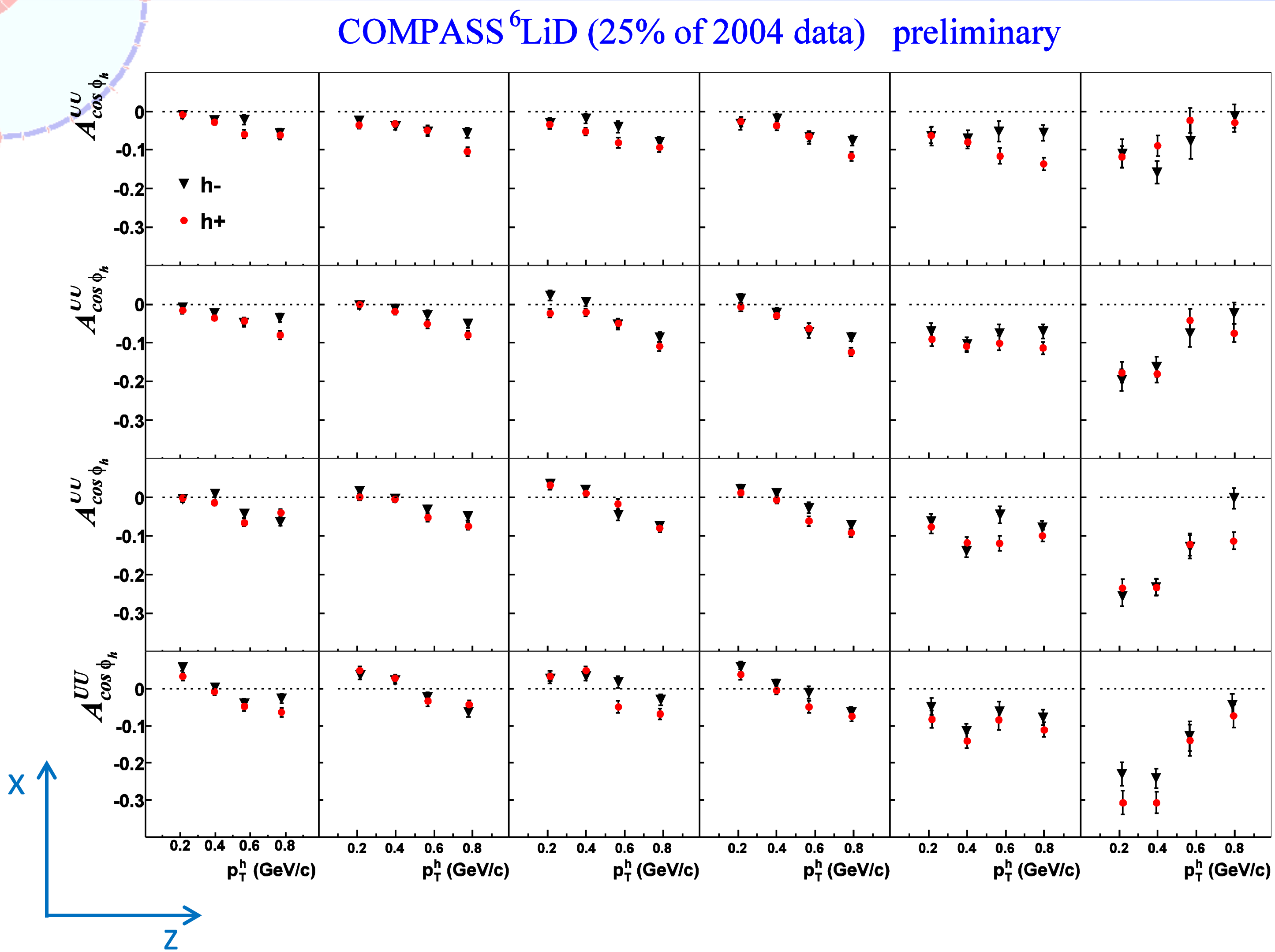
cos2Φ asymmetries multi-dimensional analysis

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 using 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 of the unpolarized azimuthal asymmetries in parallel to DVCS with a LH target measurement in 2012 and at COMPASS II starting from 2015