Latest results from COMPASS TMD physics

Anna Martin
Trieste University & INFN
on behalf of the COMPASS Collaboration

OUTLINE

- **the COMPASS experiment**

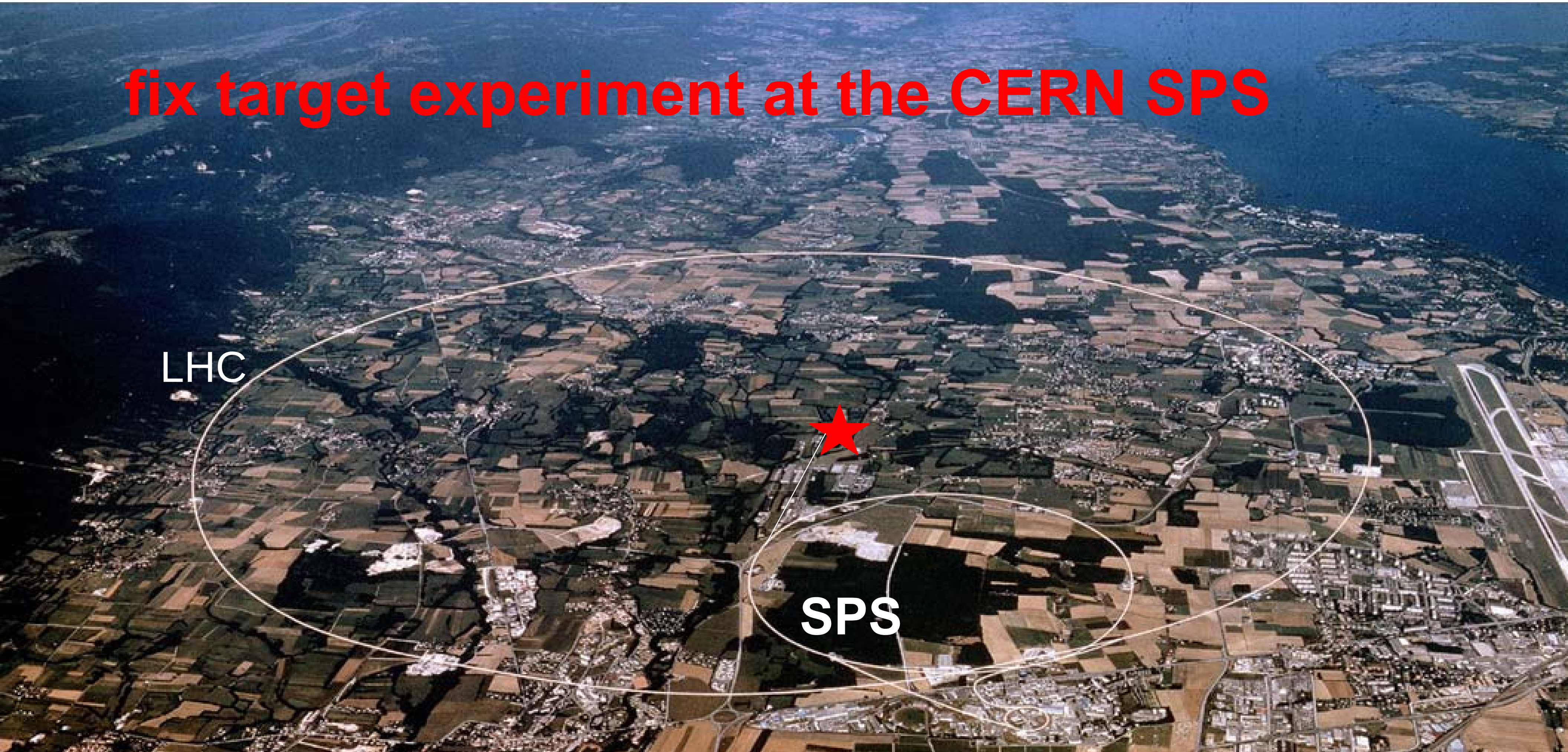
- **COMPASS results on TMDs** from SIDIS off
  - transversely polarised d and p targets
    - Collins and Sivers asymmetries
  - longitudinally polarised d target
  - unpolarised d target

- **future TMD measurements**

COMPASS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

fix target experiment at the CERN SPS



COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

proposed 1996, approved 1998, data taking since 2002

goals

- **meson and baryon spectroscopy**
  π polarizability

  with **high energy hadron beams**

- **nucleon spin structure** with a **high energy muon beam** and **longitudinally polarised targets**
  - **gluon polarisation**
  - **helicity PDFs**

  and **transversely polarised targets**
  - **transversity PDFs**

COMPASS spectrometer

- **high energy beams**
- **large angular acceptance**
- **broad kinematical range**

two stages spectrometer

Large Angle Spectrometer (SM1)

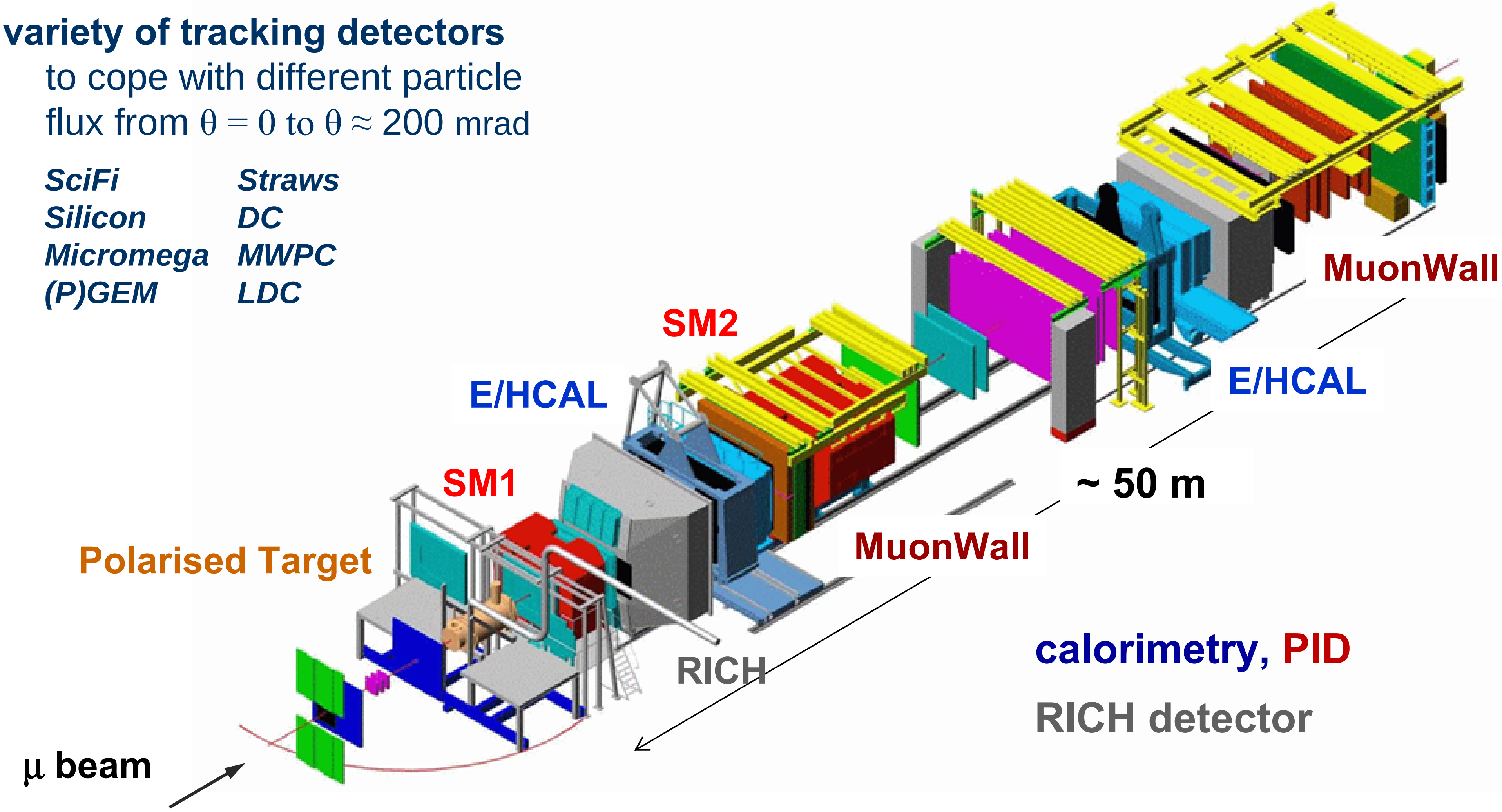
Small Angle Spectrometer (SM2)

variety of tracking detectors

to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

SciFi
Silicon
Micromega
(P)GEM

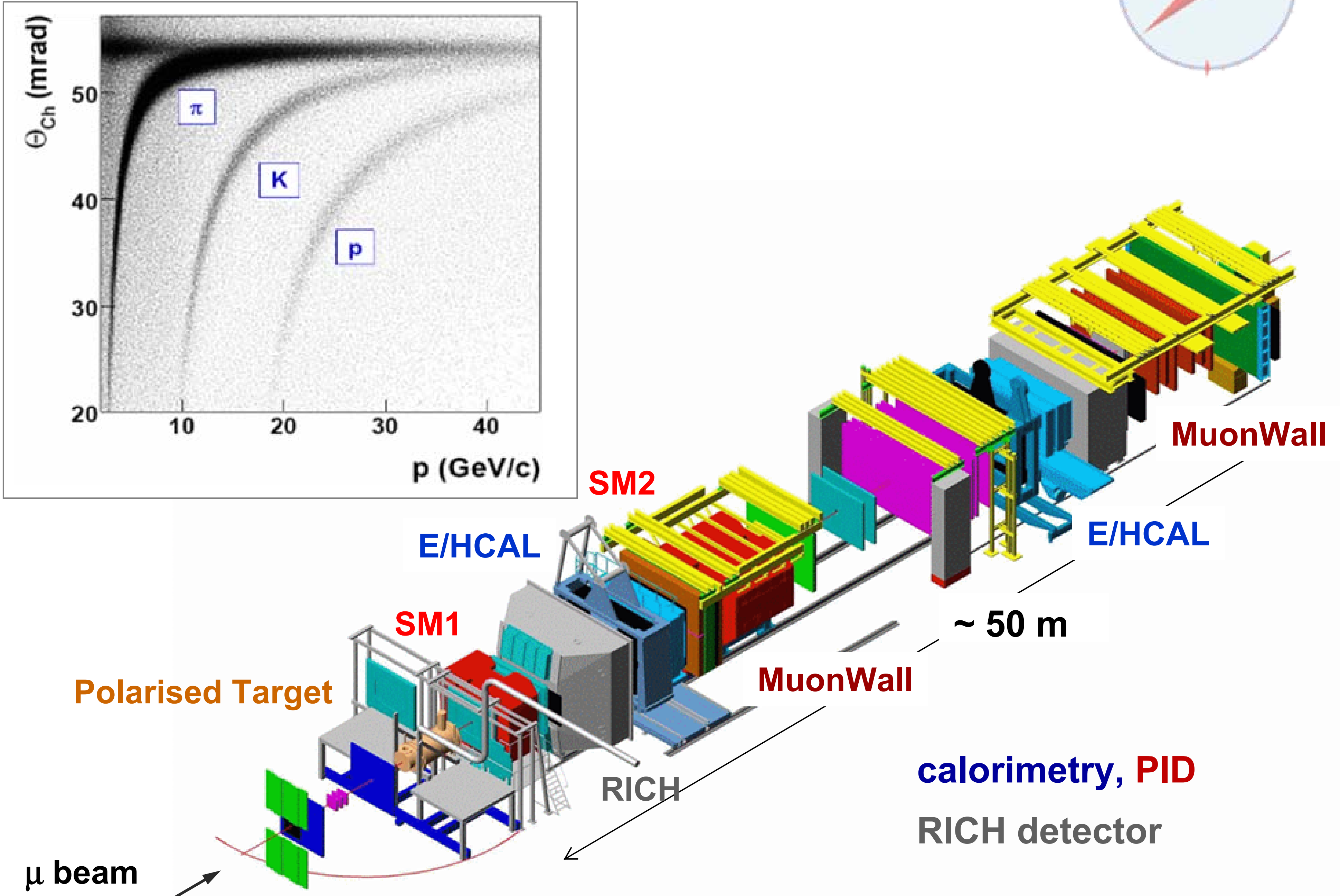
Straws
DC
MWPC
LDC



calorimetry, PID

RICH detector

COMPASS spectrometer



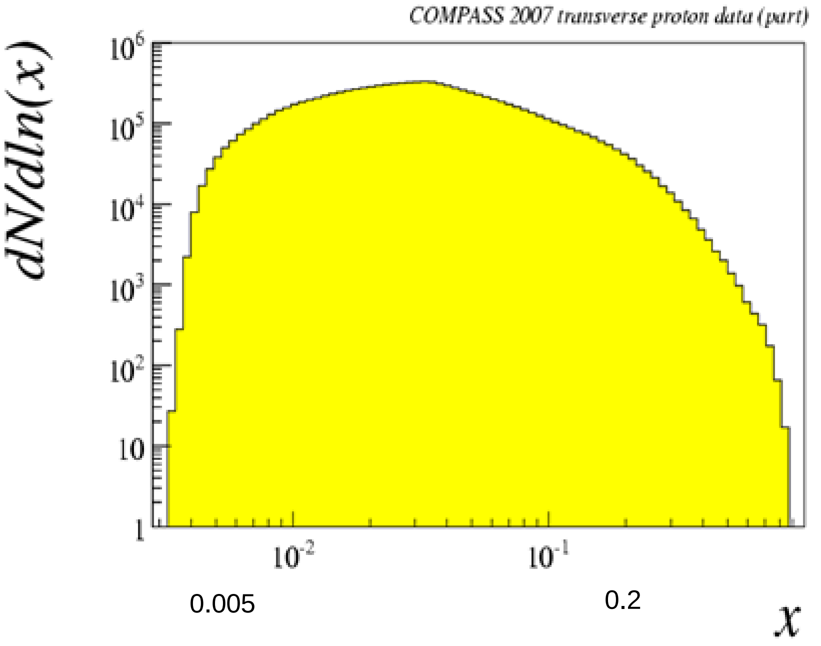
calorimetry, PID

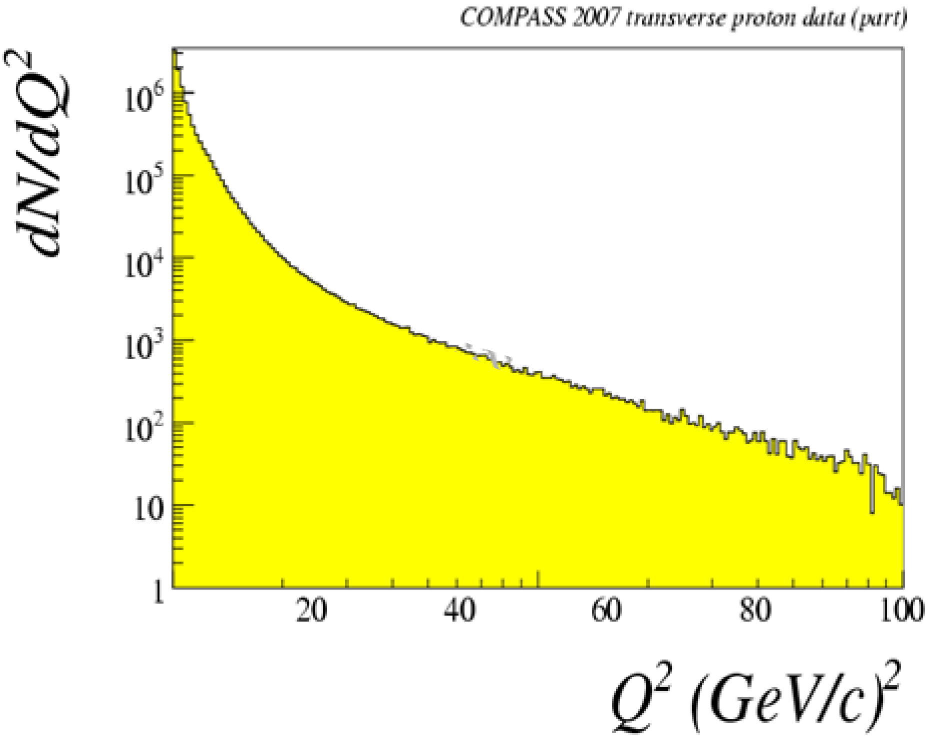
RICH detector

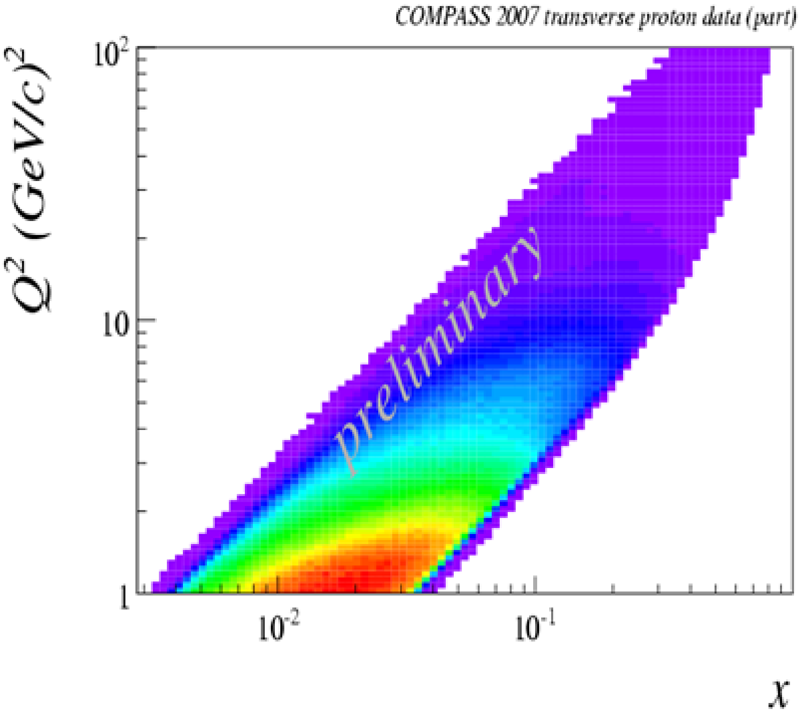
longitudinally polarised muon beam

p_μ = 160 GeV/c

DIS cuts: $Q^2 > 1$ (GeV/c)^2
$0.1 < y < 0.9$
$W > 5$ GeV/c^2



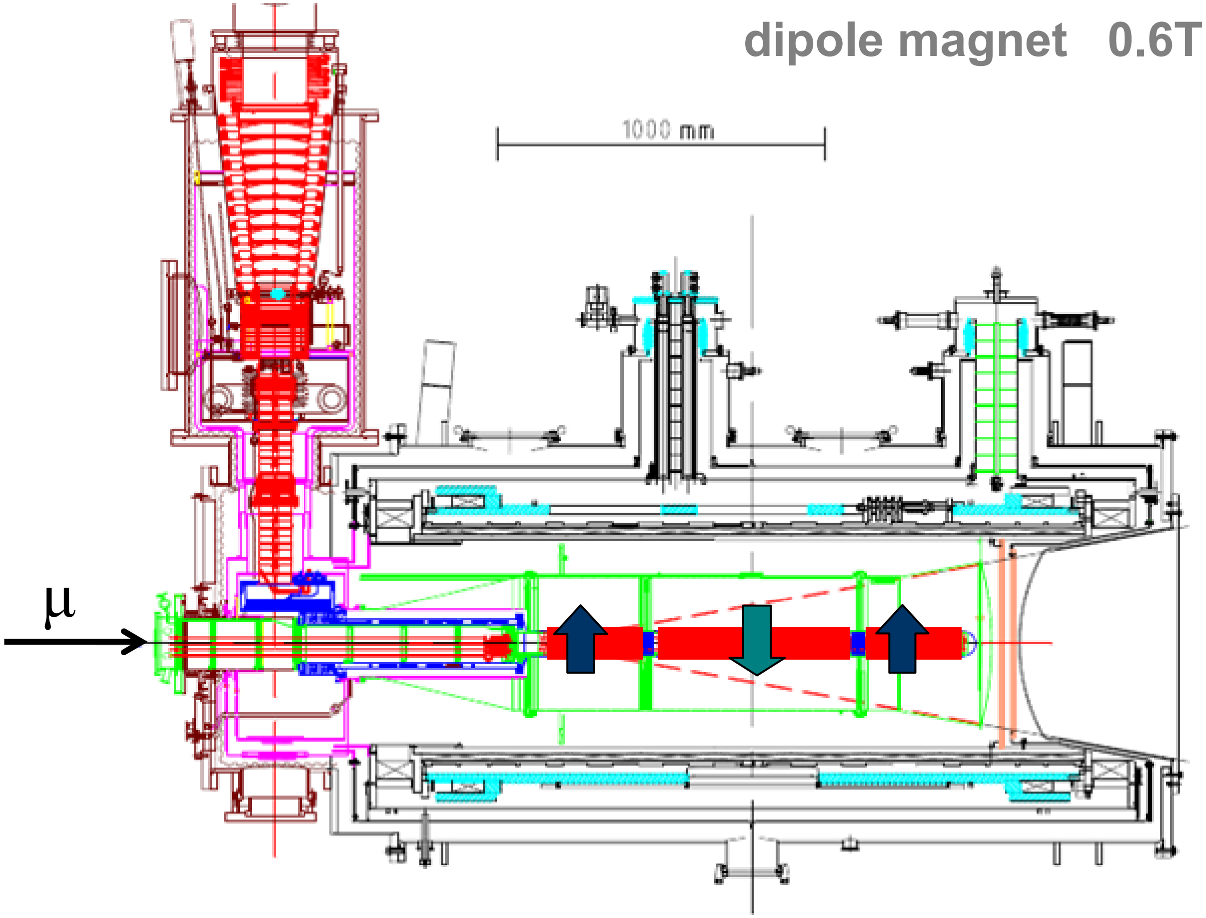




the polarized target system (>2005)

^{3}He – ^{4}He dilution refrigerator (T~50mK)

solenoid	2.5T
dipole magnet	0.6T



acceptance ± 180 mrad

3 target cells
30, 60, and 30 cm long

opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

COMPASS data taking

2002
2003 **polarised deuteron target** **— L & T** (25% of the time)
2004

2005 *CERN shutdown*

2006 **polarised deuteron target** **— L only**

2007 **polarised proton target** **— L & T** (50% of the time)

Δ**G**

results

2008 / 2009 spectroscopy

2010 **polarised proton target** **— T only**

2011 ***polarised proton target*** ***— L only***

data analysis ongoing
first results soon

some
results on TMDs
from 2002-2007 data

Collins asymmetry and the transversity PDF

Sivers asymmetry

other azimuthal asymmetries and TMD PDFs
from SIDIS off transversely polarised
longitudinally polarised
unpolarised targets

The Structure of the Nucleon

three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case

Jaffe and Ji, '91

transversity PDF $\Delta_T q$ or h_1 : correlation between the transverse spin of the nucleon and the transverse spin of the quark

nucleon **polarisation**

quark **polarisation**

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

$\Delta_T q$

tensor charge

$$\int dx\ [\Delta_T q(x) - \Delta_T \bar{q}(x)]$$

chiral odd

can be measured in SIDIS off transversely polarised nucleons

Collins effect: LR asymmetry in the hadronisation of transversely polarised quarks

Collins asymmetry

in SIDIS off transversity polarised nucleons

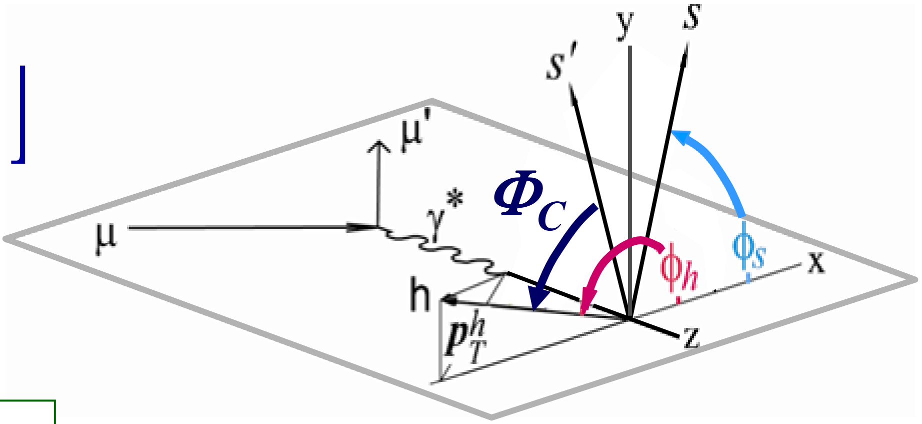
$$\Phi_C = \phi_h + \phi_S - \pi$$

ϕ_h azimuthal angle of the hadron,

ϕ_S azimuhtal angle of the nucleon spin

amplitude of the $\sin\Phi_C$ modulation in the azimuthal distribution of the final state hadrons

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$



transversity

"Collins FF"

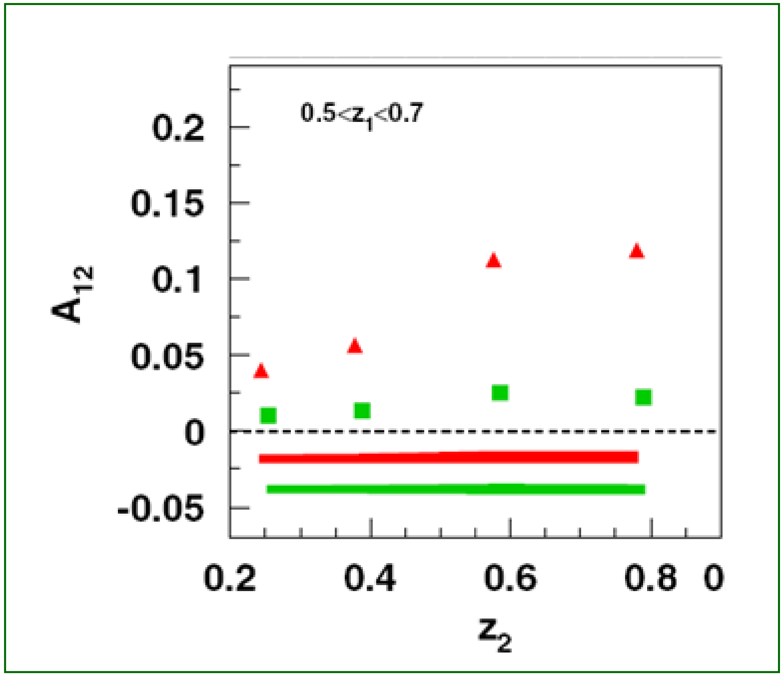
$$A_{Coll} \approx \frac{\sum_q e_q^2 \, \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2 \, q \otimes D_q^h}$$

today the most promising way to access transversity

Collins asymmetry

in SIDIS off transversity polarised nucleons

Collins FF: **gives a LR asymmetry in the hadronisation of transversely polarised quarks**



products of Collins FFs can be measured in

$$e^+e^- \rightarrow \pi^+\pi^- X$$

first low statistics results from LEP data

2005 first data from BELLE

"Collins FF"

$$A_{Coll} \approx \frac{\sum_q e_q^2\ \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2\ q \otimes D_q^h}$$

today the most promising way to access transversity

Collins asymmetry

$$A_{Coll} \approx \frac{\sum_q e_q^2\ \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2\ q \otimes D_q^h}$$

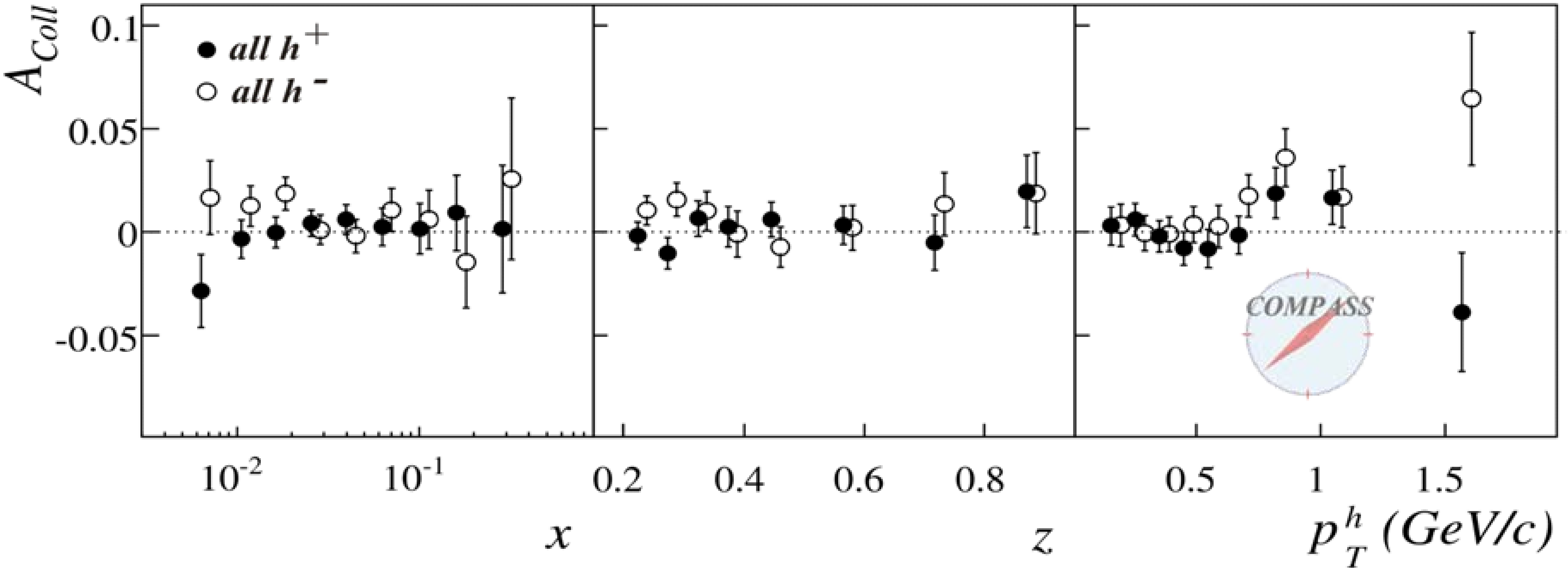
first results in

2005 measured by HERMES (proton target) and COMPASS (deuteron target)

different from zero ***compatible with zero***

final COMPASS results on deuteron

2002-2004 data *PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127*



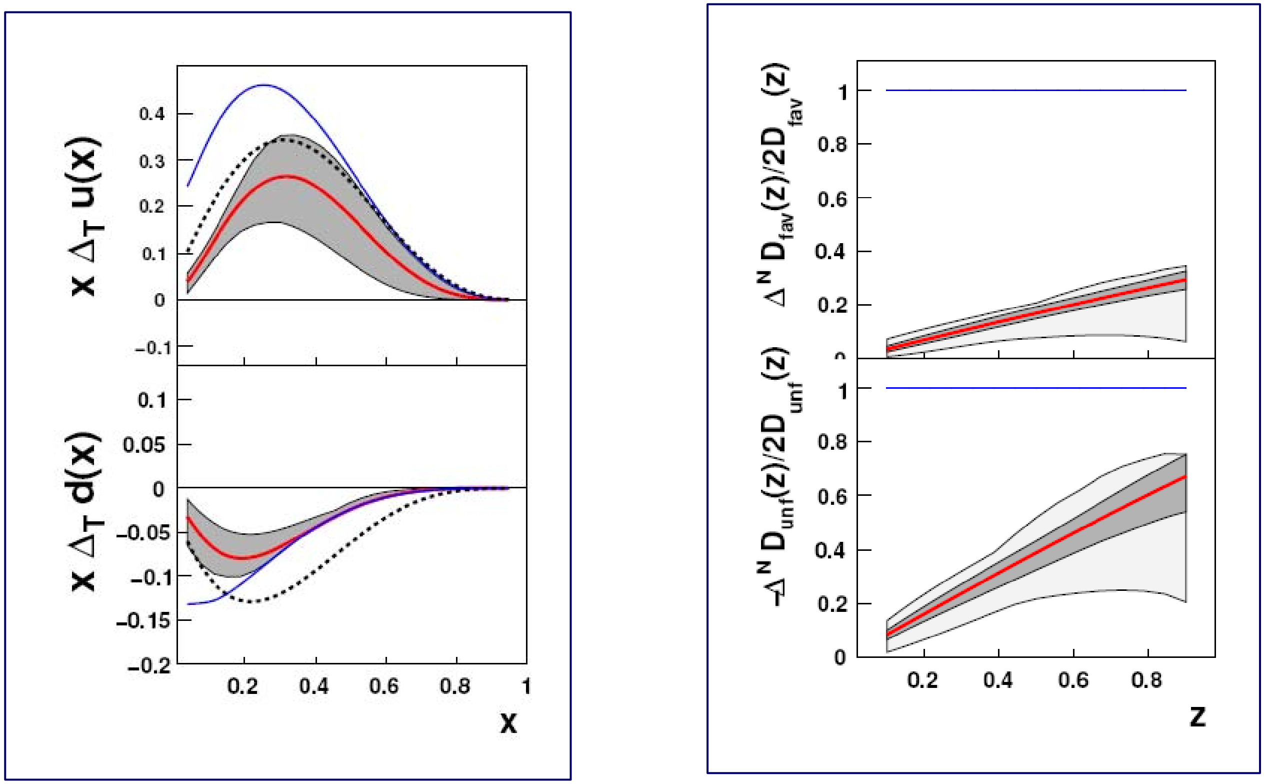
charged pion and kaon asymmetries also compatible with zero

understood as u – d cancellation

Collins asymmetry

the COMPASS d, HERMES p, and BELLE data are well described in global fits

→ *first extractions of the Collins FFs and the transversity PDFs, and tensor charge*



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

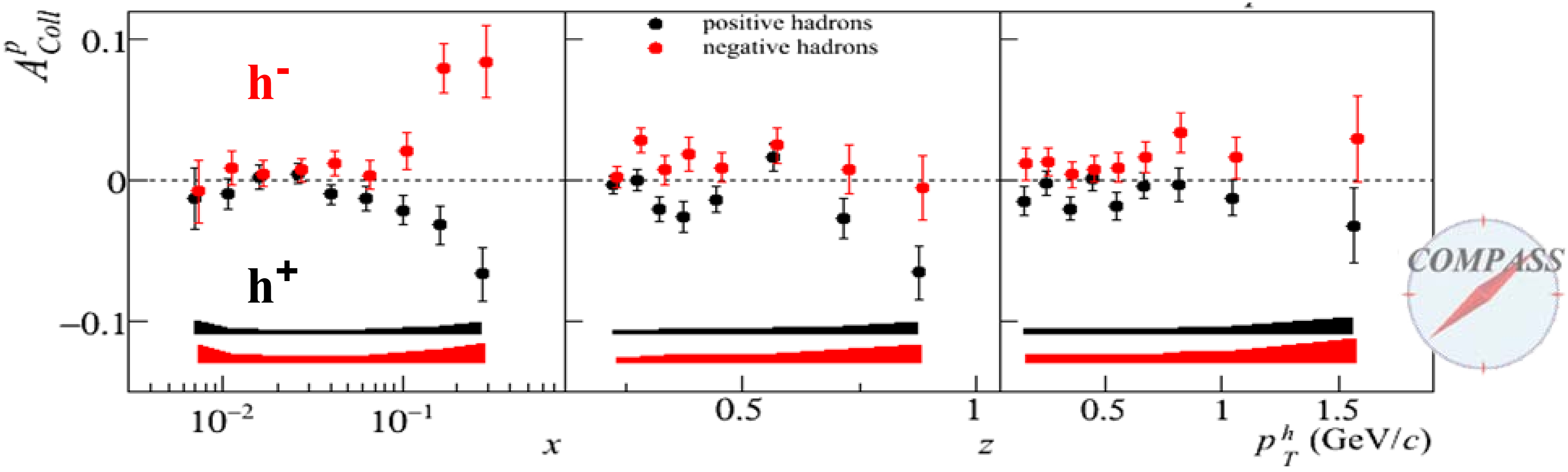
Q^2 dependence?

→ COMPASS p data

Collins asymmetry – proton

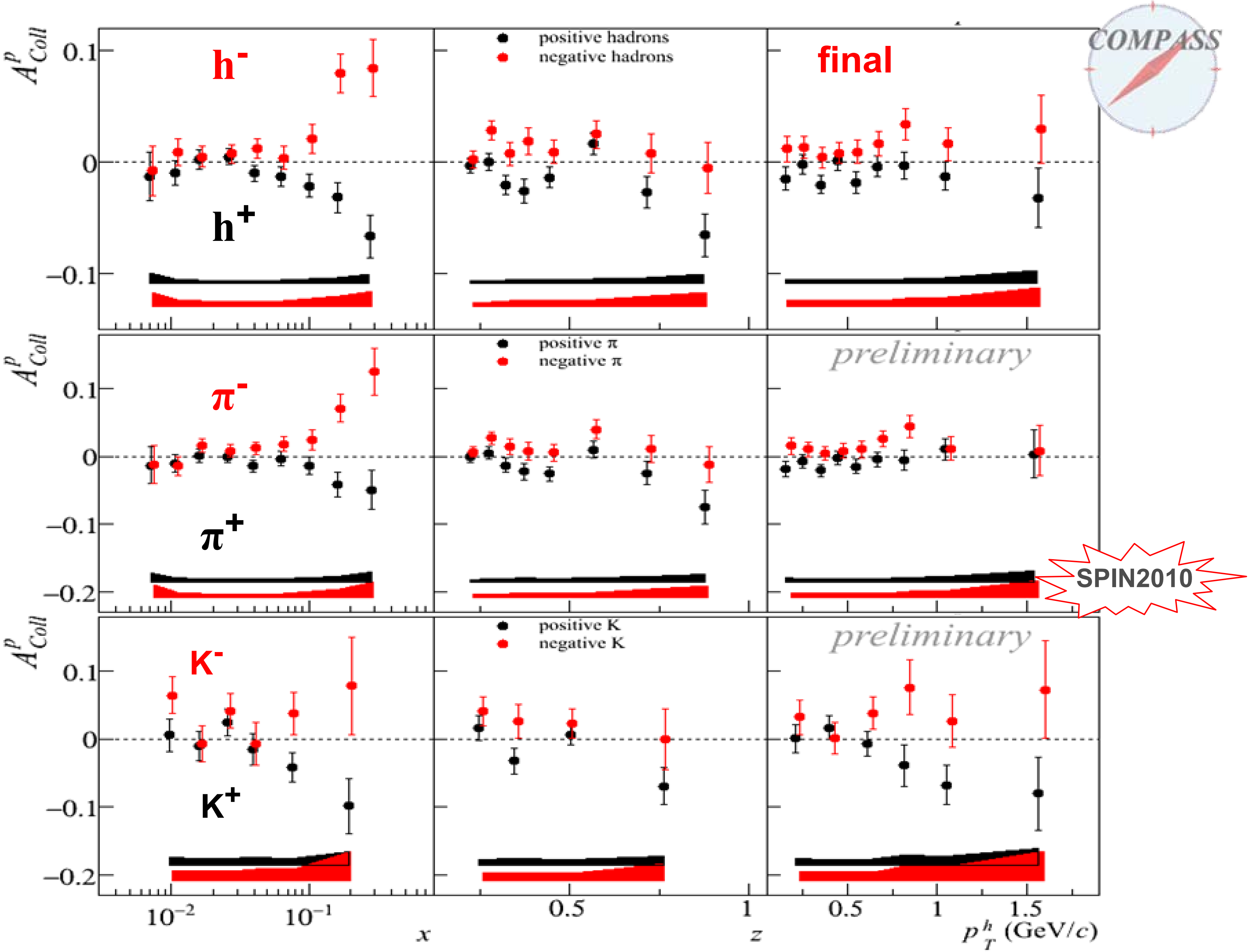
final COMPASS results from 2007 data

PLB 692 (2010) 240

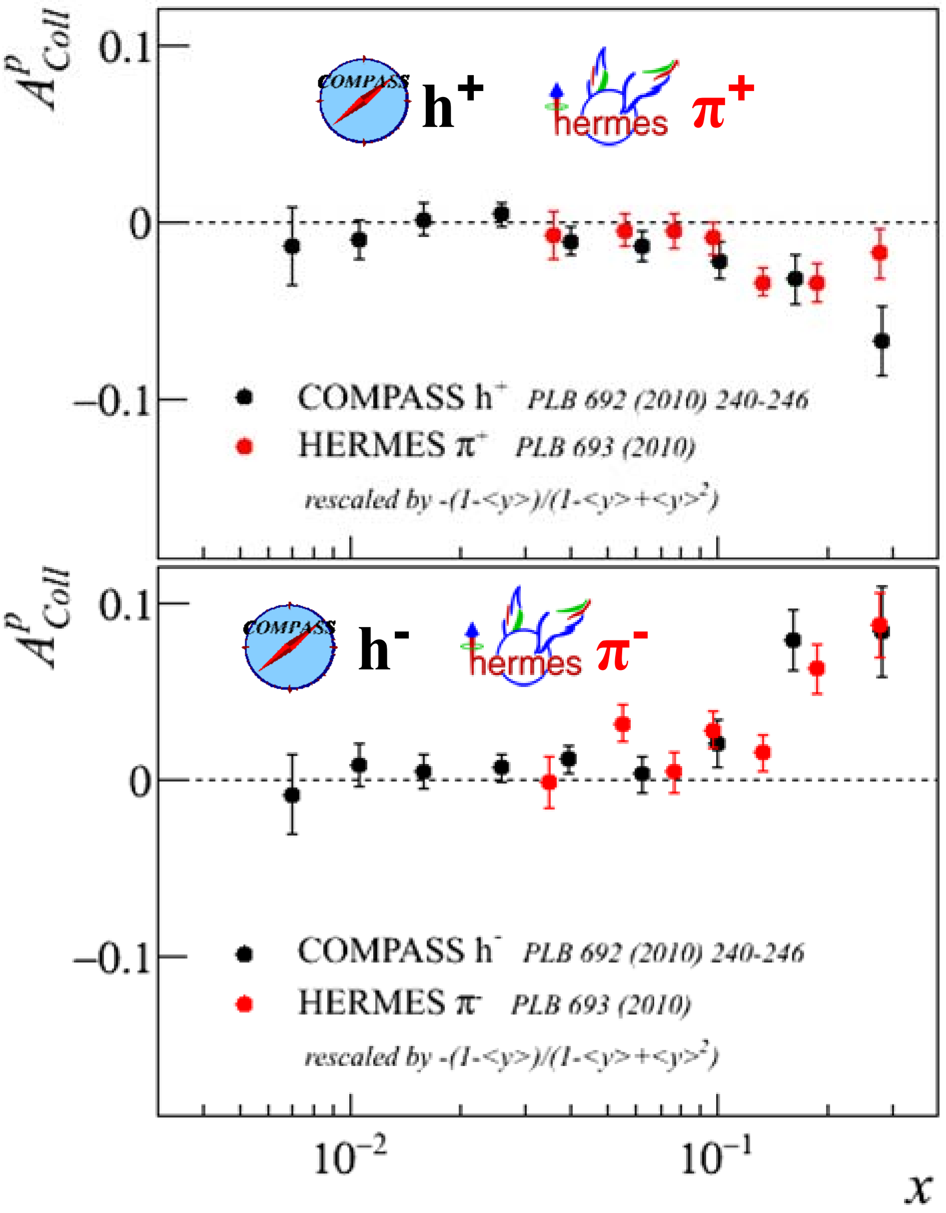


- **at small x,** the asymmetries are **compatible with zero**
- **large signal in the valence region**
  of opposite sign for positive and negative hadrons

Collins asymmetry – proton   2007 data

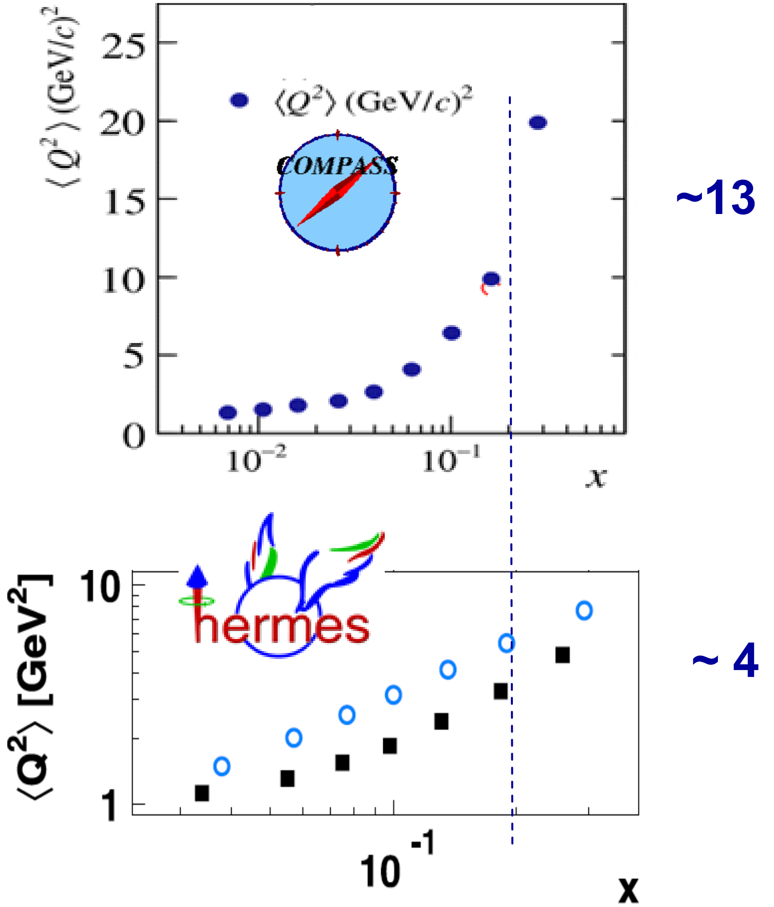


Collins asymmetry – proton



COMPASS sign convention

same sign and strength:
a very important, not obvious result!



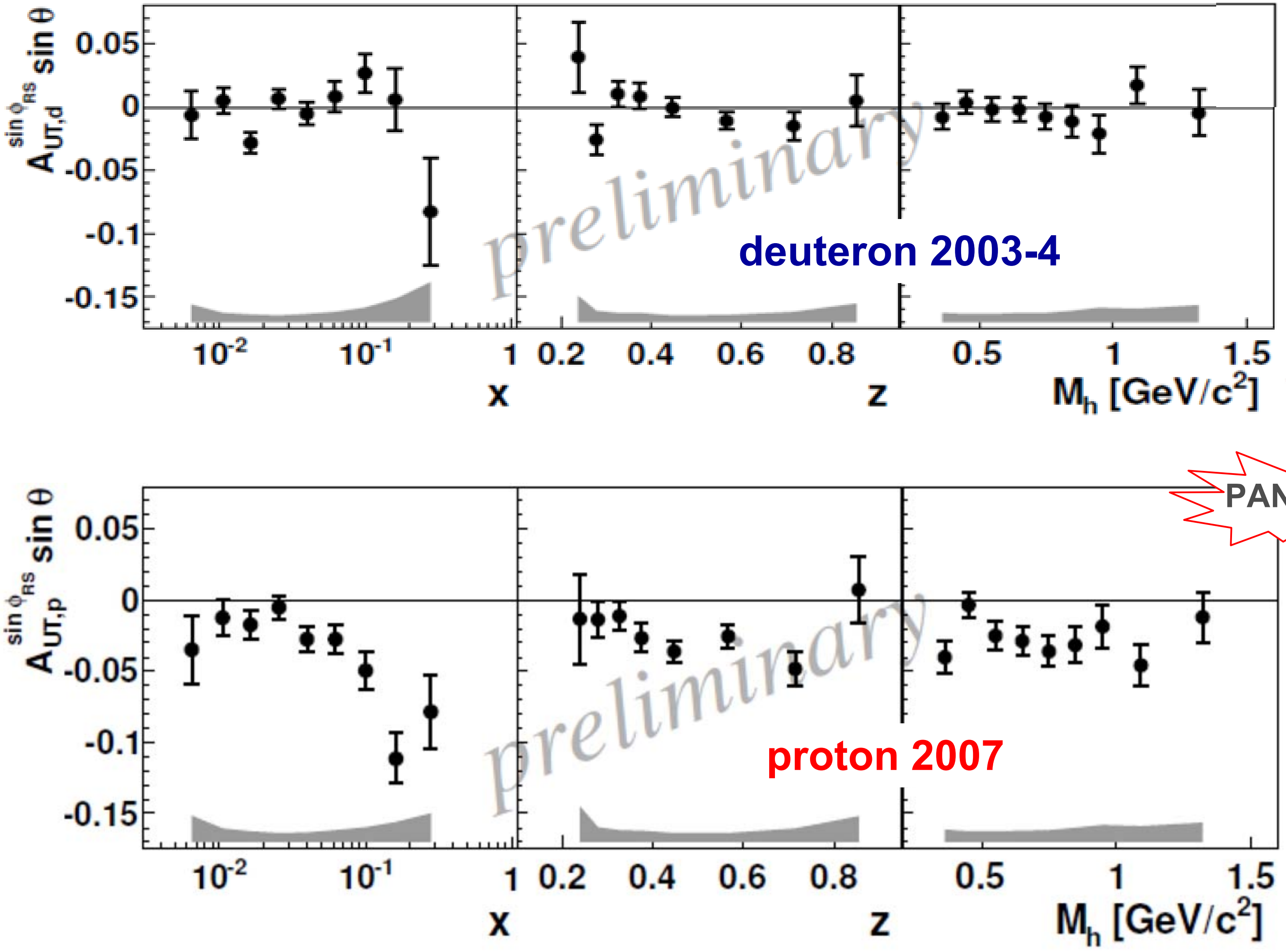
indication for not a higher twist effect,

no strong Q^2 dependence of the Collins FF

Two Hadron Asymmetry

$$A_{RS} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{2h}(z,M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z,M_h^2)}$$

final COMPASS statistics (2003-2004; 2007)



deuteron 2003-4

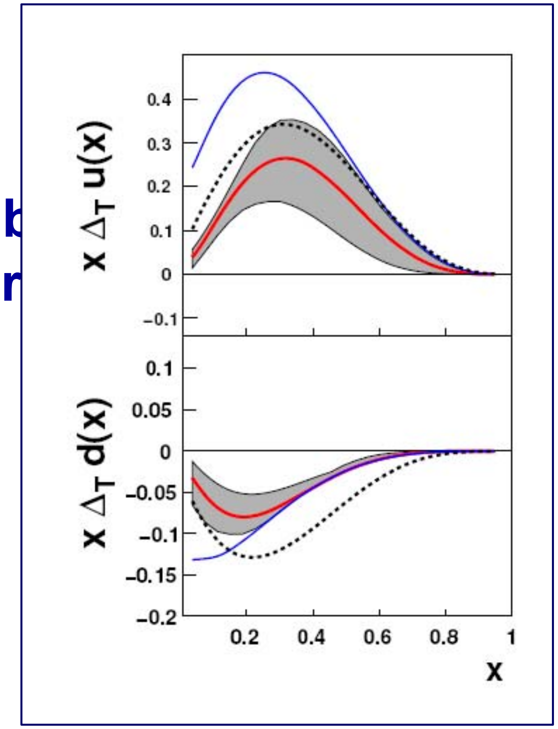
proton 2007

h+h- pairs

PANIC2011

Collins asymmetry

summary:



- **large transverse spin effects observed in SIDIS off p b COMPASS and HERMES experiments in the valence r**

- **there is a left-right asymmetry in the hadronisation of transversely polarised quarks**
- **the transversity distribution is different from zero**

- **the transversity distribution can be measured in SIDIS off transversely polarised nucleons**

more precise SIDIS data are needed, over all the x range, at different Q^2 to study its properties

COMPASS contribution in the near future:

results from the 2010 proton data

factor ~ 4 in statistics with respect to the 2007 results

results on TMDs

from 2002-2007 data

Collins asymmetry and the transversity PDF

Sivers asymmetry

other azimuthal asymmetries and TMD PDFs

from SIDIS off transversely polarised
longitudinally polarised
unpolarised targets

The Structure of the Nucleon

three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case

taking into account the quark intrinsic transverse momentum k_T,

at leading order 8 PDFs are needed for a full description of the nucleon structure

“TMDs”

Sivers function

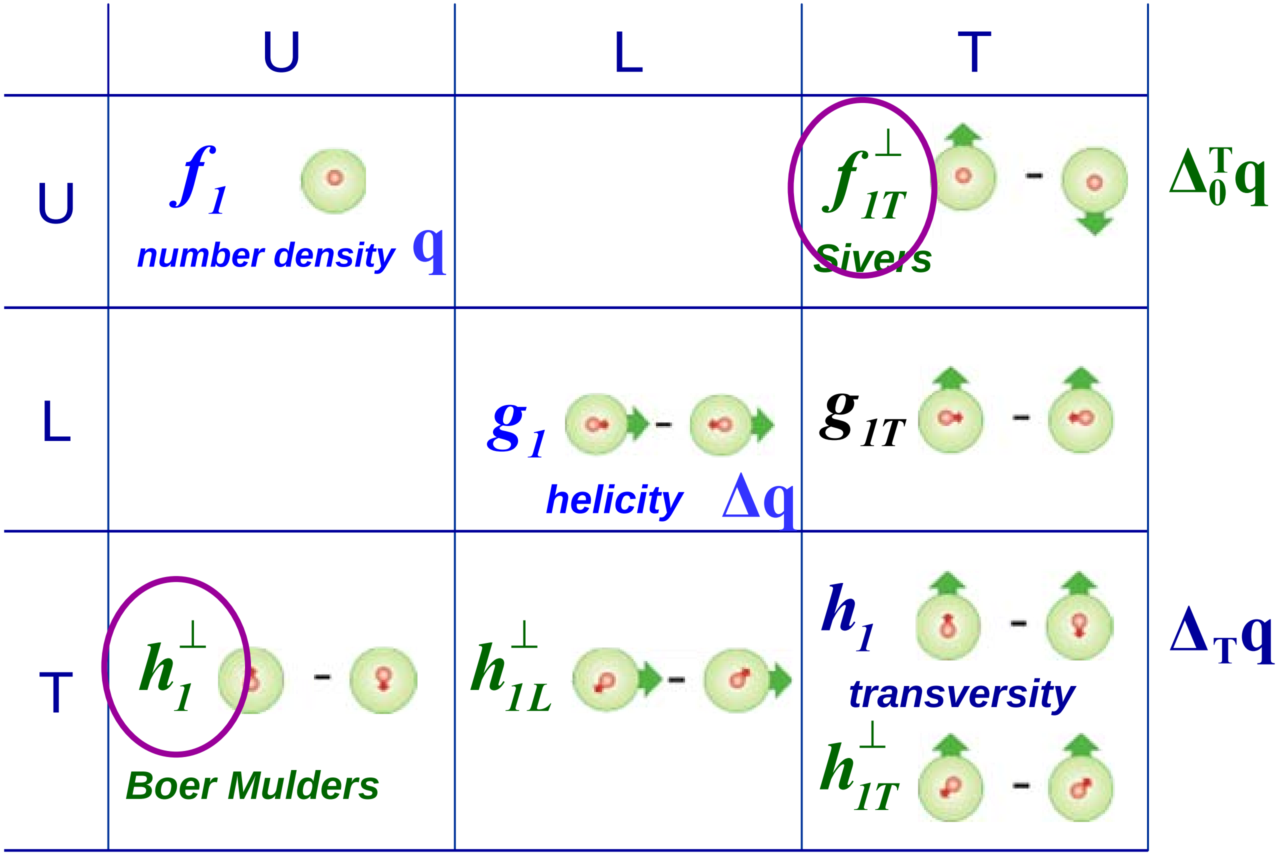
correlation between the transverse spin of the nucleon and the transverse momentum of the quark

sensitive to orbital angular momentum

Boer-Mulders function

correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

T-odd



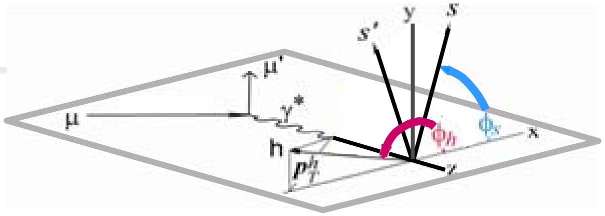
nucleon **polarisation**

quark **polarisation**

	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ - *Sivers*	$\Delta_0^T q$
L		g_1 - *helicity* Δq	g_{1T} -	
T	$h_1^{\perp}$ - *Boer Mulders*	$h_{1L}^{\perp}$ -	h_1 - *transversity* $h_{1T}^{\perp}$ -	$\Delta_T q$

SIDIS give access to all of them

SIDIS cross-section



$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\overset{h_1^\perp H_1^\perp}{\boxed{\cos(2\phi_h)}}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\overset{h_{1L}^\perp H_1^\perp}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad+\boxed{|\boldsymbol{S}_\perp|}\Bigg[\overset{f_{1T}^\perp D_1\ \ \text{Sivers}}{\boxed{\sin(\phi_h-\phi_S)}}\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
&\qquad+\varepsilon\underset{\text{Collins}\quad h_1 H_1^\perp}{\boxed{\sin(\phi_h+\phi_S)}}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\overset{g_{1T}D_1}{\boxed{\cos(\phi_h-\phi_S)}}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},
\end{aligned}
$$

A Bacchetta et al., 2006

18 structure functions
14 azimuthal modulations

the Sivers function

a long debate

1992	**introduced by D. Sivers**
1993	**J. Collins demonstrate that it must vanish**
2002	**S. Brodsky et al.: it can be ≠ 0 because of FSI**
2002	**J. Collins: process dependent, change of sign SIDIS ↔ DY**
	....
2005	**first measurements of the Sivers asymmetry in SIDIS**

$$A_{Siv} = \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_1^q}{\sum_q e_q^2 \, f_1 \otimes D_1^q} \qquad \frac{F_{UT}^{sin(\phi_h - \phi_S)}}{F_{UU}}$$

strong signal seen by HERMES for π^+ on protons

no signal seen by COMPASS for h^+ and h^- on deuterons

Sivers asymmetry

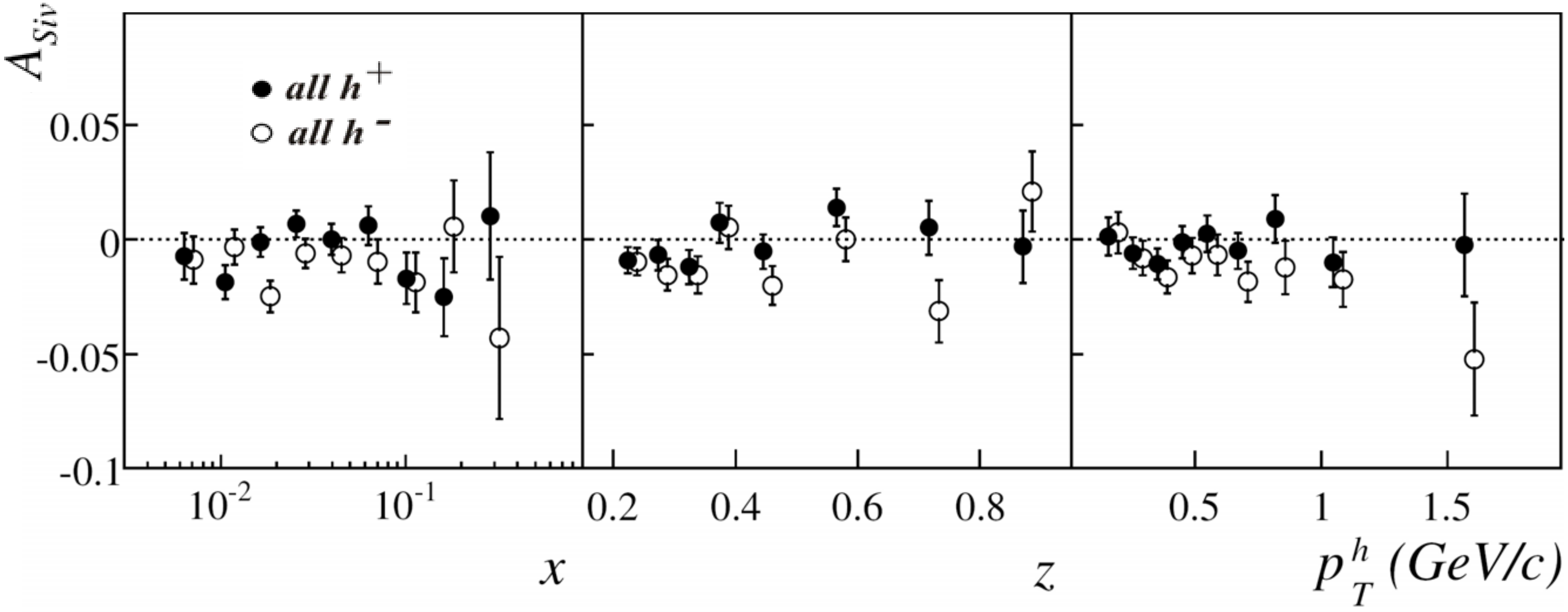
2005 first measurements of the Sivers asymmetry in SIDIS

strong signal seen by HERMES for π^+ on protons

no signal seen by COMPASS for h^+ and h^- on deuterons

final COMPASS results on deuteron

2002-2004 data *PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127*



similar results for identified hadrons

u and d quark contributions cancel in the deuteron

Sivers asymmetry

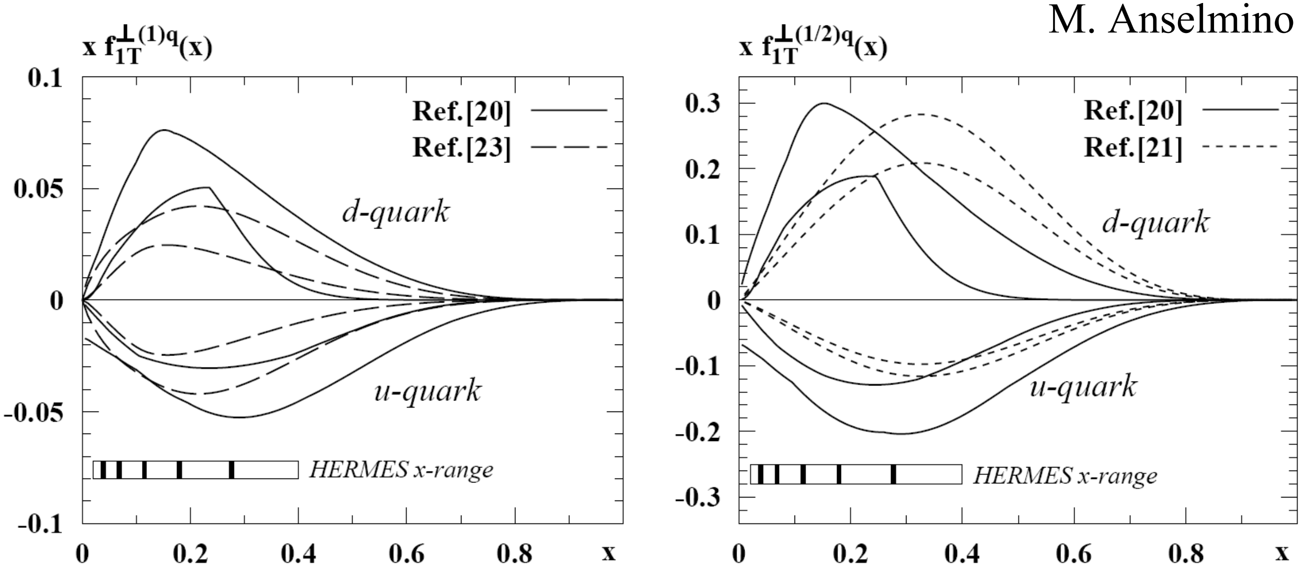
2005 **first measurements of the Sivers asymmetry in SIDIS**

strong signal seen by HERMES for π^+ on protons

no signal seen by COMPASS for h^+ and h^- on deuterons

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

M. Anselmino et al., Transversity2005



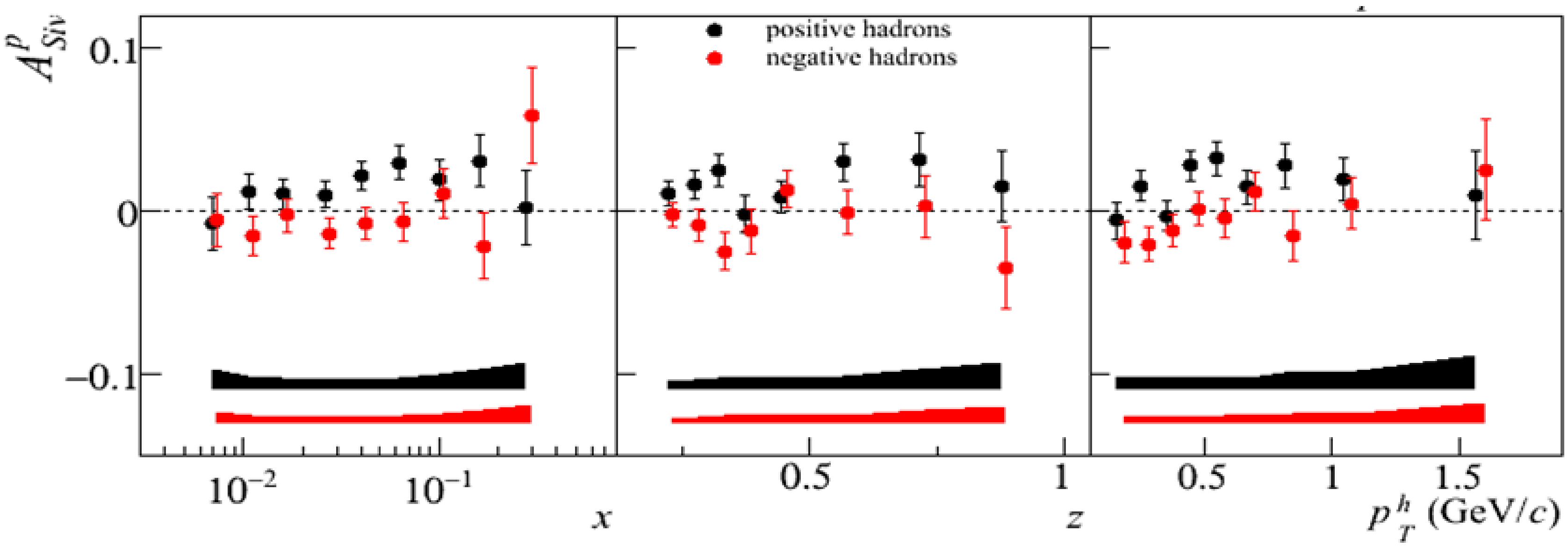
good description of the experimental results

still, waiting for higher energy proton data

Sivers asymmetry

2010: final COMPASS results from 2007 proton data

PLB 692 (2010) 240



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

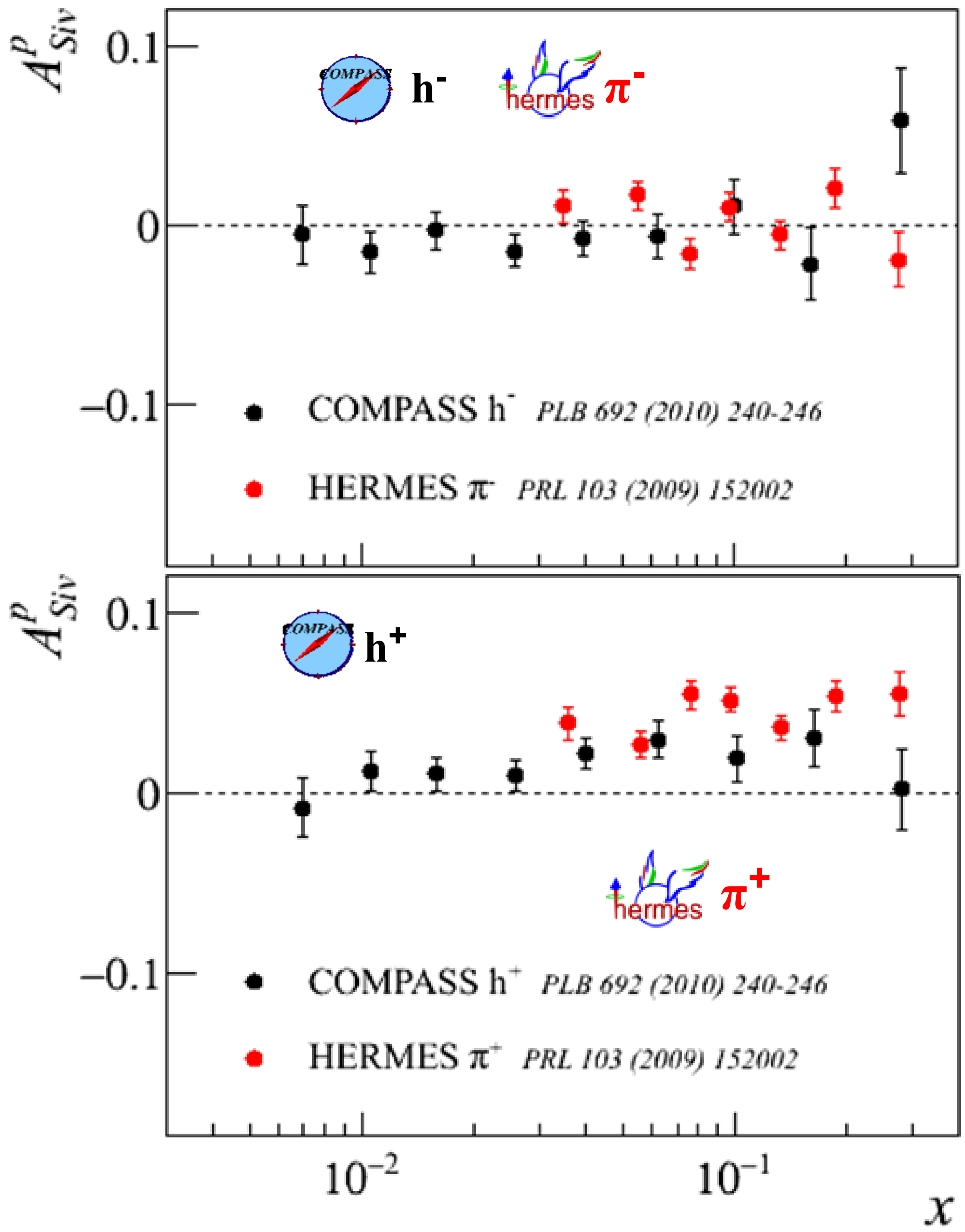
systematic errors

h$^-$ ~ 0.5 σ_{stat}

h$^+$ ~ 0.8 σ_{stat} plus a scale (abs) uncertainty of ± 0.01

preliminary results for charged π e K: SPIN2010

Sivers asymmetry



- **good agreements**

- **same sign**
- **COMPASS results in the overlap region smaller by a factor ~ 2**

higher precision
measurements needed soon
→ 2010 run
also to investigate W dependence

the Sivers function

a long debate

1992 introduced by D. Sivers

1993 J. Collins demonstrate that it must vanish

2002 S. Brodsky et al.: it can be ≠ 0 because of FSI

2002 J. Collins: process dependent, change of sign SIDIS ↔ DY

...

2005 first measurements of the Sivers asymmetry in SIDIS

strong signal seen by HERMES for π^+ on protons

no signal seen by COMPASS for h^+ and h^- on deuterons

2010 final results for the Sivers asymmetry from COMPASS 2007 proton data different from zero for h^+

results from 2010 proton data coming soon

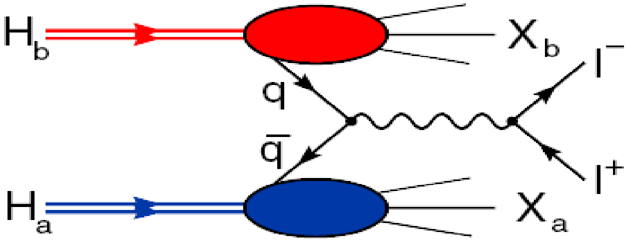
(factor ~8 in statistics, much smaller systematic uncertainty)

conclusion: the Sivers function is different from zero and can be measured in SIDIS

and one can try to test the change of sign SIDIS ↔ DY

COMPASS II proposal – Drell Yan

COMPASS-II proposal:
190 GeV/*c* π^- beam on
transversely polarised proton target



cross section
≈ convolution of H_a and H_b PDFs

in valence region (u-quark dominance)

$$\boxed{\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}}$$

→ extraction of the u-quark Sivers (and Boer-Mulders) function

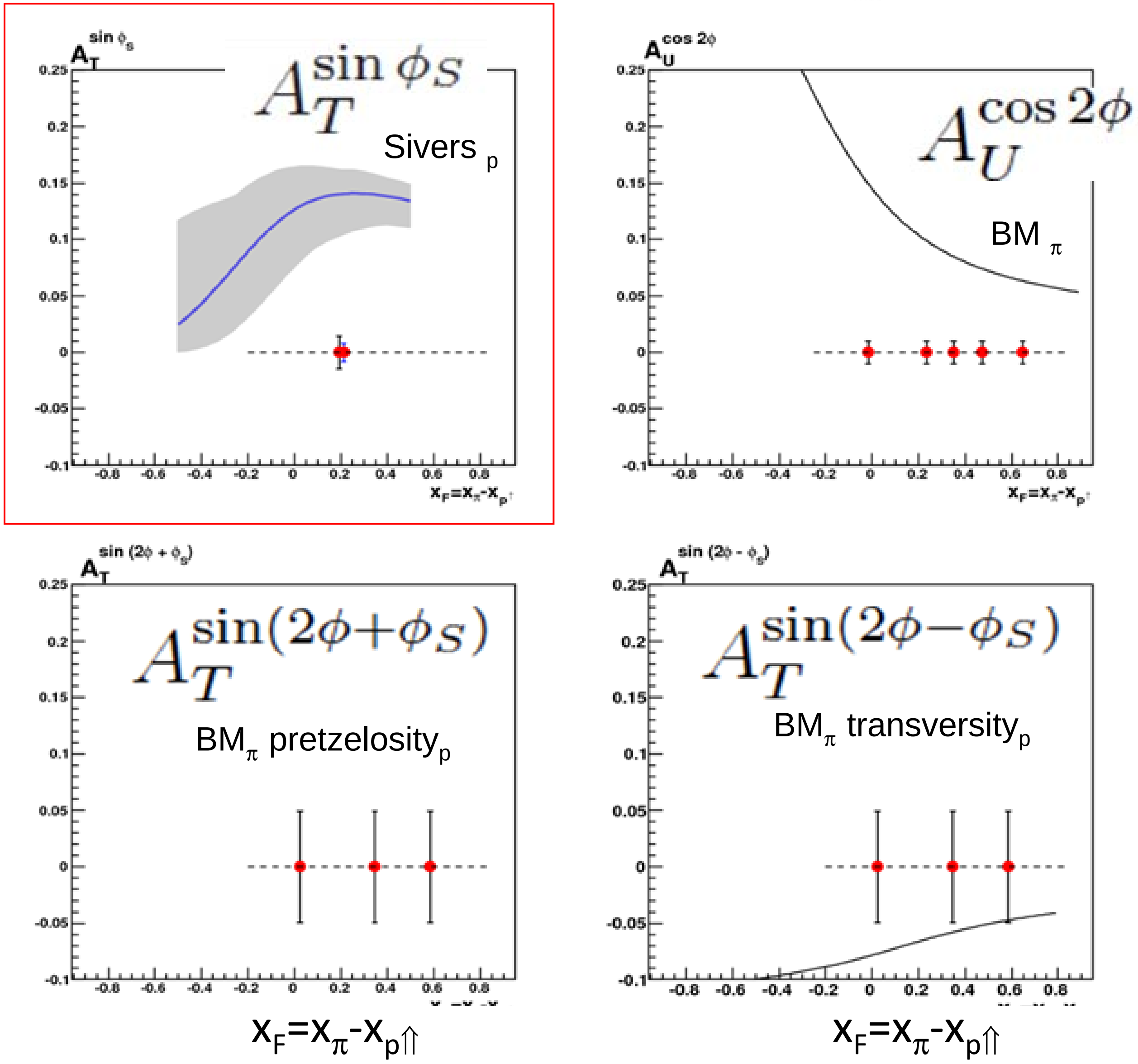
COMPASS II proposal – Drell Yan

projections with
2 years of data
$6 \cdot 10^8\ \pi$ spill $(9.6\ s)$
1.1 m pol. NH_3

one year of data taking approved (December 2010)

with the present CERN schedule
(shut down in 2013)
the data taking will be in 2014

$$4. \leq M_{\mu\mu} \leq 9.\ \mathrm{GeV}/c^2$$



results on TMDs

from 2002-2007 data

Collins asymmetry and the transversity PDF

Sivers asymmetry

other azimuthal asymmetries and TMD PDFs

from SIDIS off transversely polarised
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SIDIS cross-section

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

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

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

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

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

$$+\,\varepsilon\,\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

$$+\,\boxed{|\boldsymbol{S}_\perp|\lambda_e}\Big[\sqrt{1-\varepsilon^2}\,\overset{g_{1T}D_1}{\boxed{\cos(\phi_h-\phi_S)}}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}$$

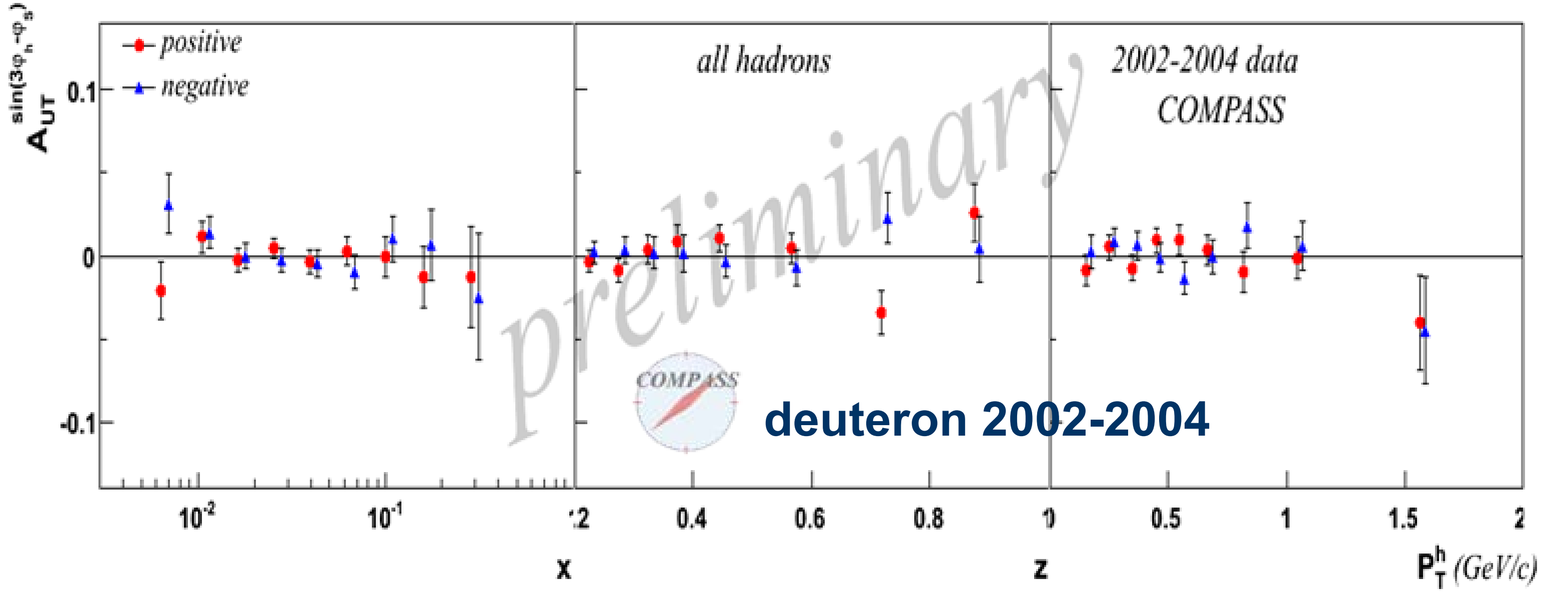
$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

all the other 6 transverse
spin azimuthal asymmetries
have been measured
on d (2002-2004) **and p** (2007)**:**
all compatible with zero!

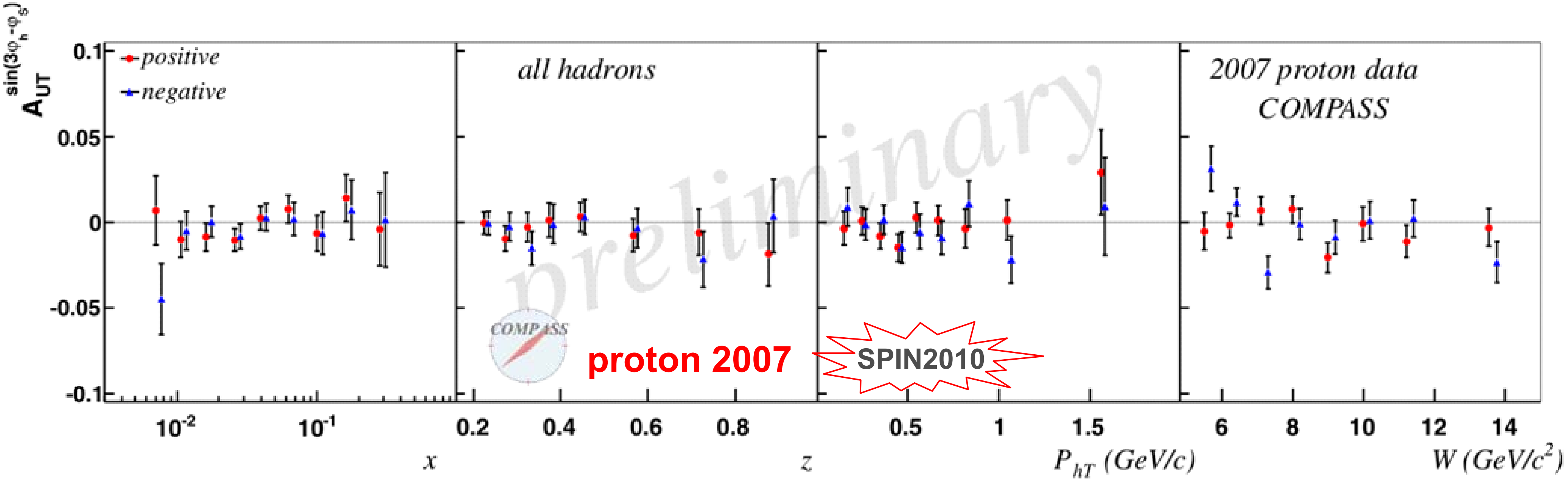
transversely polarised target

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

“pretzelosity” PDF
⊗ Collins FF



deuteron 2002-2004



proton 2007

SPIN2010

SIDIS cross-section

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

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

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

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

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

$$+\,\varepsilon\,\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

$$+\,\boxed{|\boldsymbol{S}_\perp|\lambda_e}\Bigg[\sqrt{1-\varepsilon^2}\,\overset{g_{1T}D_1}{\boxed{\cos(\phi_h-\phi_S)}}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}$$

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

all the other 6 transverse spin azimuthal asymmetries have been measured
on d (2002-2004) **and p** (2007)**:**
all compatible with zero!

next:
results from 2010 p data

SIDIS cross-section

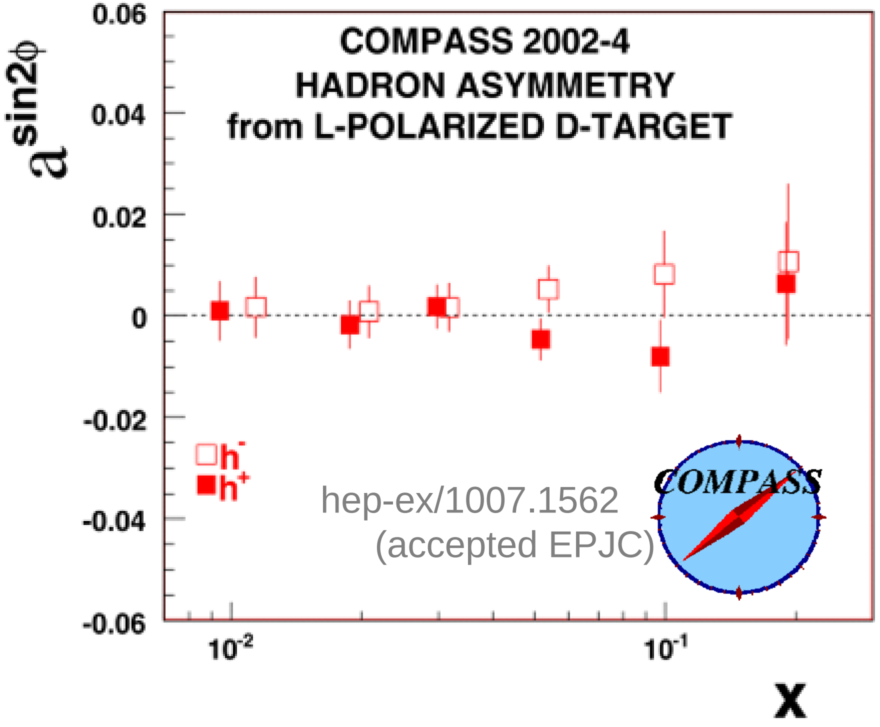
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad +\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad \boxed{+\,S_{\|}}\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h}+\varepsilon\,\overset{h_{1L}^{\perp}H_1^{\perp}}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\Big]\boxed{+\,S_{\|}\lambda_e}\Big[\sqrt{1-\varepsilon^2}\;F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_h}\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad +|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\,\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
&\qquad +\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad +\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\quad +|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad +\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

all the longitudinal
spin azimuthal asymmetries
have been measured
on d (2004)**:**
all compatible with zero!

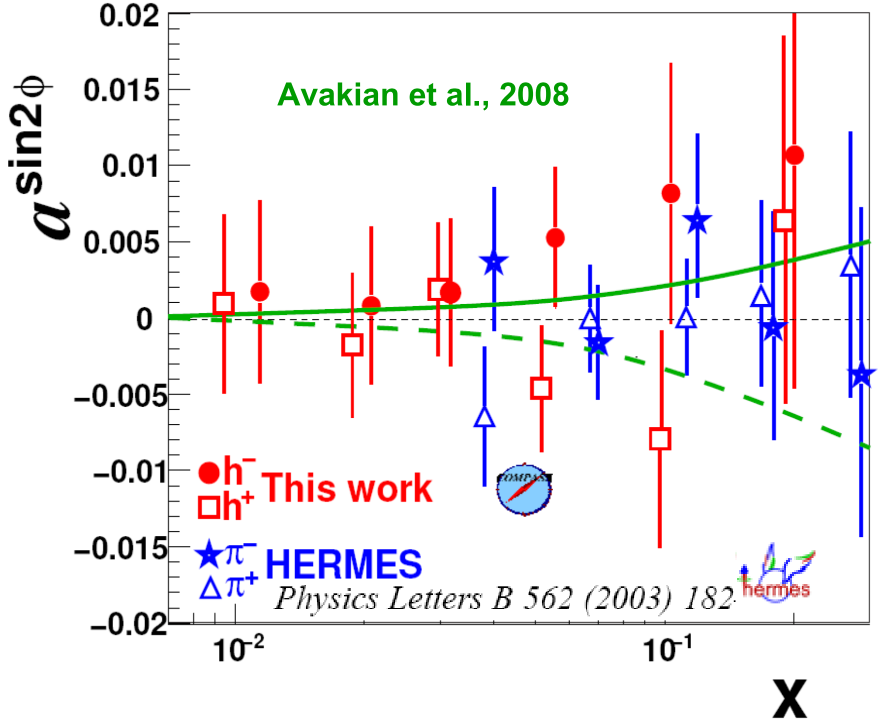
longitudinally polarised target

$$F_{UL}^{sin2\phi_h} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

“worm gear” PDF
⊗ Collins FF



hep-ex/1007.1562
(accepted EPJC)



small, compatible with zero within the statistical errors

COMPASS sign convention

SIDIS cross-section

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

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

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

$$\boxed{+\,S_\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h}+\varepsilon\,\overset{h_{1L}^{\perp}H_1^{\perp}}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\right]\boxed{+\,S_\parallel\lambda_e}\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_h}\,F_{LL}^{\cos\phi_h}\right]$$

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

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

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

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

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

all the longitudinal spin azimuthal asymmetries have been measured on d (2004): all compatible with zero!

next: results from
2006 d data
2007, 2010 p data

results on TMDs

from 2002-2007 data

Collins asymmetry and the transversity PDF

Sivers asymmetry

other azimuthal asymmetries and TMD PDFs

from SIDIS off transversely polarised
longitudinally polarised
unpolarised **targets**

SIDIS cross-section

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

$f_1 D_1$

$h_1^\perp H_1^\perp$

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

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

twist3

$$\boxed{F_{UU}^{\cos 2\phi_h}=\mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M\,M_h}h_1^\perp H_1^\perp\right]}$$

Boer-Mulders DF x Collins FF

+ Cahn effect (twist 4, 1/Q²)

Boer-Mulders DF

Cahn effect

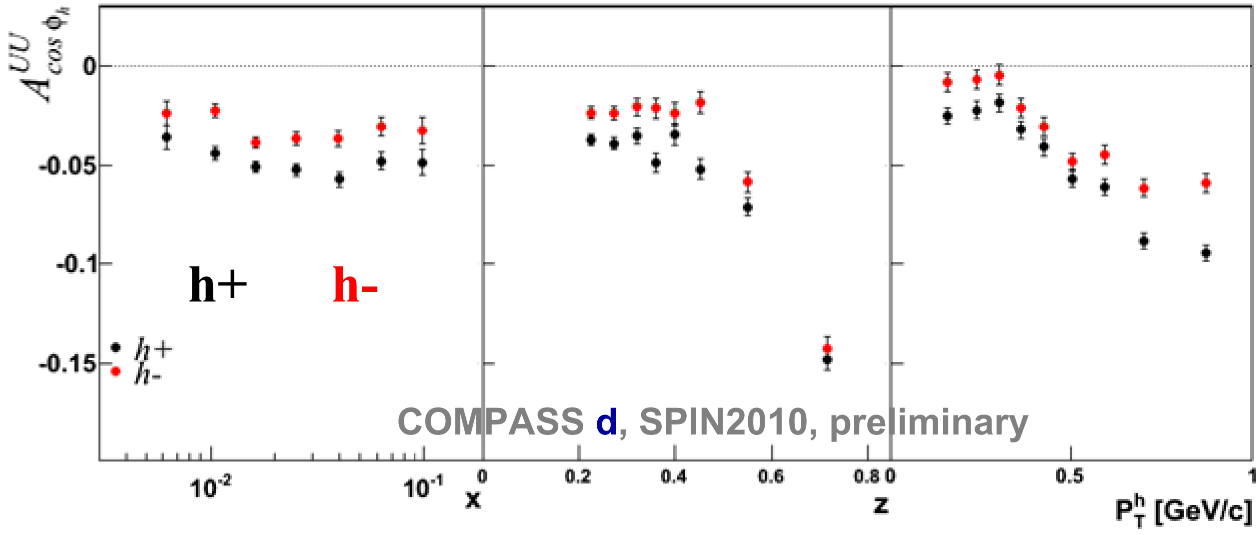
$$\boxed{F_{UU}^{\cos\phi_h}=\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh\,H_1^\perp+\frac{M_h}{M}\,f_1\frac{\tilde{D}^\perp}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf^\perp D_1+\frac{M_h}{M}\,h_1^\perp\frac{\tilde{H}}{z}\right)\right]}$$

$$xh = x\tilde{h}+\frac{p_T^2}{M^2}h_1^\perp \qquad xf^\perp = x\tilde{f}^\perp + f_1 \quad F_{UU}^{\cos\phi_h}\approx\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\,f_1 D_1\right]$$

→ $<k_T^2>$

$\cos\phi$ and $\cos2\phi$ modulations

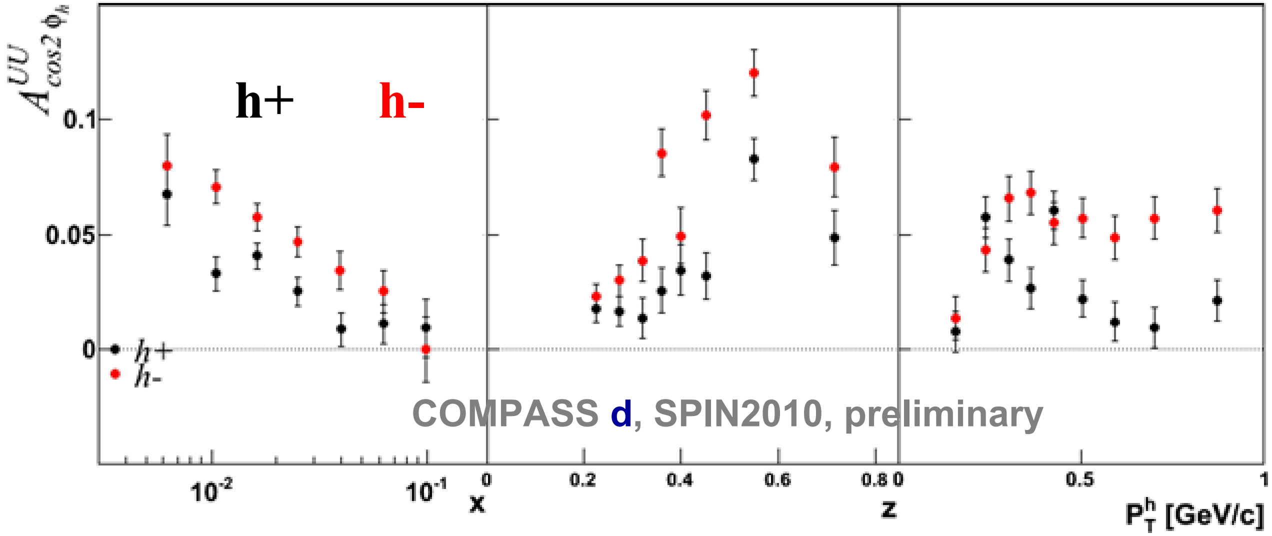
first results for h+ and h- separately from COMPASS in 2008



cos ϕ

large signals over all the x range

- strong dependence on x, z, $P_T{}^h$
  difficult to describe
- different for h^+ and h^-
  Boer-Mulders contribution?



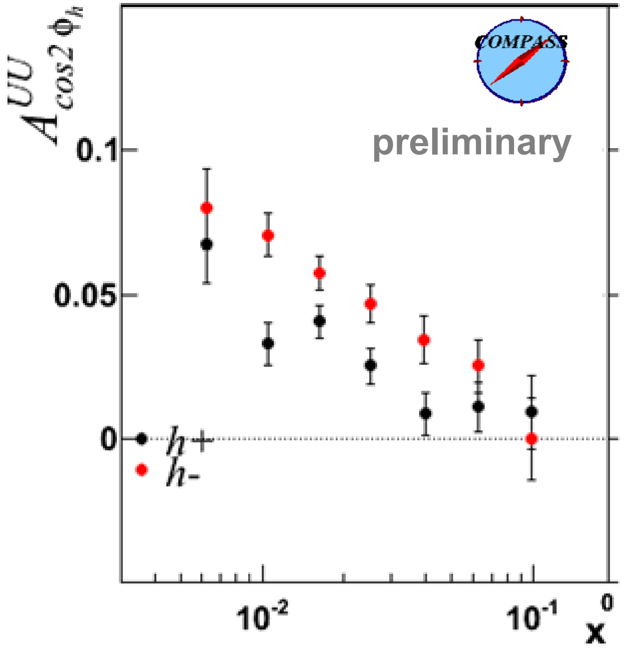
cos 2ϕ

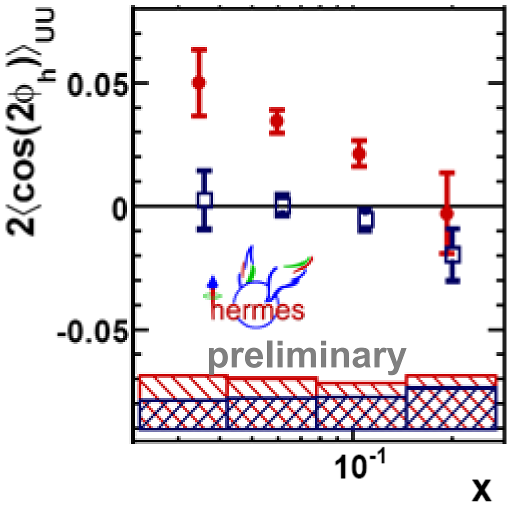
large signals at small x

- strong dependence on x, z, $P_T{}^h$
  difficult to describe
- different for h^+ and h^-

cos2ϕ modulation

deuteron data





different contributions of the Boer-Mulders term at HERMES and COMPASS?

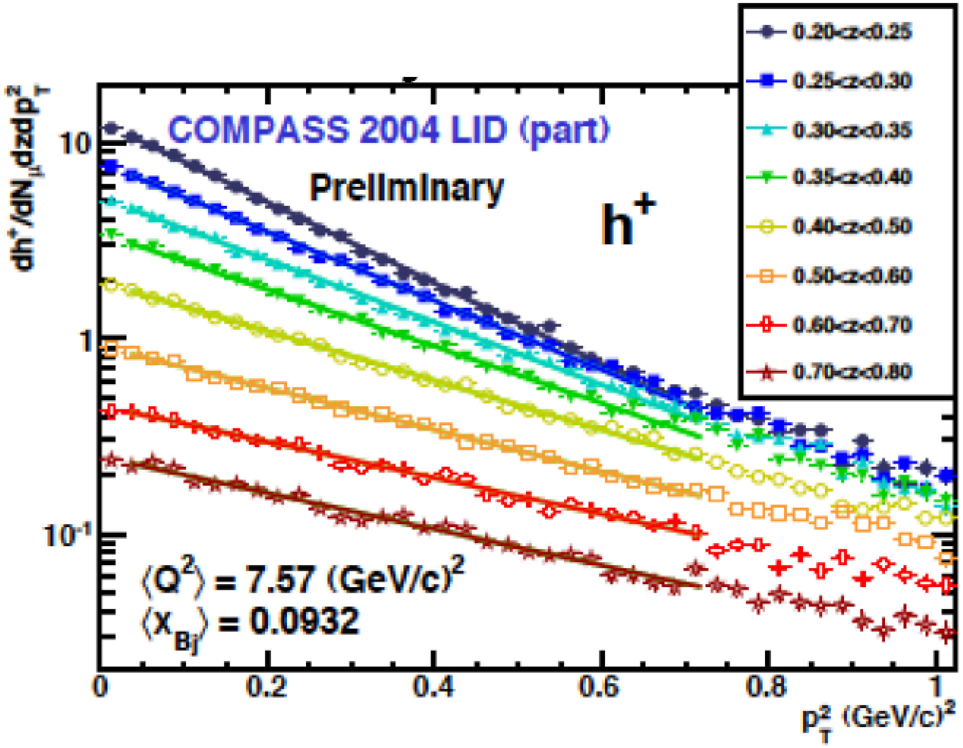
first fits to extract
the B-M function from
the cos2ϕ asymmetries
(Barone et al. 2009)

Cahn contribution not
negligible

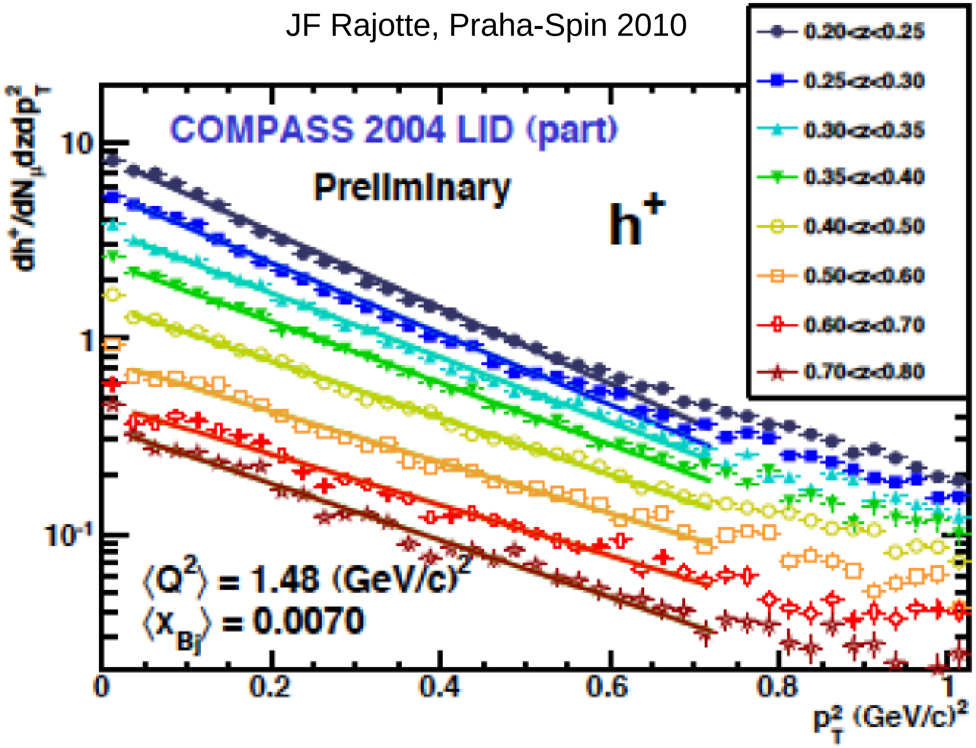
work ongoing

and interesting results on hadron distributions in SIDIS off unpolarised deuteron target

hadron multiplicity vs transverse momentum of the final state hadrons

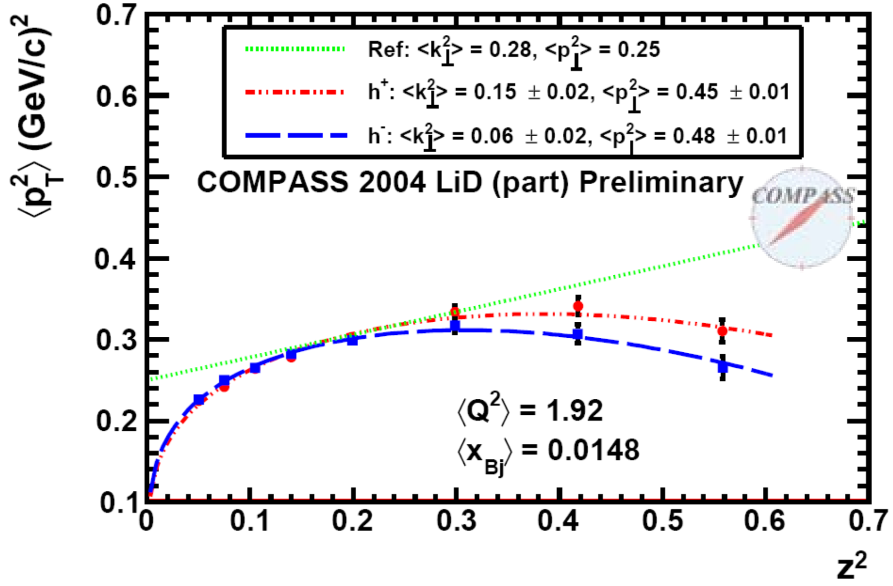


JF Rajotte, Praha-Spin 2010



as well as the cosϕ_h asymmetry, these data can be used to extract the intrinsic transverse momentum

hadron multiplicity vs transverse momentum of the final state hadrons



JF Rajotte, Praha-Spin 2010

the expected behaviour

$$\boxed{\langle p_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle}$$

final state hadron

FF

PDF

does not reproduce the data
as already known

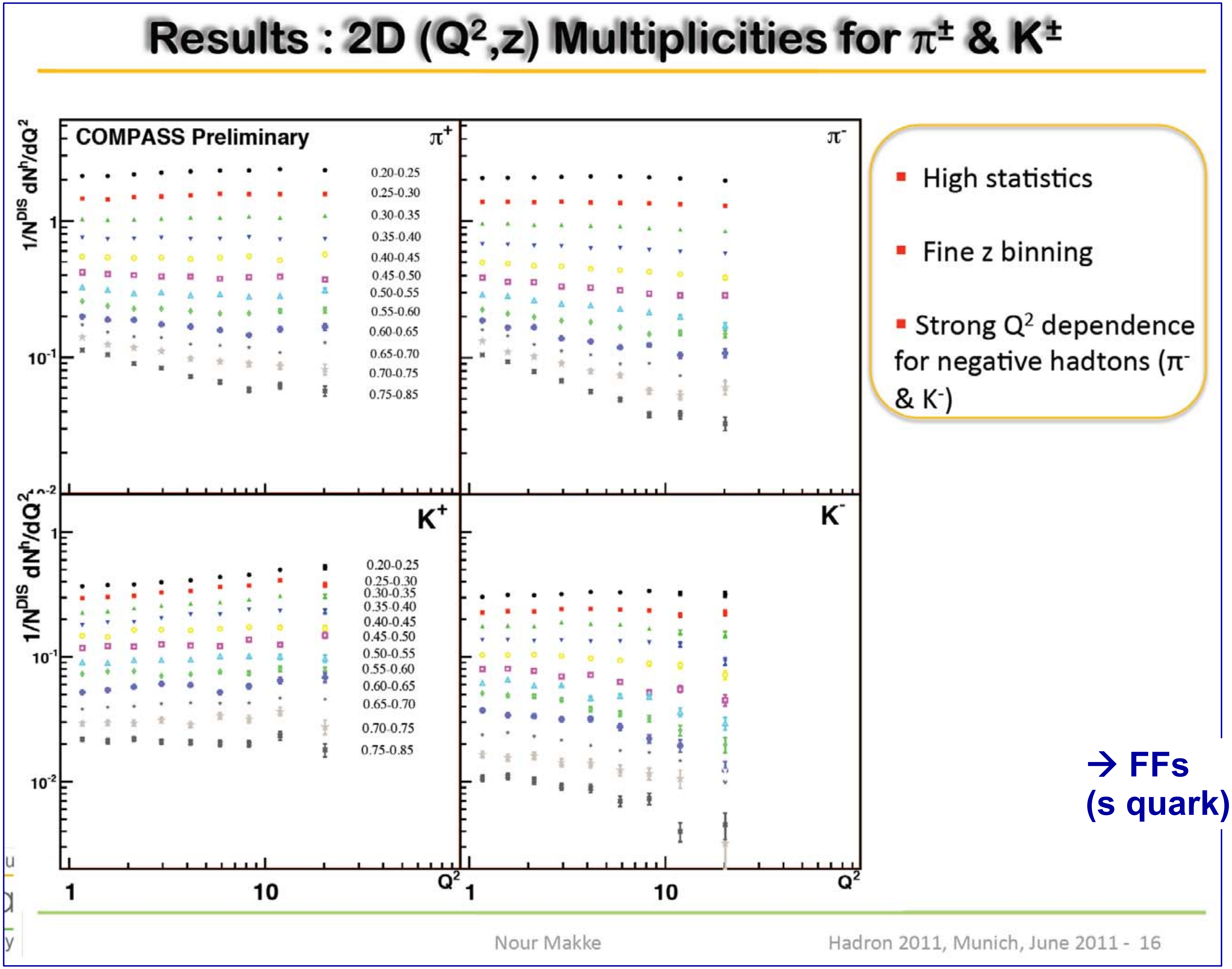
using $$\langle p_T^2 \rangle = z^\alpha (1-z)^\beta \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$

the extracted $\langle k_\perp^2 \rangle$ **is**

- **smaller than in previous extractions**
- **different for h+ and h-**
- **Q^2 dependent**

interpretation work ongoing: news soon ?

hadron multiplicity vs x, z and Q^2



Results : 2D (Q^2,z) Multiplicities for $\pi^\pm$ & $K^\pm$

- High statistics
- Fine z binning
- Strong Q^2 dependence for negative hadtons (π^- & K^-)

Nour Makke

Hadron 2011, Munich, June 2011 - 16

→ FFs
(s quark)

future

COMPASS II Proposal

- pion (and kaon) polarizabilities 2012
- **Drell-Yan** **2014**
- **Deeply Virtual Compton Scattering with**
  - **LH target**
  - **160 GeV muons**

  to access GPDs

2015-2016

test run in 2012

2 years of data taking approved by CERN in December 2010

in parallel to DVCS we proposed to measure
SIDIS off unpolarised p target

→ azimuthal asymmetries
→ P_T^2 distributions
→ multiplicities and FFs on p

future

COMPASS II Proposal

• pion (and kaon) polarizabilities	2012
• **Drell-Yan**	**2014**
• **Deeply Virtual Compton Scattering with** • **LH target** • **160 GeV muons** **to access GPDs**	**2015-2016** **test run in 2012**

in parallel to

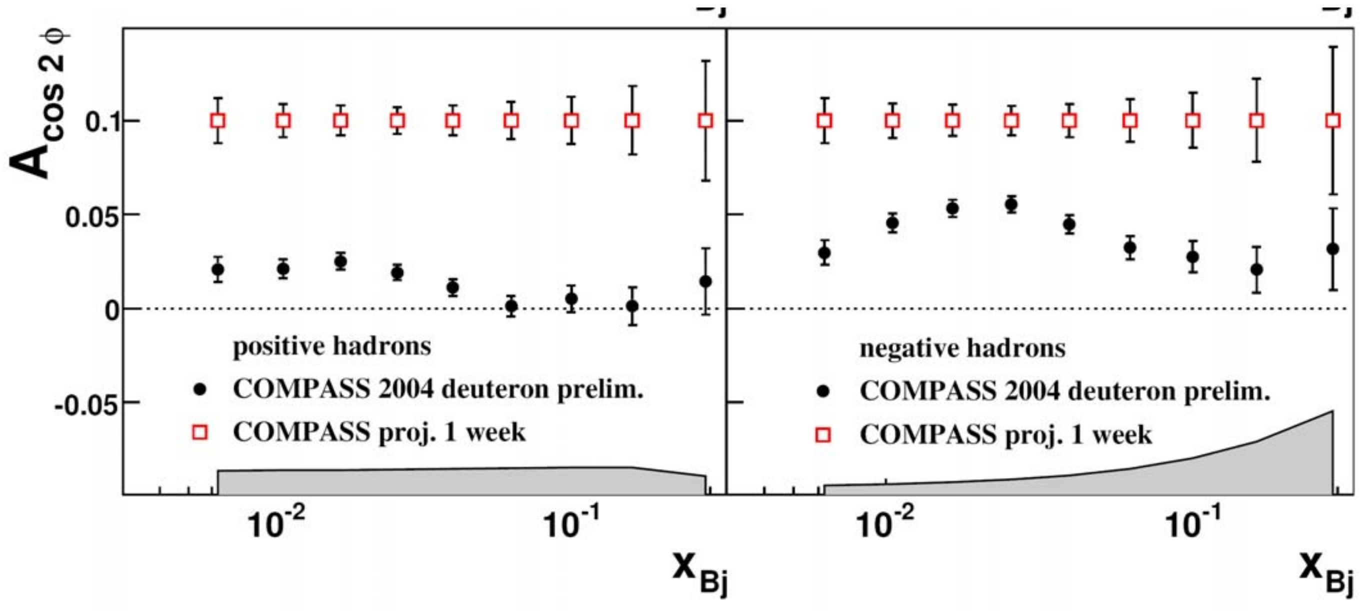
SIDIS off u

→ azimuth

→ P_T^2 distr

→ multipli

statistical errors from one week of data taking with LH target in parallel to DVCS



summary

a lot of SIDIS results on TMDs have been produced since 2005

very interesting, with some surprises

- solid evidence for: transversity PDF to be different from zero

  Sivers function to be different from zero

  new results will come very soon from COMPASS (2010 data)

- several allowed TMD asymmetries seem to be hardly measurable in SIDIS

- new interesting results from SIDIS off unpolarised nucleons

future:

- COMPASSII will contribute measuring DY and SIDIS
- much more data in different channels (SIDIS, DY, pp) at different energies are needed to study these new functions

SIDIS is an excellent tool to study the transverse spin and the transverse momentum structure of the nucleon

→ JLab 12 GeV

→ ep collider