Recent COMPASS results on transverse spin asymmetries in SIDIS.

giulio sbrizzai

DIS2015

28/04/2015 SMU, Dallas

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Collaboration
~ 250 physicists
28 institutions
12 countries

fixed target experiment at the CERN SPS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

wide physics program carried on using both **muon** and hadron beam

luminosity: $\sim 5 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

beam intensity: $2 \cdot 10^{8}\ \mu^{+}$**/spill (4.8s/16.2s)**

beam momentum: **160 GeV/*c***

longitudinally polarized muon beam

deuteron (^{6}LID) polarized target	2002	L/T
	2003	
	2004	
	2006	L
proton (NH_3) polarized target	2007	L/T
	2010	T
	2011	L
H_2 target	2012	

hadron beam

nuclear targets	2004
LH target	2008
	2009
	2012
	2014
polarised DY	2015

SIDIS:** a key process to **investigate** the **structure of the nucleon

lepton interacts with a **single constituent** of the nucleon (Q^2>1GeV^2/c^2)

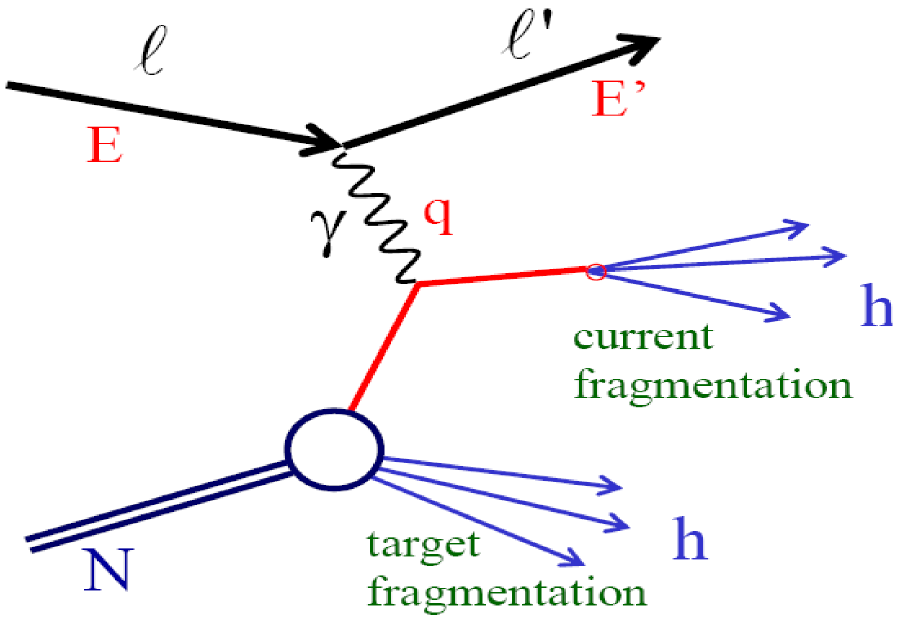
$$q = \ell - \ell'$$

$$Q^2 = -q^2 \qquad W^2 = (P+q)^2$$

$$x = \frac{Q^2}{2P \cdot q}$$ *Bjorken scaling variable*

$$y = \frac{P \cdot q}{P \cdot \ell} = \frac{E - E'}{E}$$

$$z = \frac{P \cdot P_h}{P \cdot q} = \frac{E_h}{E - E'}$$

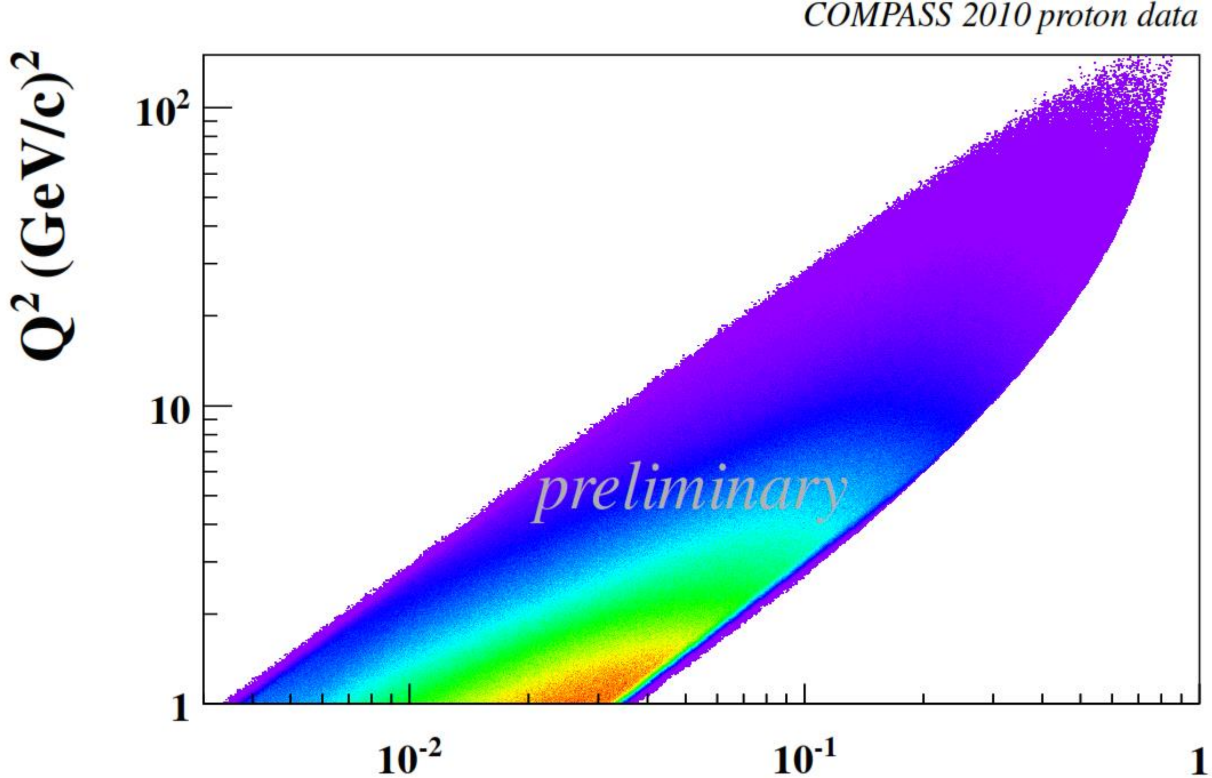


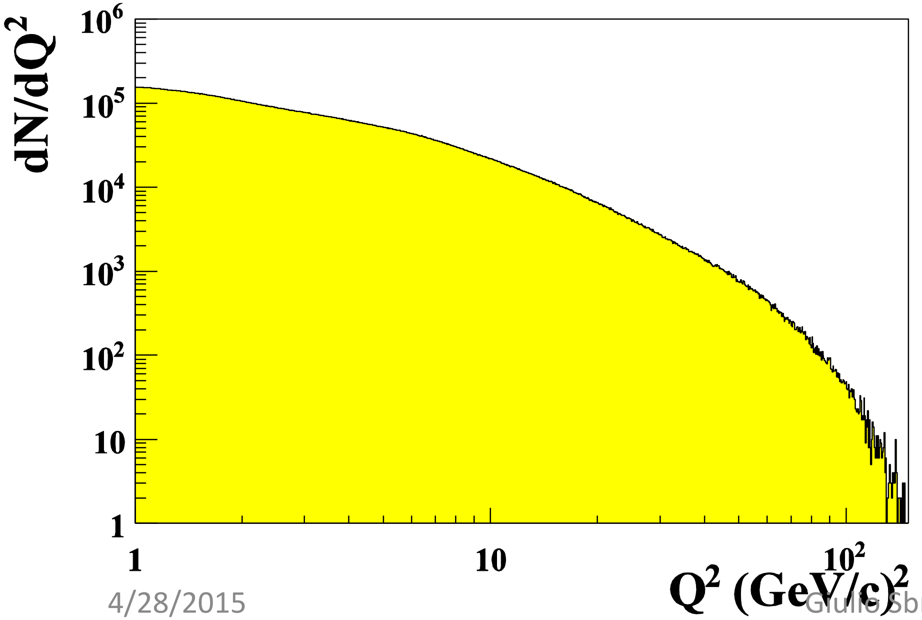
at least one hadron is detected in the final state

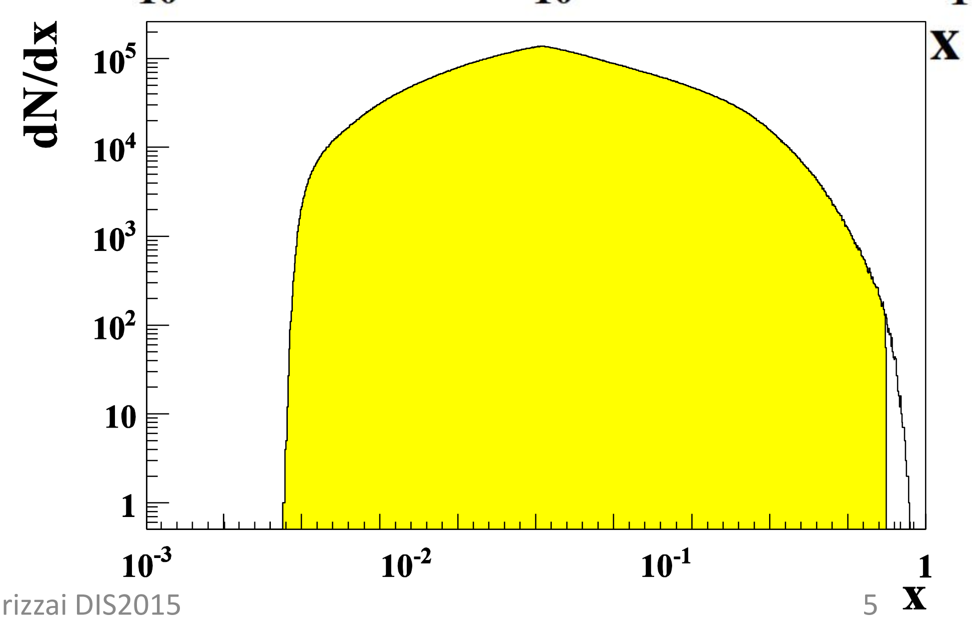
(information on the struck quark)

DIS event selection

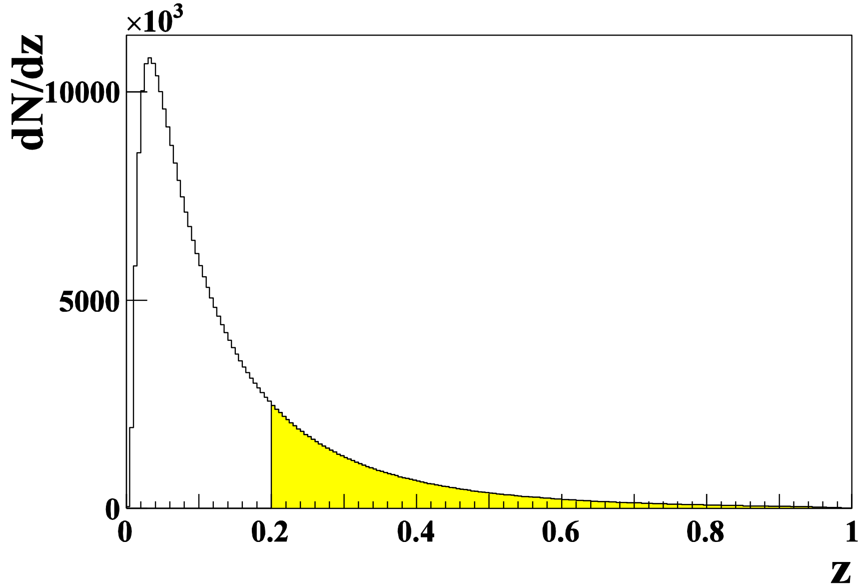
$Q2 > 1\ (GeV/c)^2$
$0.1 < y < 0.9$
$W > 5\ GeV/c^2$

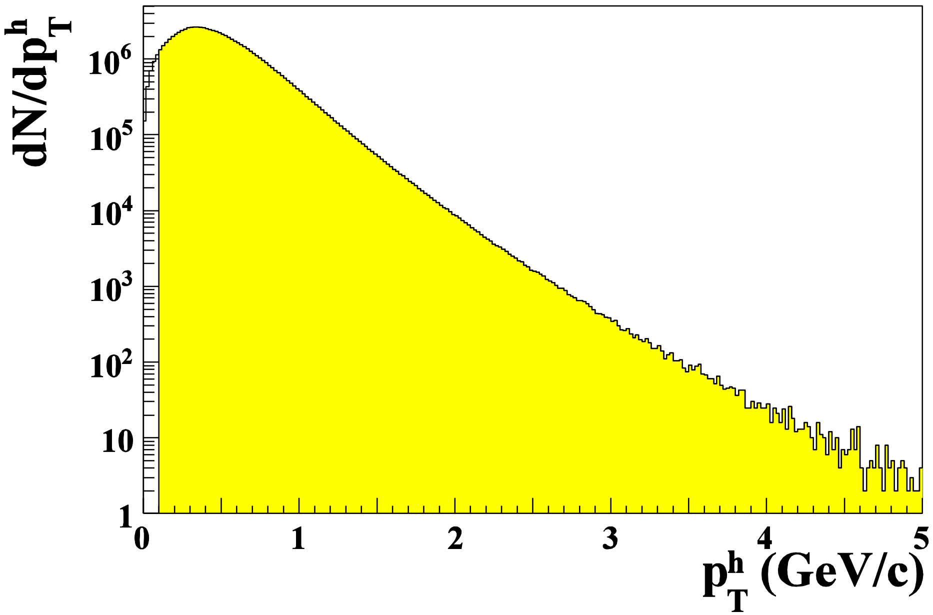






SIDIS event selection

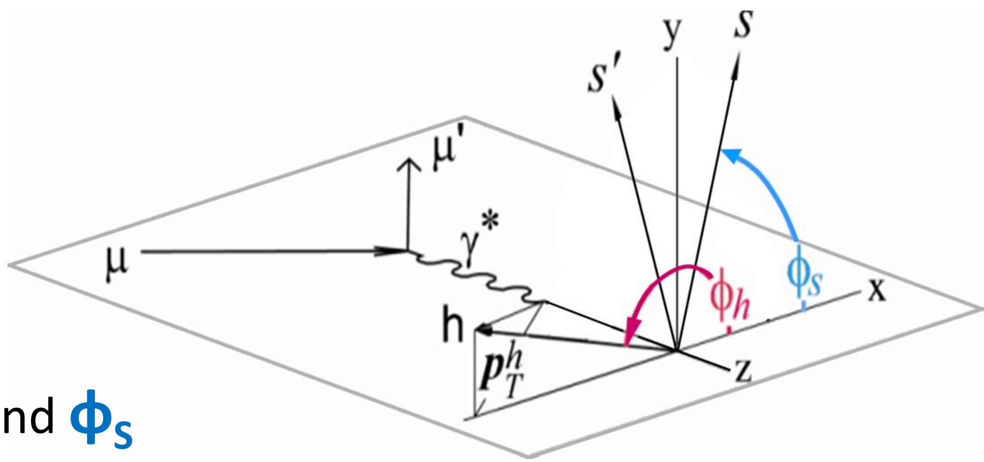




charged hadron selection

z>0.2

p_t^h > 0.1 GeV/c



definition of the produced hadron and target polarisation azimuthal angles ϕ_h and ϕ_S

SIDIS azimuthal cross section

"one photon exchange approximation"

Bacchetta et al. JHEP 0702:093,2007

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

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

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

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

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

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

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

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

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

target polarisation

beam polarisation

transverse spin dependent part

most famous amplitudes
COLLINS
SIVERS

results shown in this presentation

- Collins asymmetries
- dihadron asymmetries
- Sivers asymmetries
- “other 6” asymmetries on polarised target

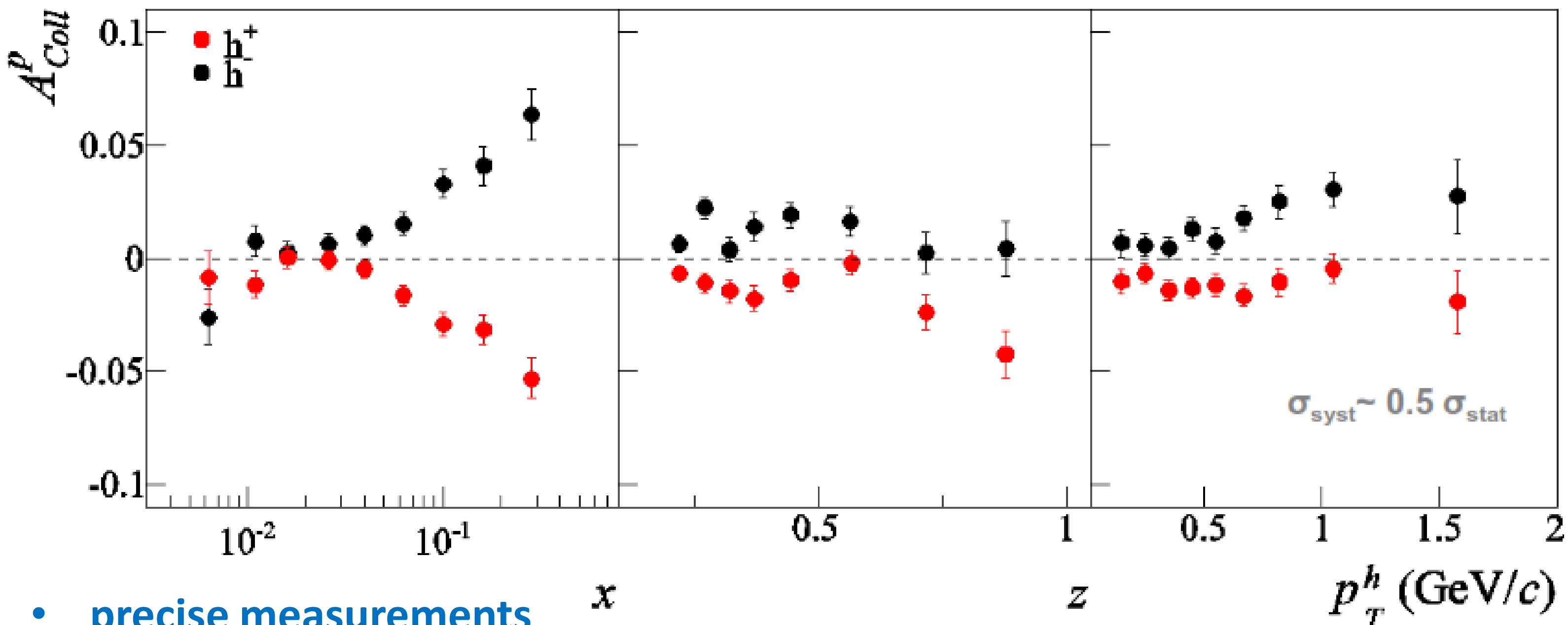
The Collins asymmetry *charged hadrons*

combined **2007** - PLB 692 (2010) 240 - and **2010** - PLB 717 (2012) 376 -

published measurements on transversely polarised proton

very good agreement between two independent data set

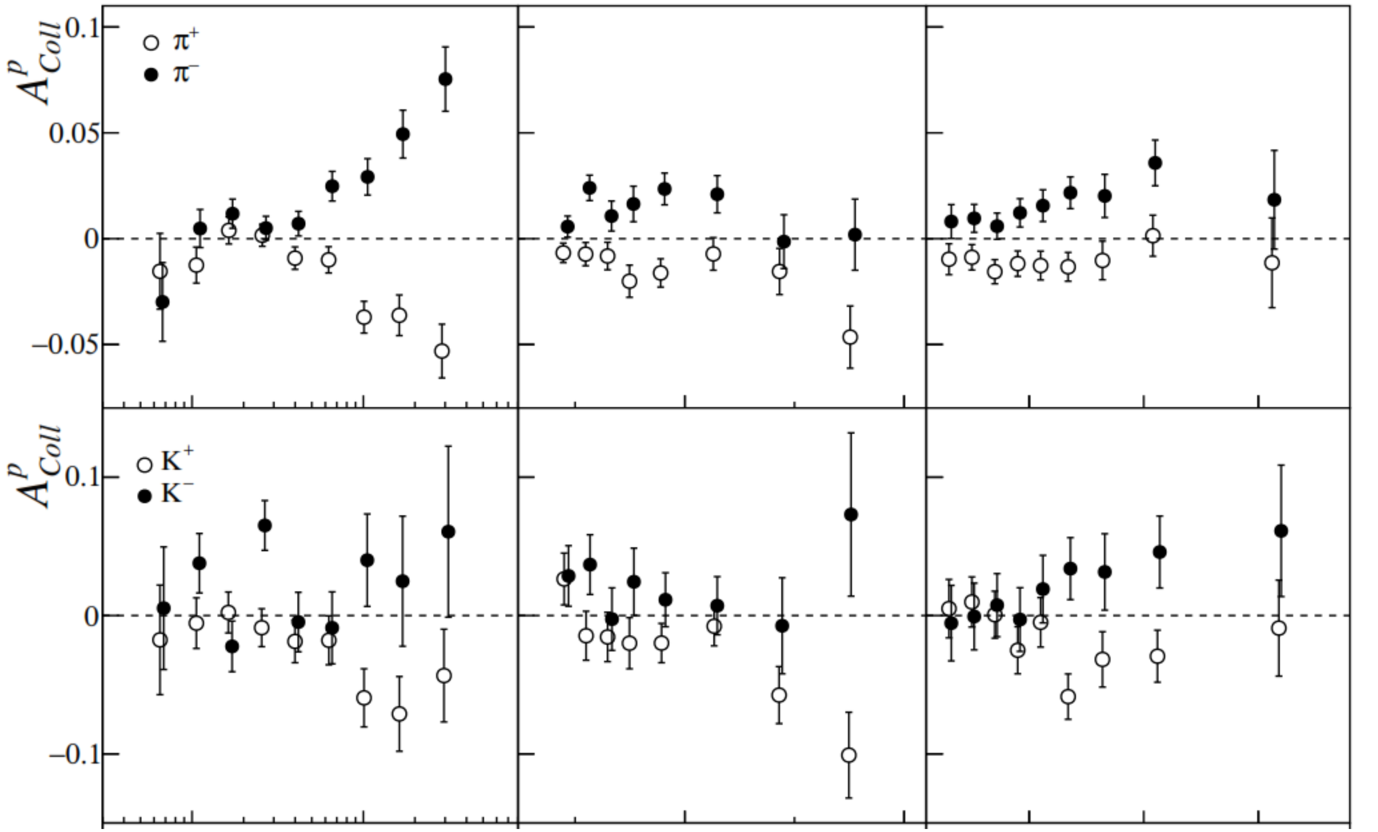
results on deuteron (2002-2004 data) compatible with zero
HERMES p + COMPASS p&d + BELLE → extraction of transversity for u and d quarks



- **precise measurements**
- **clear signal at x > 0.03, with opposite sign for h+ and h-**
  in agreement with the HERMES results

The Collins asymmetry *pions and kaons*

accepted for publication in PLB



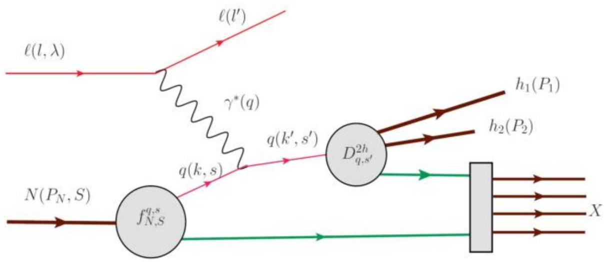
x z p_T^h (GeV/c)

$\sigma_{sys} \sim 0.6\ \sigma_{stat}$

asymmetries from deuterium compatible with zero another observable related to transversity

$$lN \to l' h^+ h^- X$$

di-hadron asymmetries



we measure

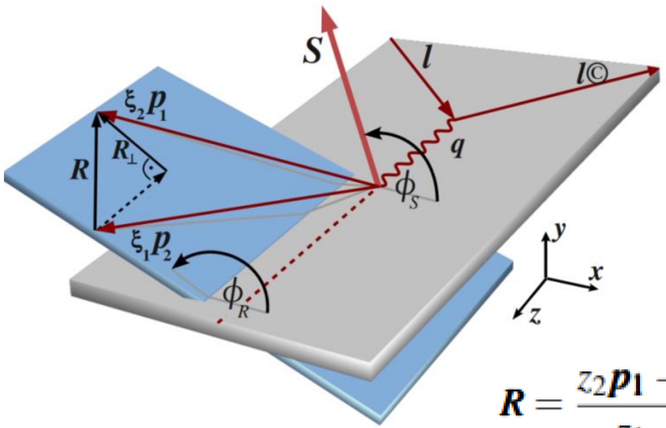
$$A_{UT}^{\sin\phi_{RS}}$$

from $$N_{h^+h^-}(\phi_{RS}) = N_h^0 \left[1 \pm f P_T D_{NN} A_{UT}^{\sin\phi_{RS}} \sin(\phi_{RS})\right]$$

*on **oppositely charged hadrons pairs***

$$A_{UT}^{\sin\phi_{RS}} \approx \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1q}^{\angle}(z, M_{hh}^2)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1q}^h(z, M_{hh}^2)}$$

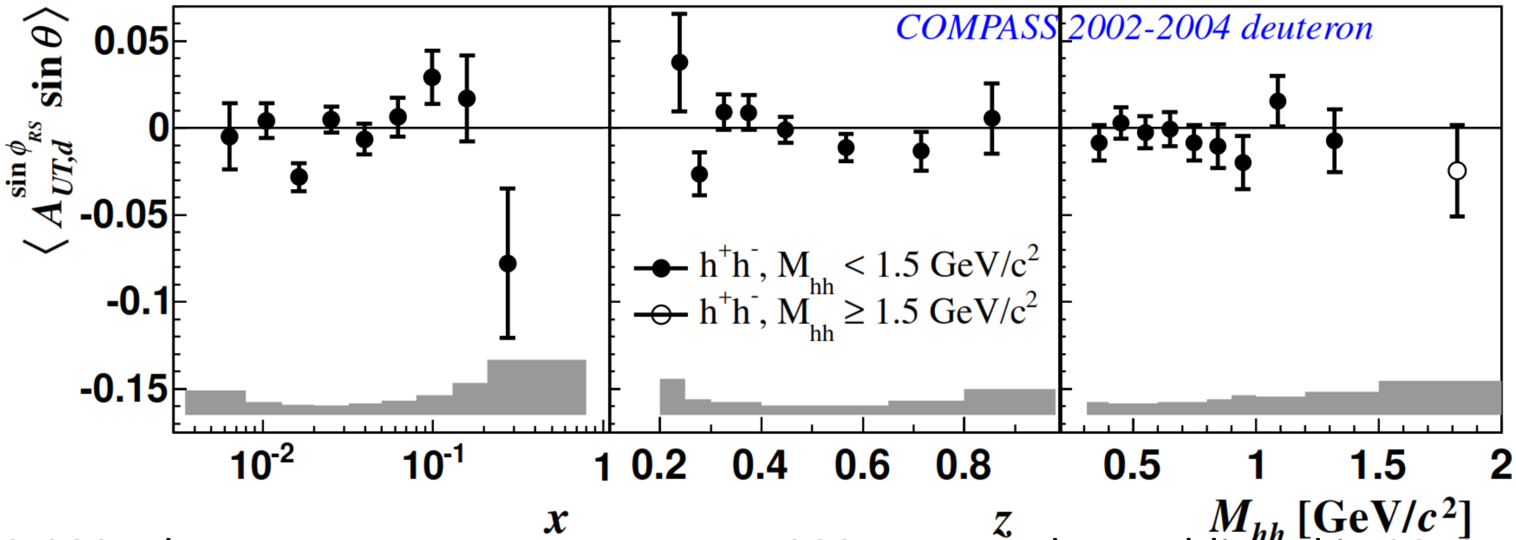
collinear !



$$\boldsymbol{R} = \frac{z_2 \boldsymbol{p}_1 - z_1 \boldsymbol{p}_2}{z_1 + z_2}$$

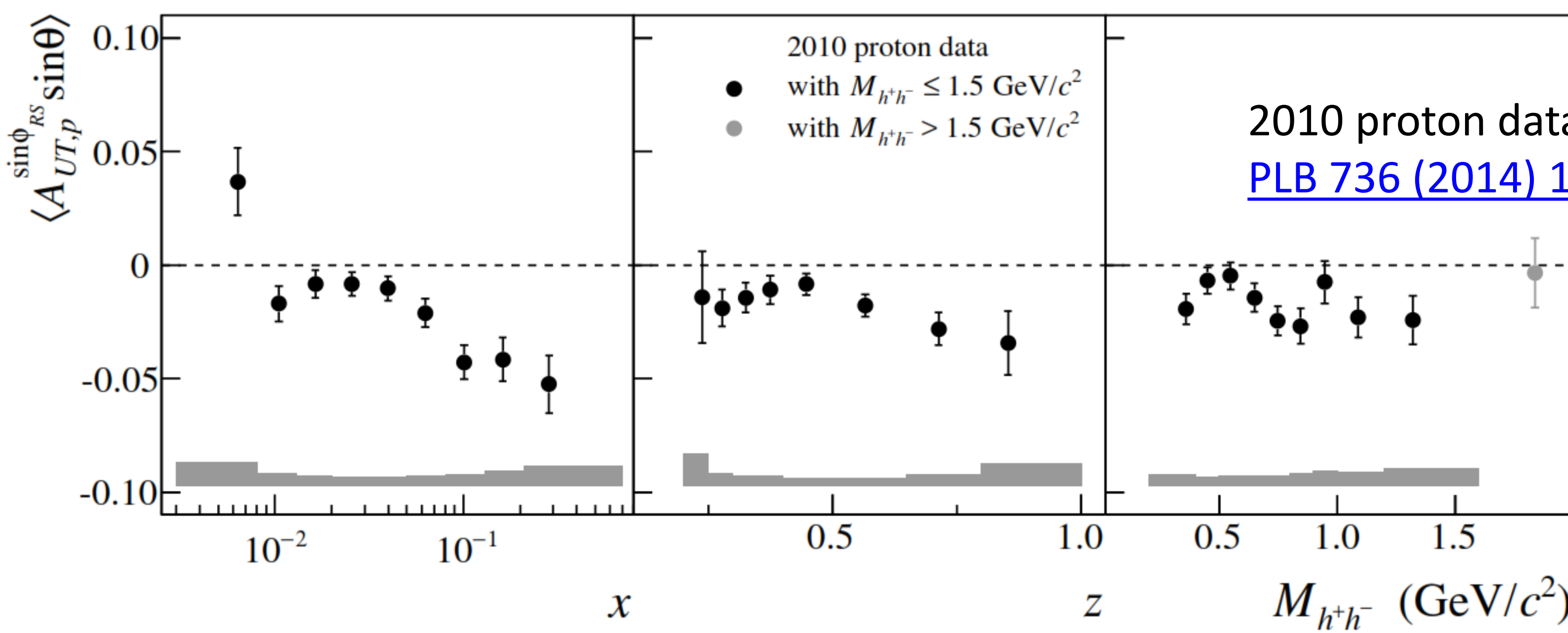
the azimuthal distribution of the hadrons pairs shows a modulation in the azimuthal angle:

$$\phi_{RS} = \phi_R + \phi_S - \pi$$



2002-2004 deuteron *(compatible with zero)* + 2007 proton data published in 2012

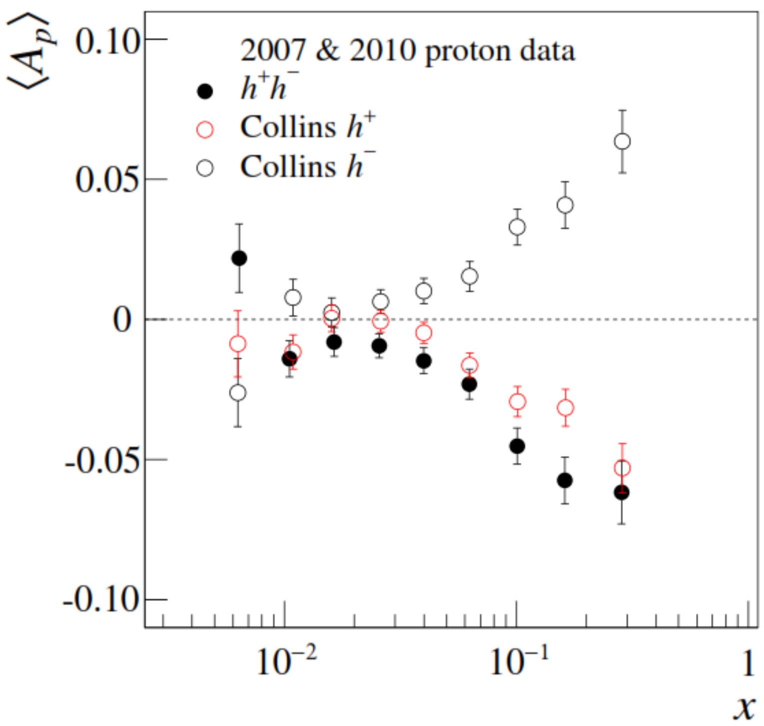
[PLB 713 (2012) 10]



2010 proton data

[PLB 736 (2014) 124]

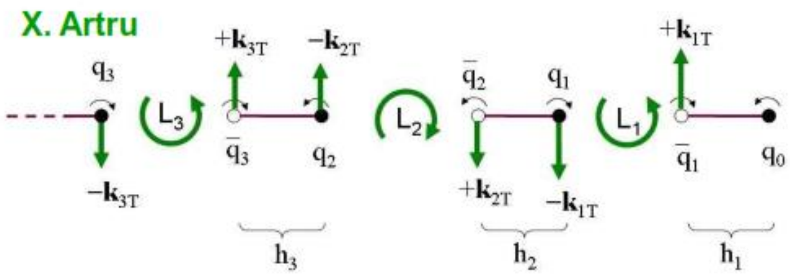
comparison between di-hadron and Collins asymmetries



[PLB 736 (2014) 124]

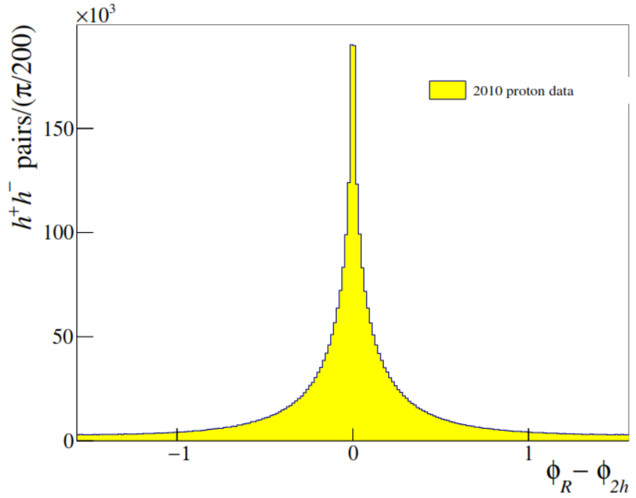
- Collins asymmetry for h+ and for h- :
  "mirror symmetry"
- dihadron asymmetry vs Collins asymmetry:
  only somewhat larger

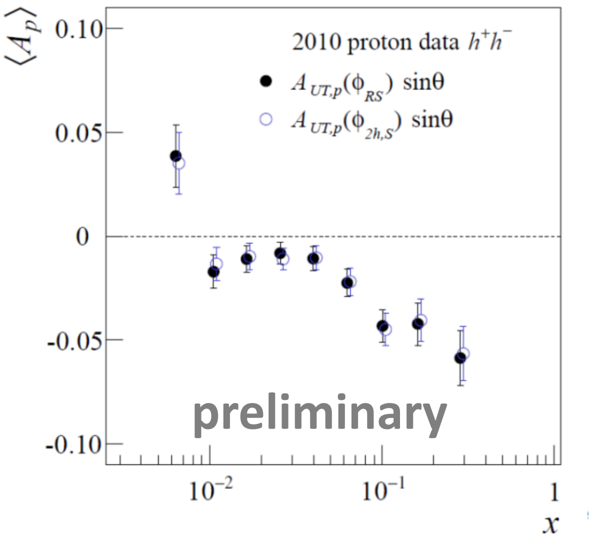
… Due to local compensation of transverse momentum, the one-particle Collins effect generates a two-particle effect, and viceversa
(X. Artru, arXiv:hep-ph/0207309)



further studies …

strong correlation between: ϕ_R and ϕ_{2h} → the azimuthal angle of the vector $\hat{P}_T^{h^+} - \hat{P}_T^{h^-}$





analysis of the single hadron and dihadron asymmetries performed
on a common data sample *(2010 transversely polarised proton)*

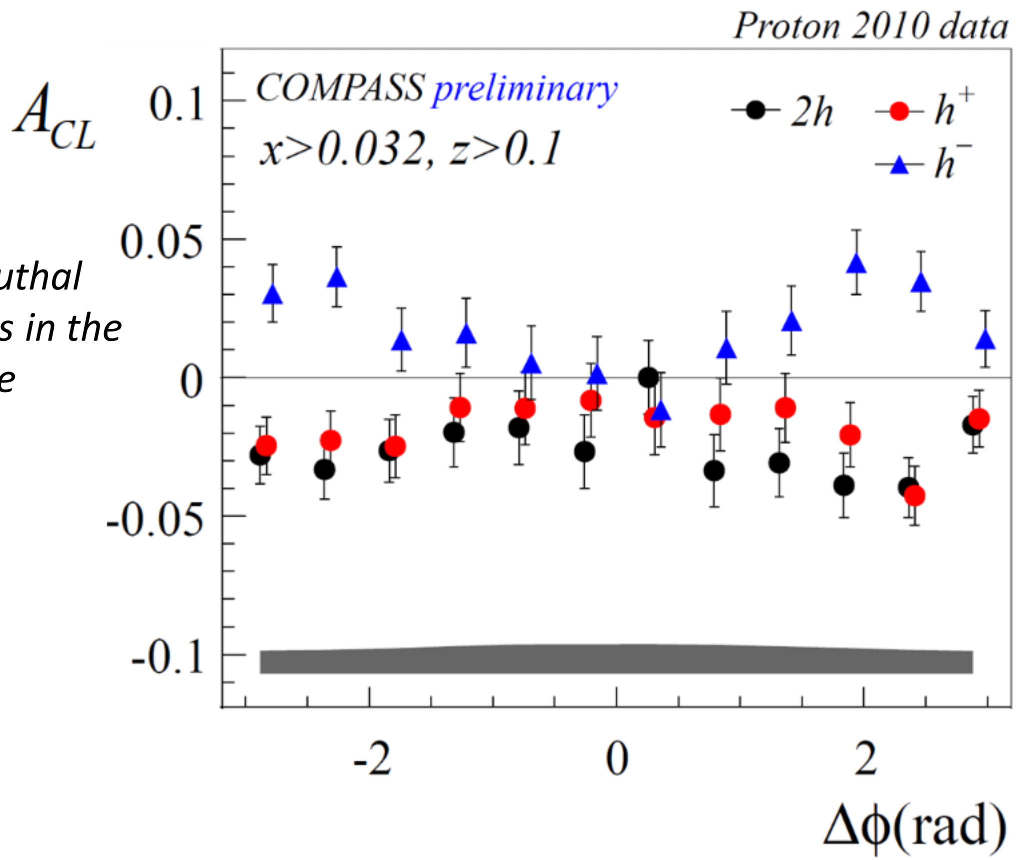
⇓

standard COMPASS SIDIS sample but wth h^+ h^- at least detected (each hadron with z >0.1)

measure **single hadron** and
di-hadron asymmetries in **ΔΦ**

$$\Delta\phi = \phi_{h^+} - \phi_{h^-}$$

amplitudes of the azimuthal modulations in the Collins angle
h⁺
h⁻
2h



signal bigger when
h+ and h-
go in opposite direction

(expected from the
string fragmentation model)

same mechanism seems to give collins asymmetries and di-hadron asymmetries ?

moreover the general expression for the $lN \to l' h^+ h^- X$ cross section

$$\frac{d\sigma^{h^+h^-}}{d\phi_{h^+} d\phi_{h^-} d\phi_S} = \sigma_U^{h^+h^-} + S_T \cdot \left[\sigma_{1C}^{h^+h^-} \sin(\phi_{h^+} + \phi_S - \pi) + \sigma_{2C}^{h^+h^-} \sin(\phi_{h^-} + \phi_S - \pi)\right]$$

A.Kotzininan PRD91 (2015) 054001

dependencies σ(Δφ) omitted ....

$$\phi_{h^+}, \phi_{h^-} \to \phi_{h^+}, \Delta\phi$$

$$\frac{d\sigma^{h^+h^-}}{d\phi_{h^+} d\Delta\phi\, d\phi_S} = \sigma_U^{h^+h^-} + S_T \cdot \left[\left(\sigma_{1C}^{h^+h^-} + \sigma_{2C}^{h^+h^-} \cos\Delta\phi\right) \sin(\phi_{h^+} + \phi_S - \pi) + \ldots\right]$$

$$\phi_{h^+}, \phi_{h^-} \to \Delta\phi, \phi_{h^-}$$

measured amplitudes !

$$\frac{d\sigma^{h^+h^-}}{d\phi_{h^-} d\Delta\phi\, d\phi_S} = \sigma_U^{h^+h^-} + S_T \cdot \left[\left(\sigma_{2C}^{h^+h^-} + \sigma_{1C}^{h^+h^-} \cos\Delta\phi\right) \sin(\phi_{h^-} + \phi_S - \pi) + \ldots\right]$$

using $\sigma_{1C}^{h^+h^-}(\Delta\phi) = -\sigma_{2C}^{h^+h^-}(\Delta\phi)$ and $\phi_{h^+}, \phi_{h^-} \rightarrow \phi_{2h}, \Delta\phi$

mirror symmetry

one obtain

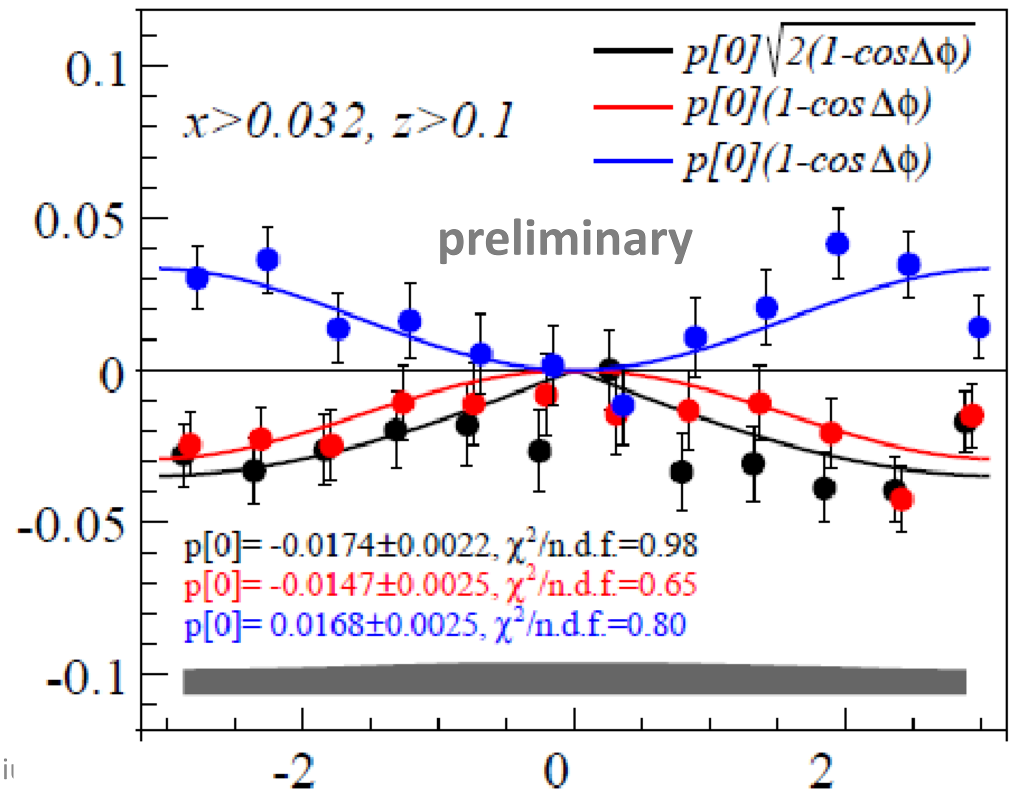
$$\frac{d\sigma^{h^+h^-}}{d\phi_{2h}\, d\Delta\phi\, d\phi_S} = \sigma_U^{h^+h^-} + S_T \cdot \sigma_{1C}^{h^+h^-} \cdot \sqrt{2(1-\cos\Delta\phi)}\,\sin(\phi_{2h}+\phi_S-\pi)$$

and writing explicitly the measured asymmetries we have

$$A_{1CL}^{\sin(\phi_{h^+}+\phi_S-\pi)} = \frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot (1-\cos\Delta\phi)$$

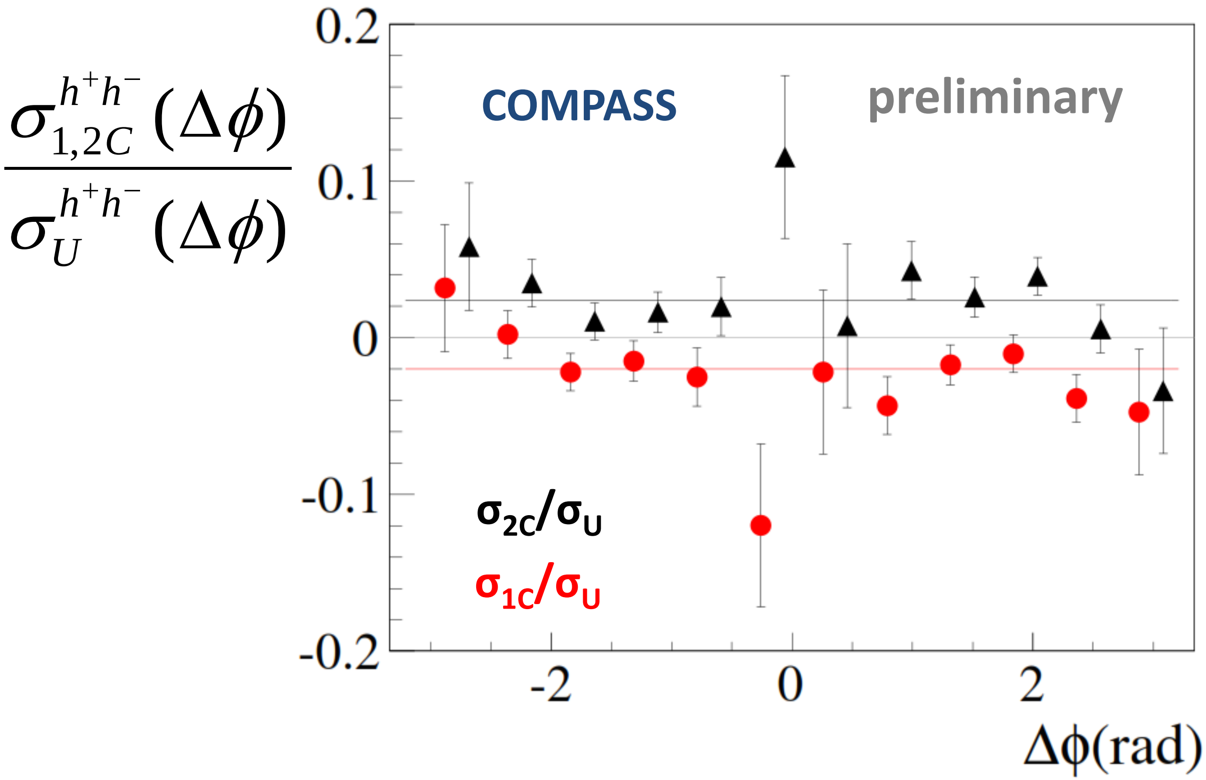
$$A_{2CL}^{\sin(\phi_{h^-}+\phi_S-\pi)} = -\frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot (1-\cos\Delta\phi)$$

$$A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)} = \frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot \sqrt{2\cdot(1-\cos\Delta\phi)}$$



dependence from **ΔΦ** in the
polarised part and ***unpolarised*** part of the cross section

$$\frac{d\sigma^{h^+h^-}}{d\phi_{h^+} d\phi_{h^-} d\phi_S} = \sigma_U^{h^+h^-} + S_T \cdot \left[\sigma_{1C}^{h^+h^-} \sin(\phi_{h^+} + \phi_S - \pi) + \sigma_{2C}^{h^+h^-} \sin(\phi_{h^-} + \phi_S - \pi)\right]$$



the ΔΦ dependence looks similar

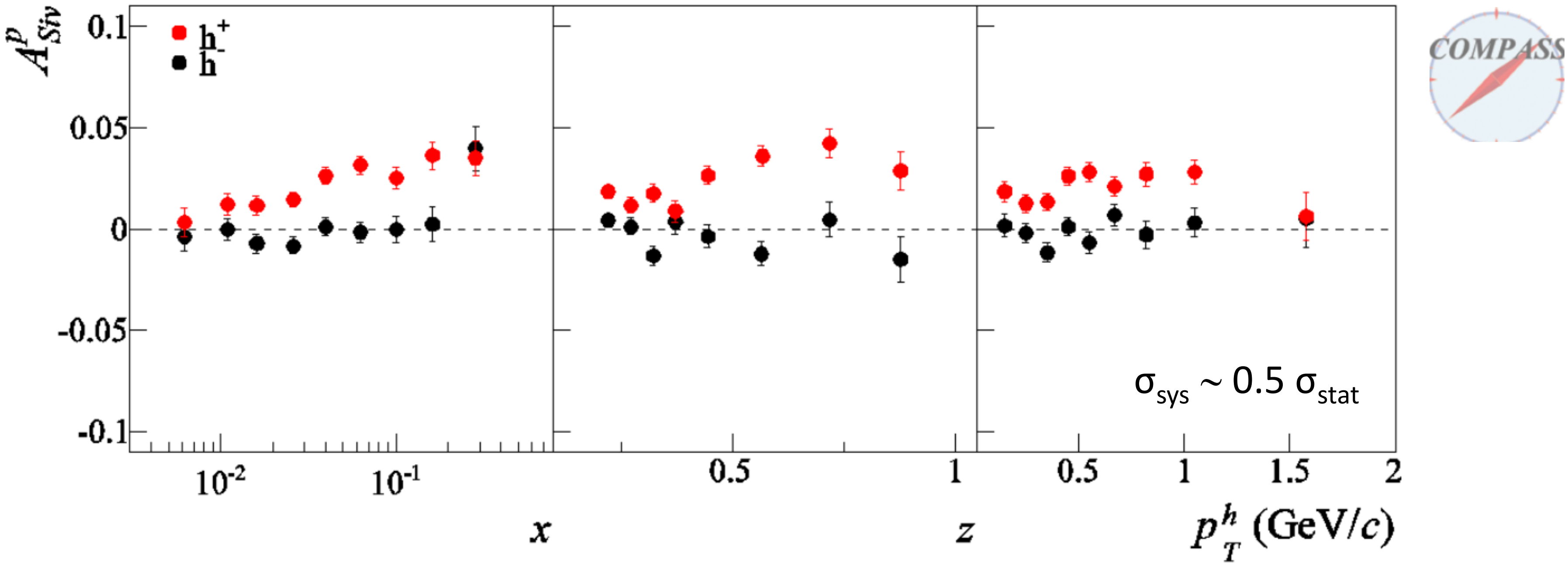
and also
mirror symmetry

interesting studies on the interplay still going on …
(paper in preparation)

The Sivers asymmetry *charged hadrons*

combined **2007** - PLB 692 (2010) 240 - and **2010** - PLB 717 (2012) 383 - **measurements on proton**

very good agreement between two independent data set

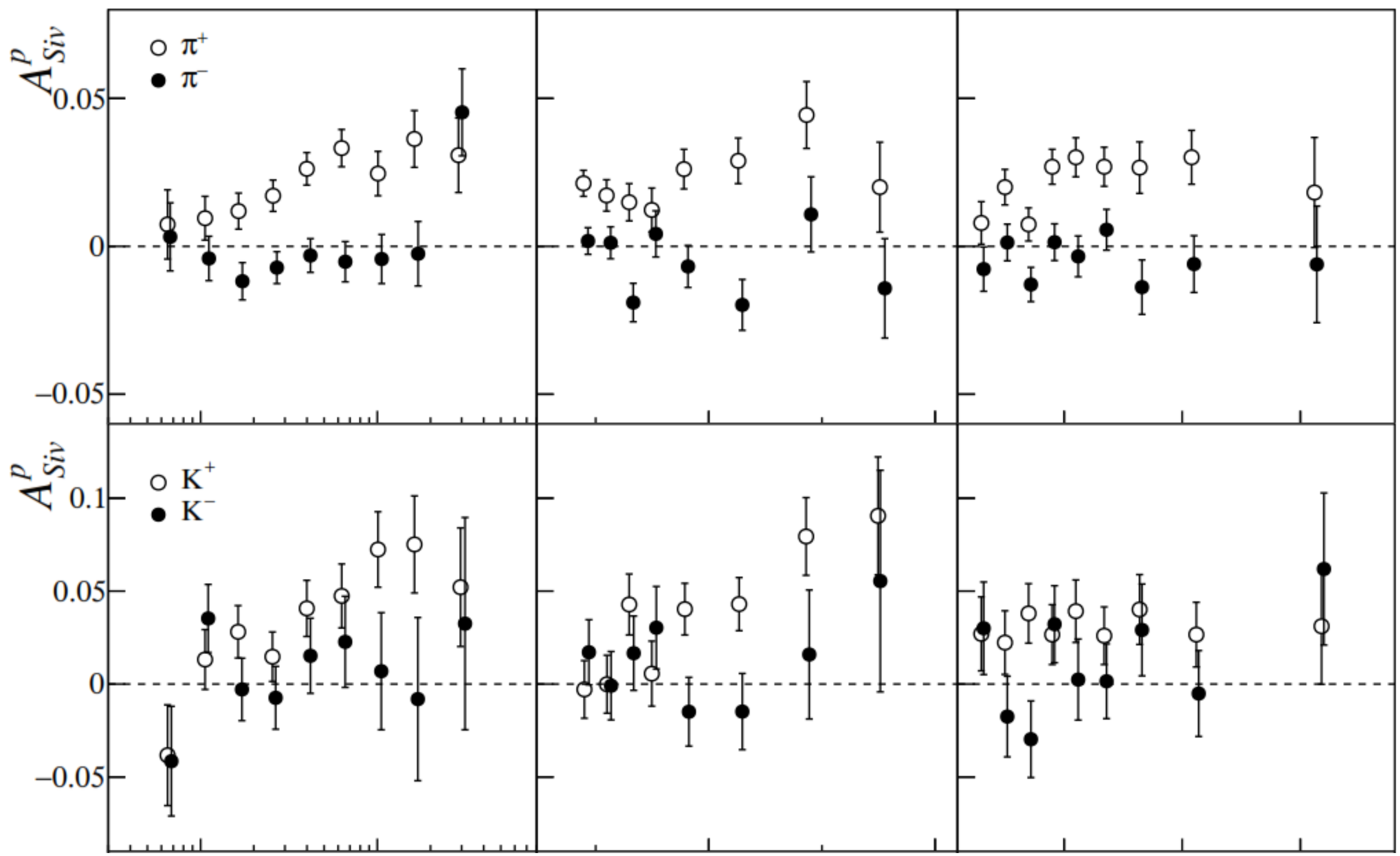


h+ : clear signal down to low x, in the previously unmeasured region

results on deuteron (2002-2004 data) compatible with zero

The Sivers asymmetry *pions and kaons*

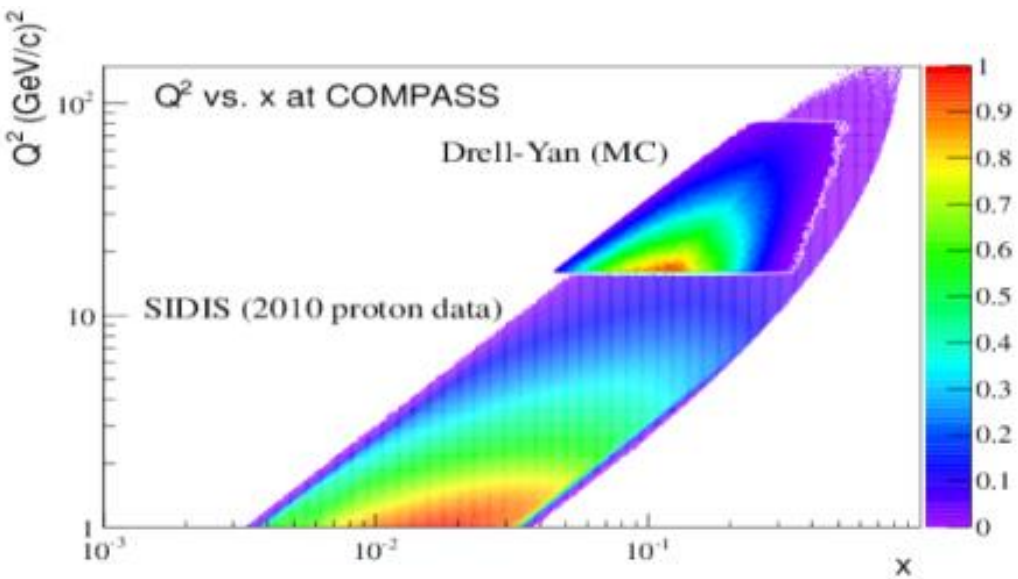
larger than for π^+



x z p_T^h (GeV/c)

fundamental QCD prediction $$f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$$

COMPASS is taking Drell-Yan data with transversely polarised target
(full year dedicated)



superposition DY – SIDIS kinematical region at COMPASS

Other transverse spin dependent asymmetries

there are also other 6 modulations related to different TMDs
they all have been measured at COMPASS

$$
\begin{aligned}
&+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) \\
&\quad + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big] \\
&+ |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},
\end{aligned}
$$

sivers
collins

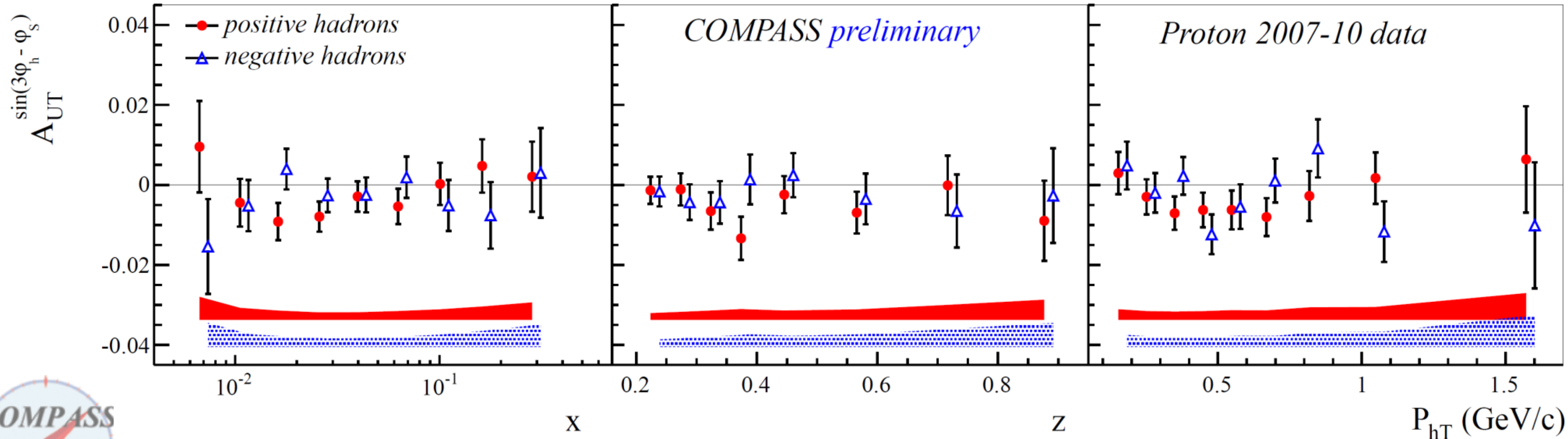
pretzelosity

worm-gear

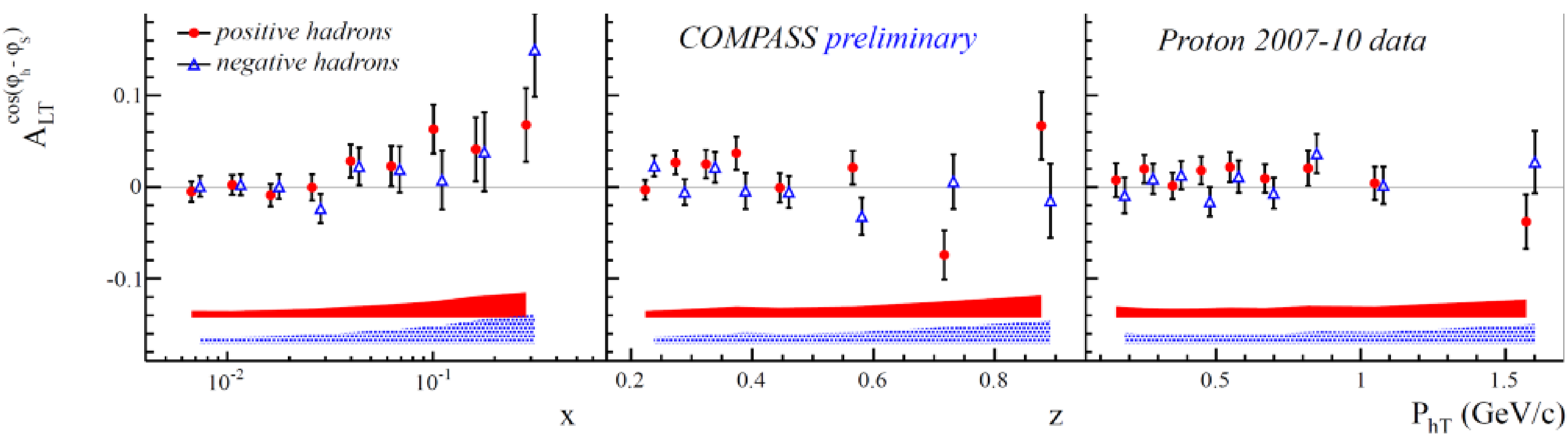
higher twist effects

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$, **pretzelosity** $h_{1T}^{\perp q}$:

sensitive to the D-wave component
non spherical shape of the nucleon



$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$, **worm-gear** g_{1T}^{q} :



Other transverse spin dependent asymmetries

there are also other 6 modulations related to different TMDs
they all have been measured at COMPASS

$$
\begin{aligned}
&+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \Big) \\
&\quad + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)} \Big] \\
&+ |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},
\end{aligned}
$$

both on deuteron and on proton
in general the asymmetries are small and compatible with zero

conclusions

COMPASS produced lot of interesting new results on target transverse spin dependent asymmetries in SIDIS (both on deuteron and on proton)

this year 2015 DY with **transversely** polarised target and pion beam data taking

high precision measurements thanks to the dedicated 2010 data taking (polarised proton)

studies recently begun and still going on

- multi dimensional analysis
- interplay between dihadron and single hadron asymmetries and azimuthal correlations

spares

the 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

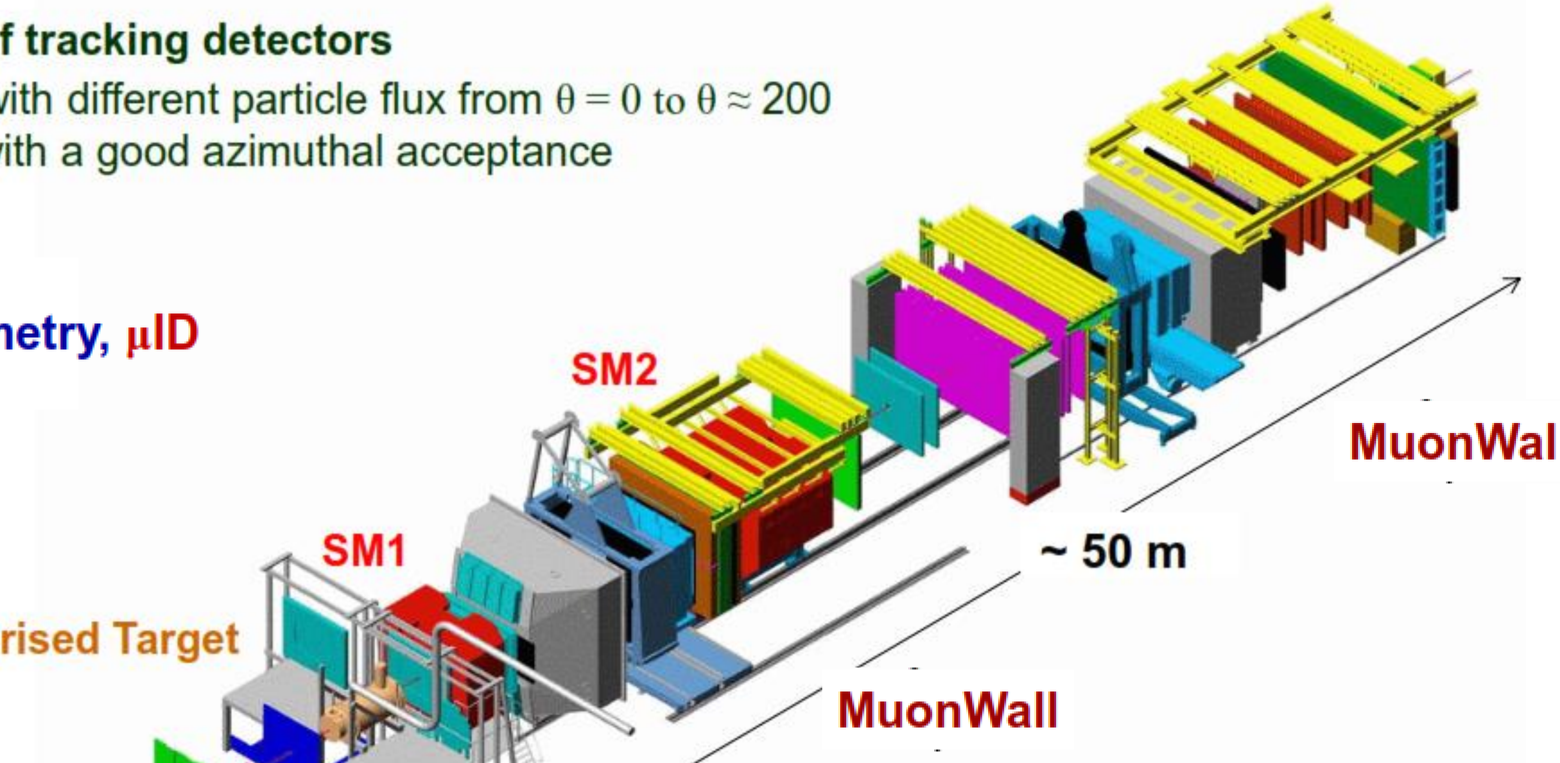
to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance

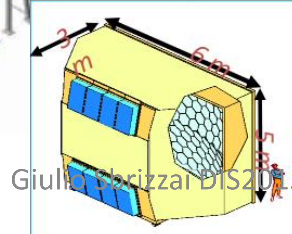
calorimetry, μID

RICH

Polarised Target

μ beam



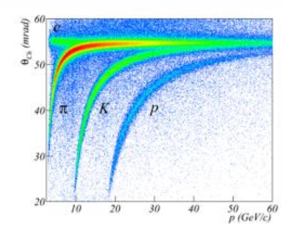


Hadron identification:

$\pi^{\pm}$ $K^{\pm}$

based on RICH-1 response

(likelihood algorithm)



Cherenkov thresholds

π ~ 3 GeV/c

K ~ 9 GeV/c

p ~ 18 GeV/c

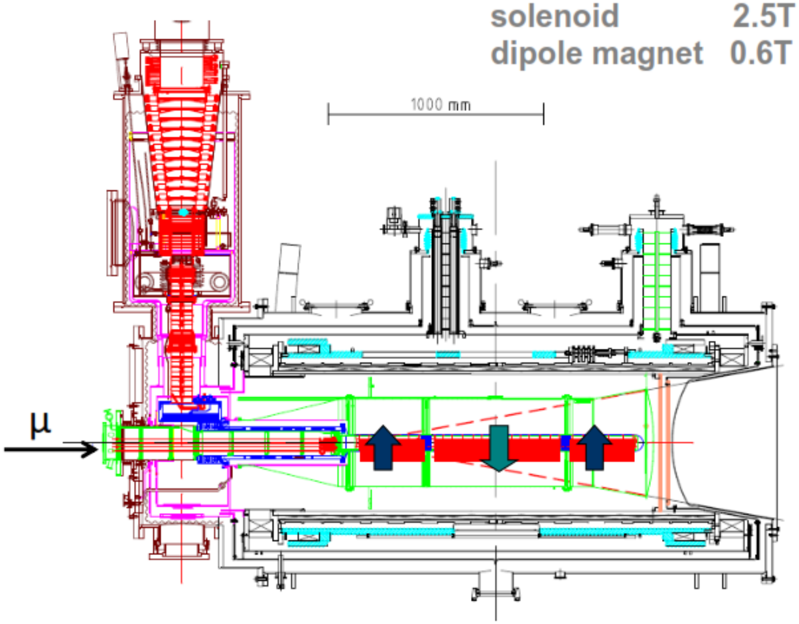
polarized target system (>2005)

solid state target operating in frozen spin mode

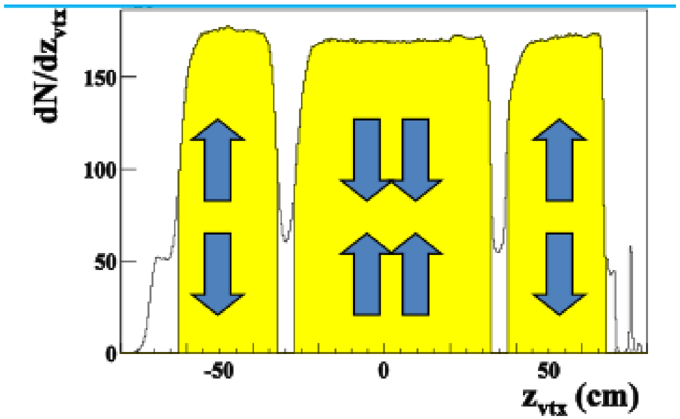
	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

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

solenoid 2.5T
dipole magnet 0.6T

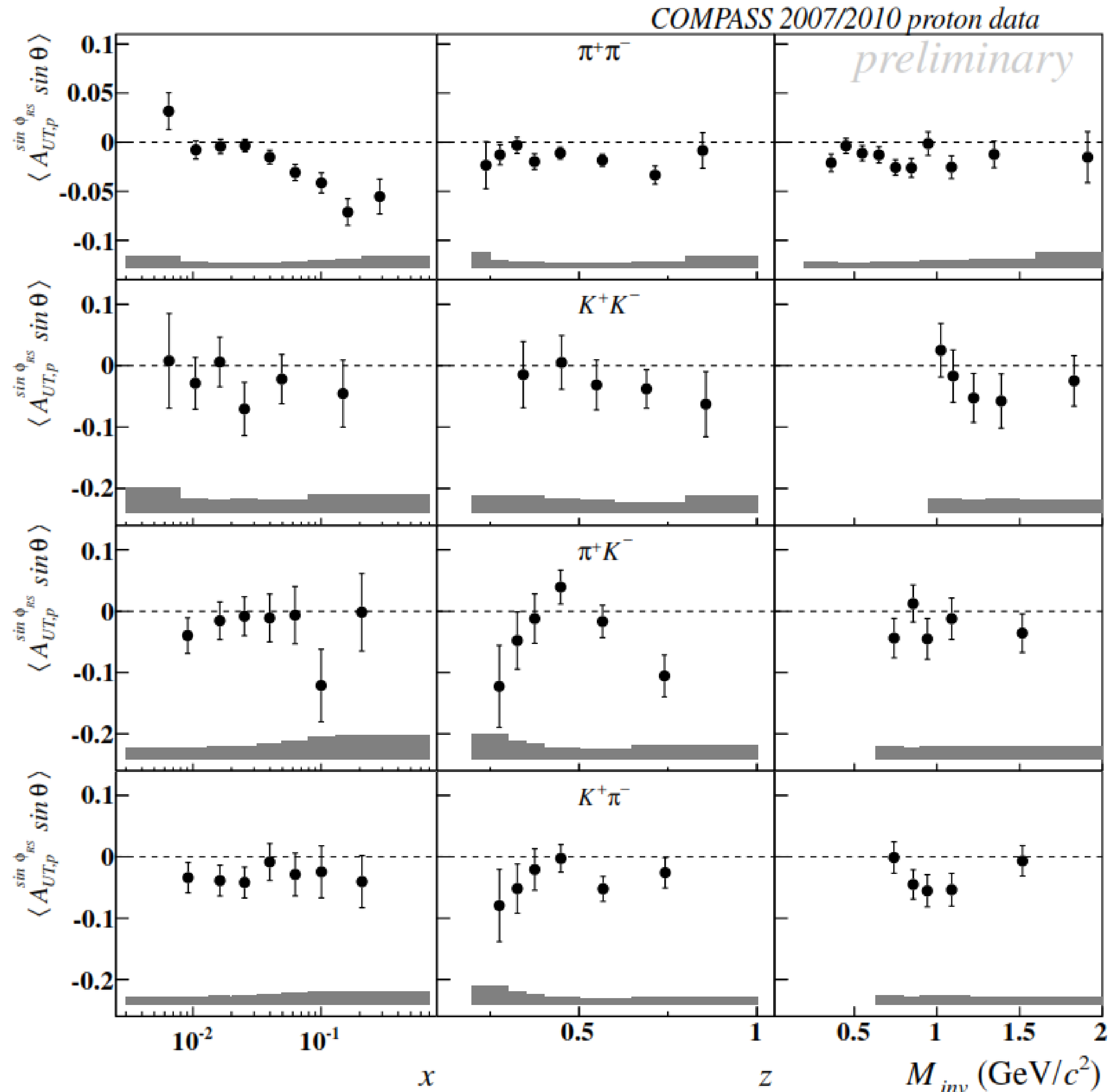


3 cells target with opposite polarizations



2 configurations:
polarisation reversed each week
to minimize possible systematic errors

identified hadrons pairs



multiD Sivers asymmetries (h^+h^-)