Transverse spin and transverse momentum distributions from COMPASS

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QNP 2012 – Palaiseau

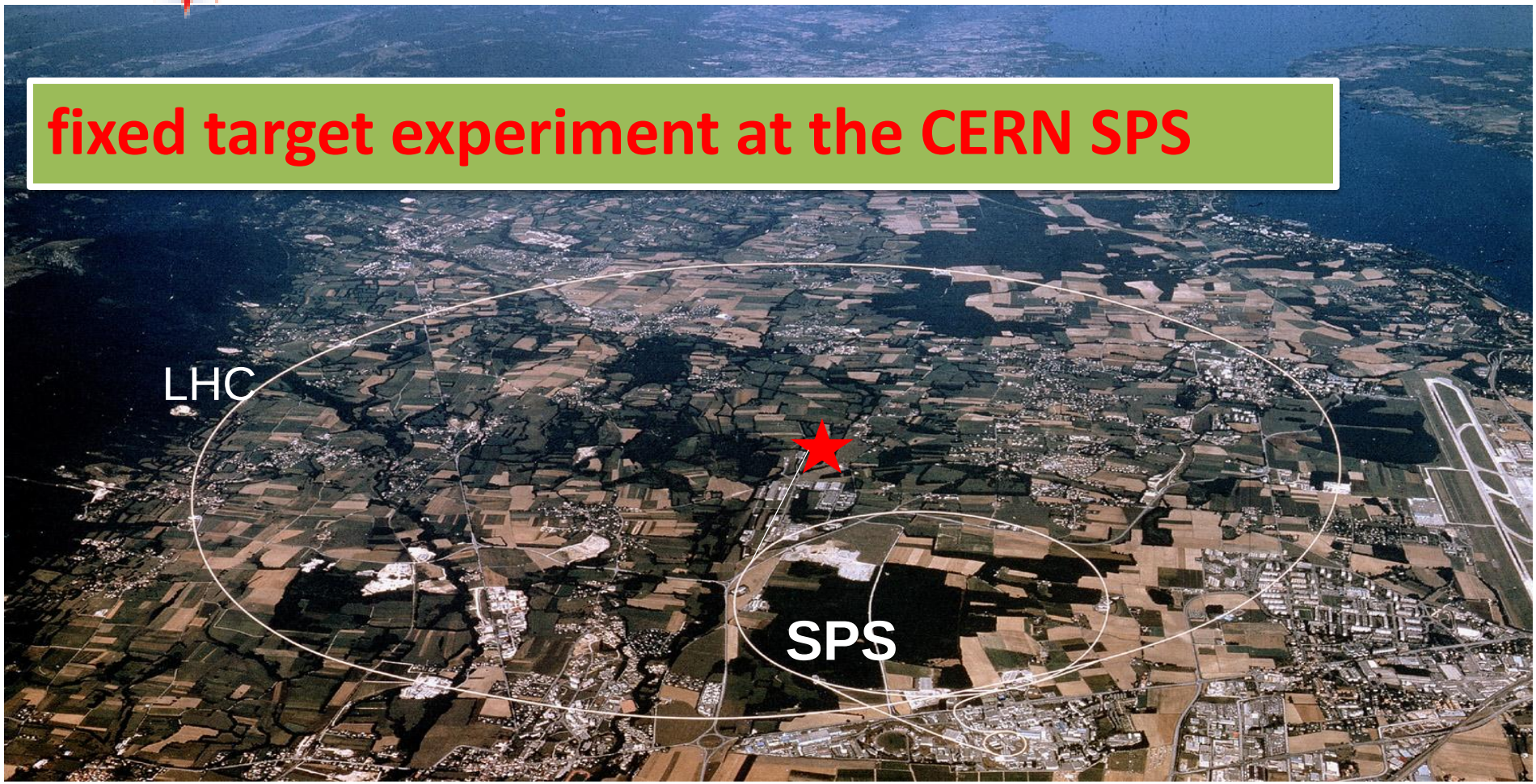
16/04/2012

COMPASS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

wide physics program carried on
using both muon and hadron beam

fixed target experiment at the CERN SPS



muon beam on polarized target

nucleon spin structure

transverse spin and
transverse momentum effects

SIDIS

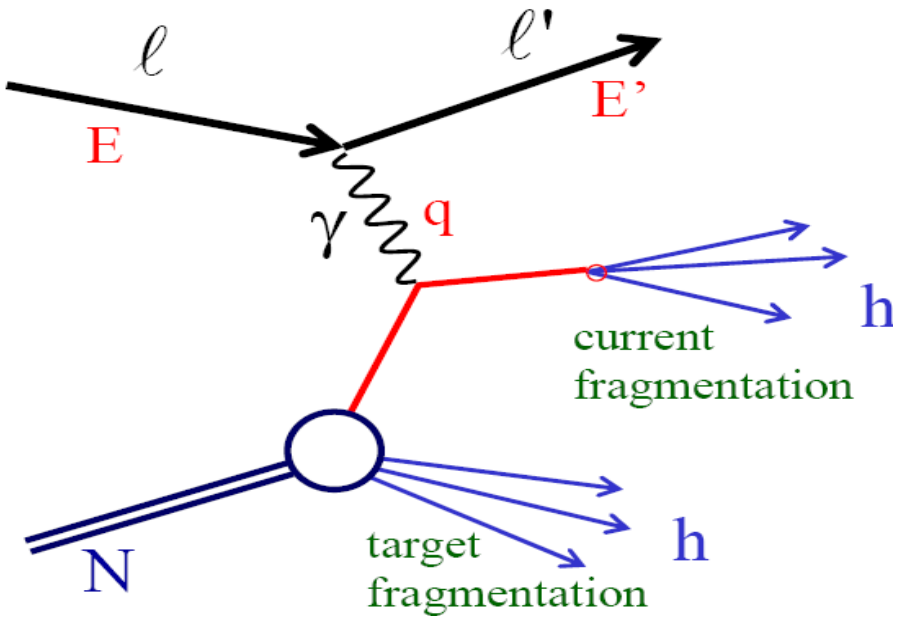
lepton interacts with a **single constituent** of the nucleon ($Q^2>1GeV^2/c^2$)

$$q = \ell - \ell' \qquad Q^2 = -q^2$$

$$W^2 = (P+q)^2$$

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

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



at least one hadron is detected in the final state
(information on the struck quark)

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

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

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

$$\boxed{h_1^\perp H_1^\perp}$$

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

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

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

$$\boxed{f_{1T}^\perp D_1}$$

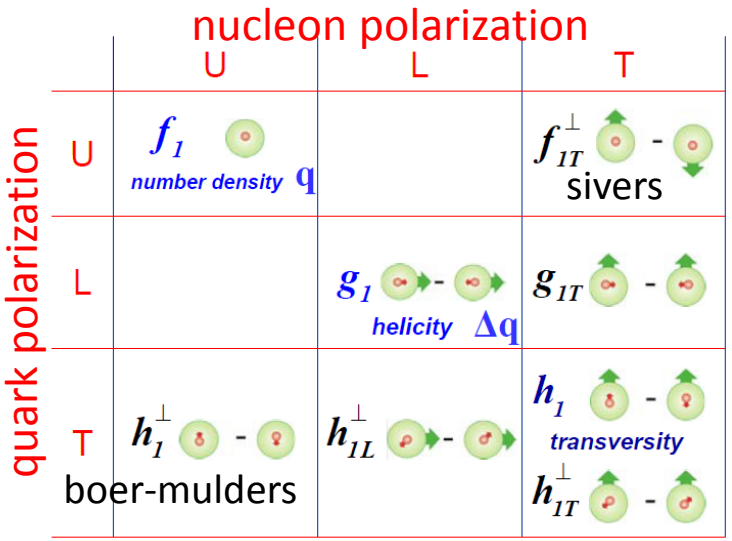
$$+\,|\boldsymbol{S}_\perp|\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right.$$

$$\boxed{h_1 H_1^\perp}\;+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

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

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



14 independent azimuthal modulations

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

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

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

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

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

$$+\,|\boldsymbol{S}_\perp|\left[\sin(\phi_h\right.$$

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

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

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

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

$h_1^\perp H_1^\perp$

$f_1 D_1$

$h_1 H_1^\perp$

all measured at COMPASS

nucleon polarization

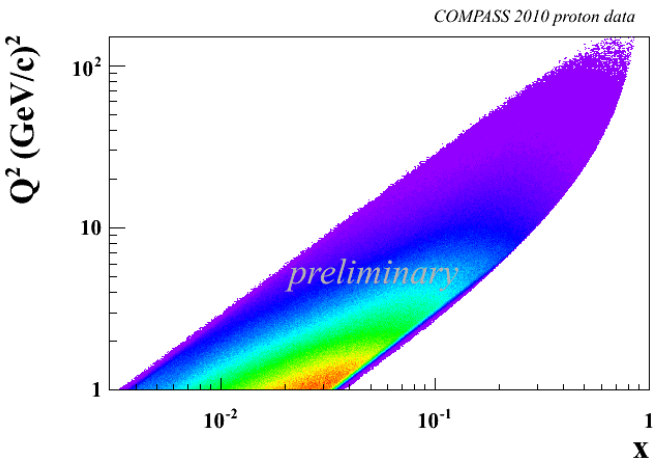
quark polarization	U	L	T
U	f_1 number density q		$f_{1T}^\perp$ sivers
L		g_1 helicity Δq	g_{1T}
T	$h_1^\perp$ boer-mulders	$h_{1L}^\perp$	h_1 transversity, $h_{1T}^\perp$

14 independent azimuthal modulations

COMPASS spectrometer

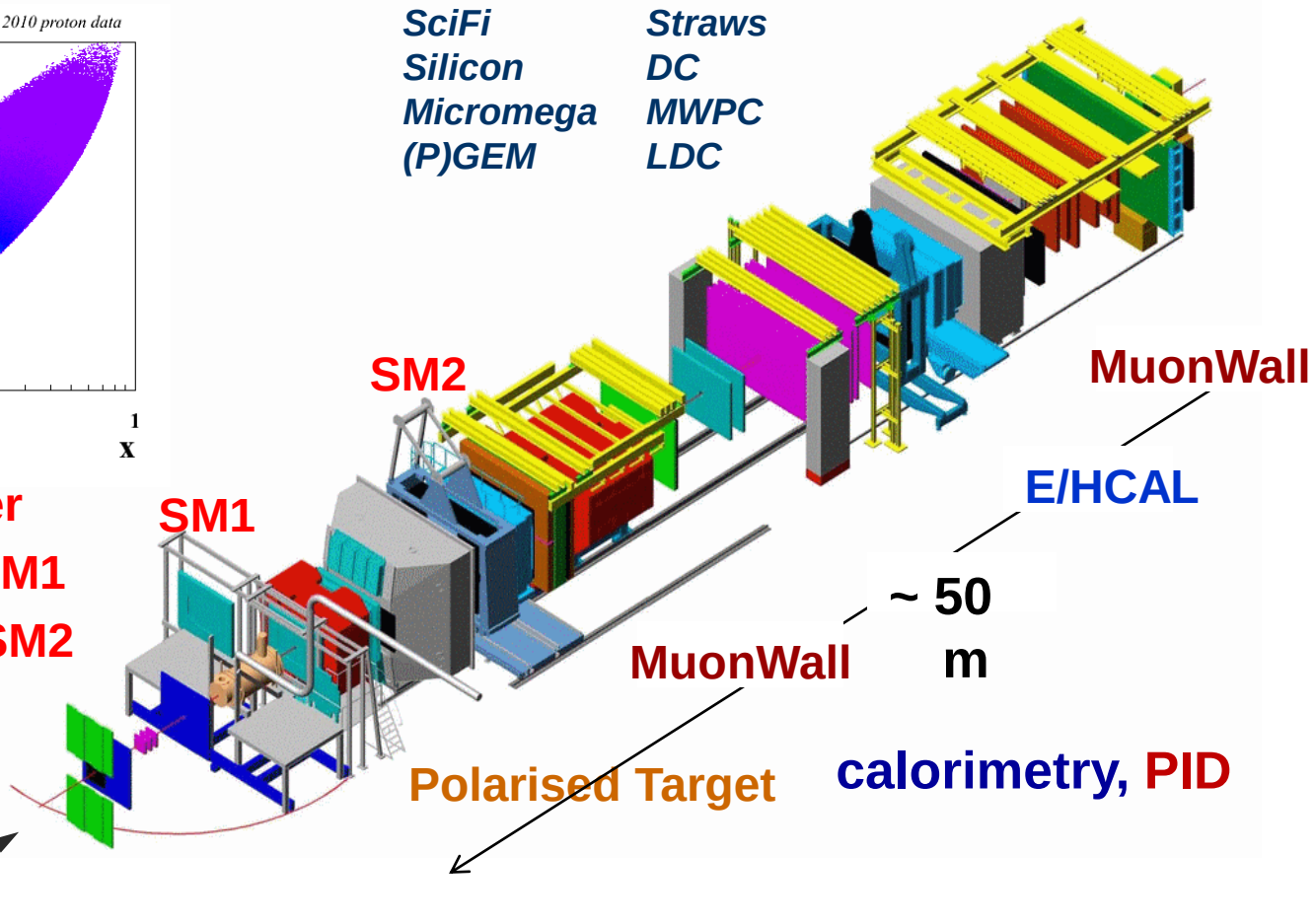
- high energy beams
- large angular acceptance
- broad kinematical range

variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad



two stages spectrometer

- large angle spec. →SM1
- small angle spec. →SM2



NIMA 577 (2007) 455–518

COMPASS data taking

muon beam 160 GeV

2002-4: ^{6}LiD target, 20% time transverse data taking.

pT ~ 50% ; f ~ 0.38

PRL 94(2005)202002
PLB 673(2009)127-135
NP B 675 (2007) 31-70

2007: NH_3 target, 50% time transverse data taking;

pT ~ 90% ; f ~ 0.15

PLB 692 (2010) 240

2010: NH_3 target, full time to transverse data taking:

preliminary results on Collins and Sivers asymmetries

(only some of the results shown here)

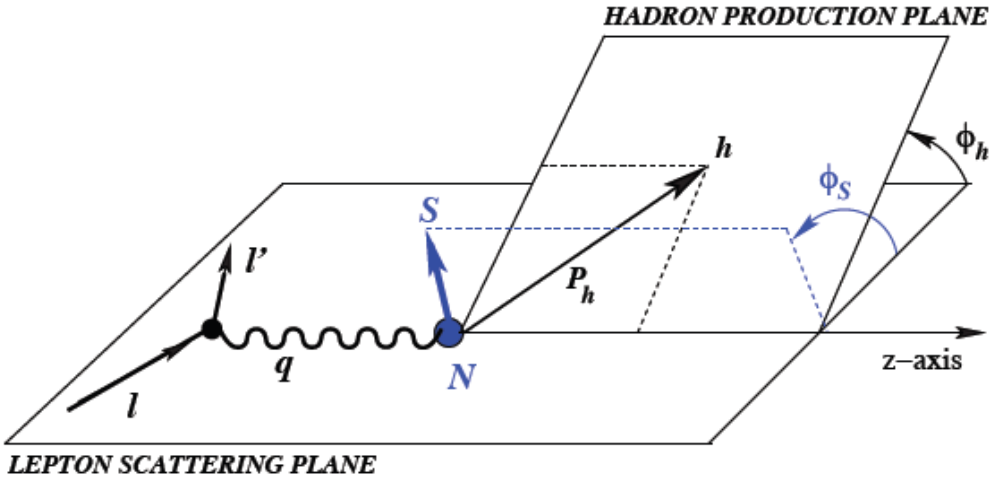
Collins asymmetry

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

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

ϕ_h azimuthal angle of the hadron,

ϕ_S azimuhtal angle of the nucleon spin



transversity

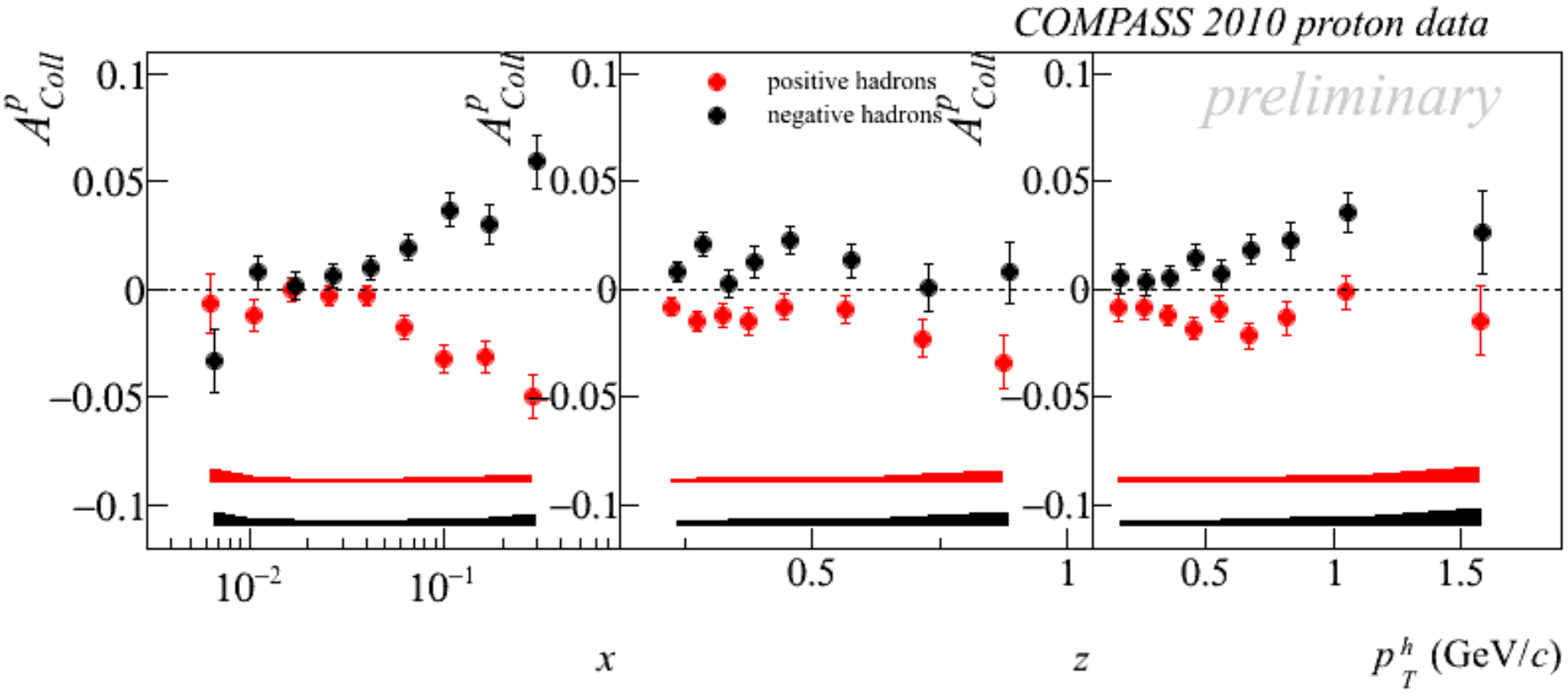
$$A_{Coll} \approx \frac{\sum_q e_q^2 \, \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2 \, q \otimes D_q^h}$$

"Collins FF"

accessible also in $e^+e^- \rightarrow$ hadrons

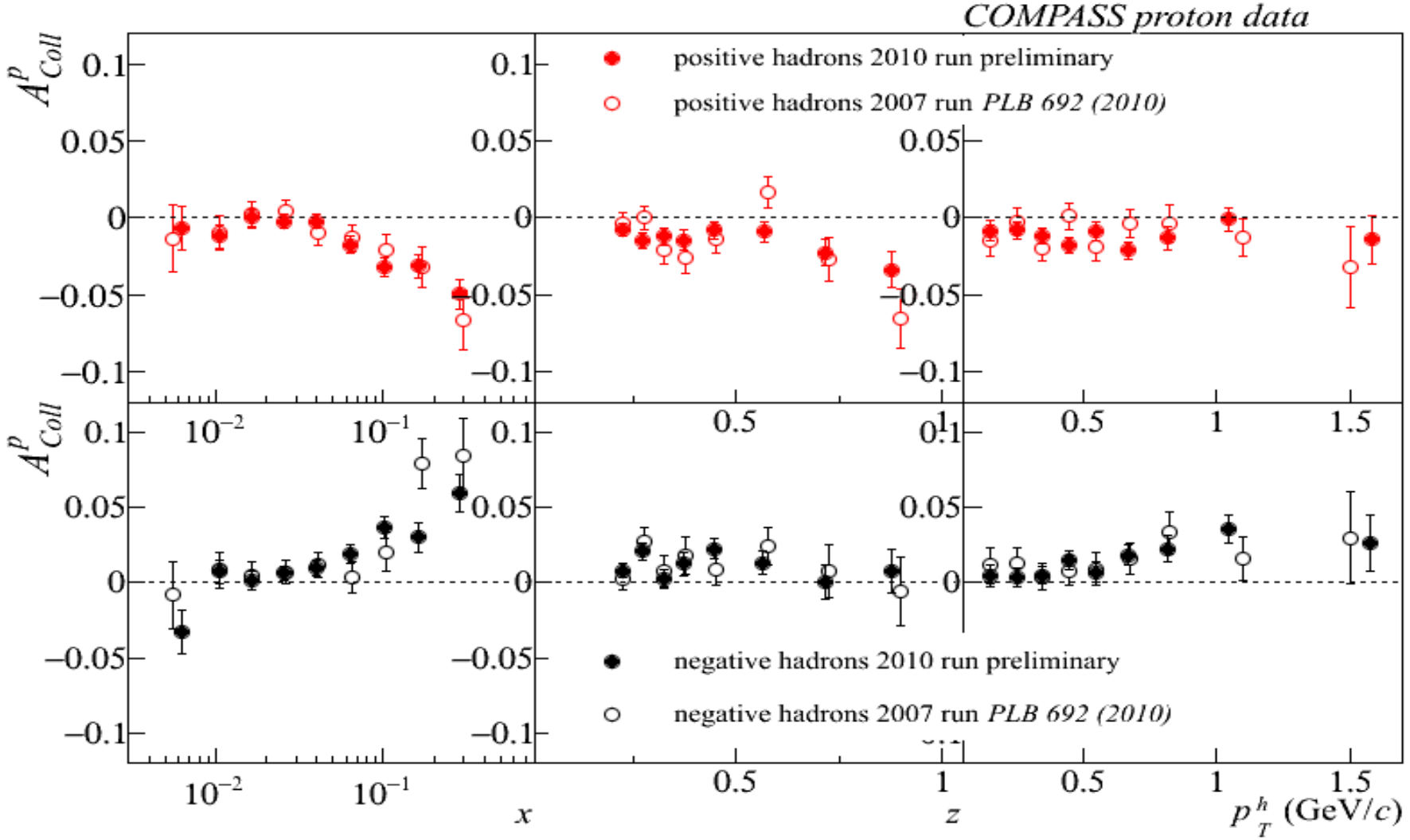
[Belle, Babar]

Collins asymmetry 2010 data



- **At small x** (range not covered by Hermes) **asymmetries compatible with zero**
- **Valence region**: **large signal of opposite sign for positive and negative hadrons**

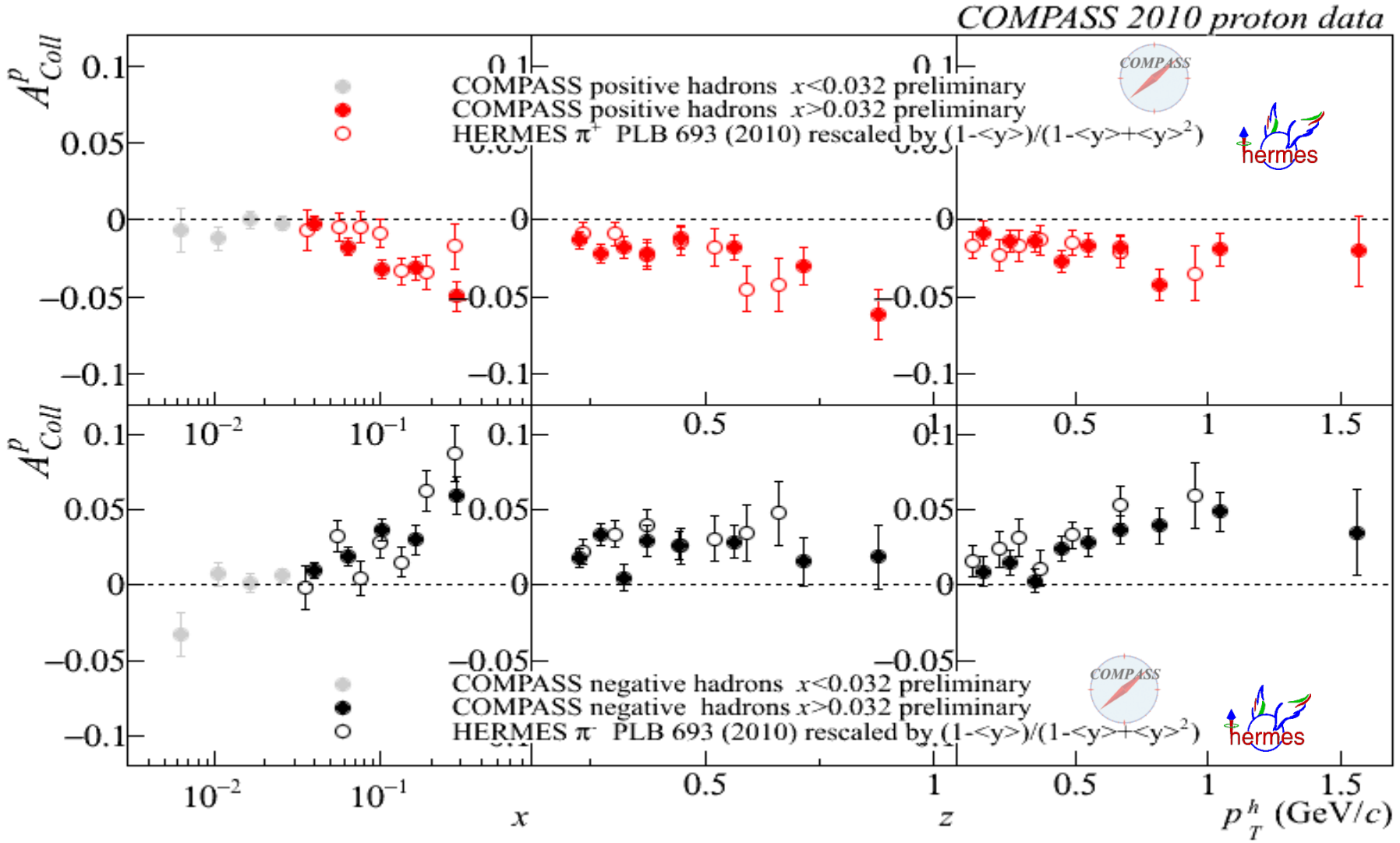
Collins asymmetry 2010 data vs 2007 data



- very good agreement
- not used yet in global fits
- will allow for a better extraction of the transversity distribution

Collins asymmetry 2010 data

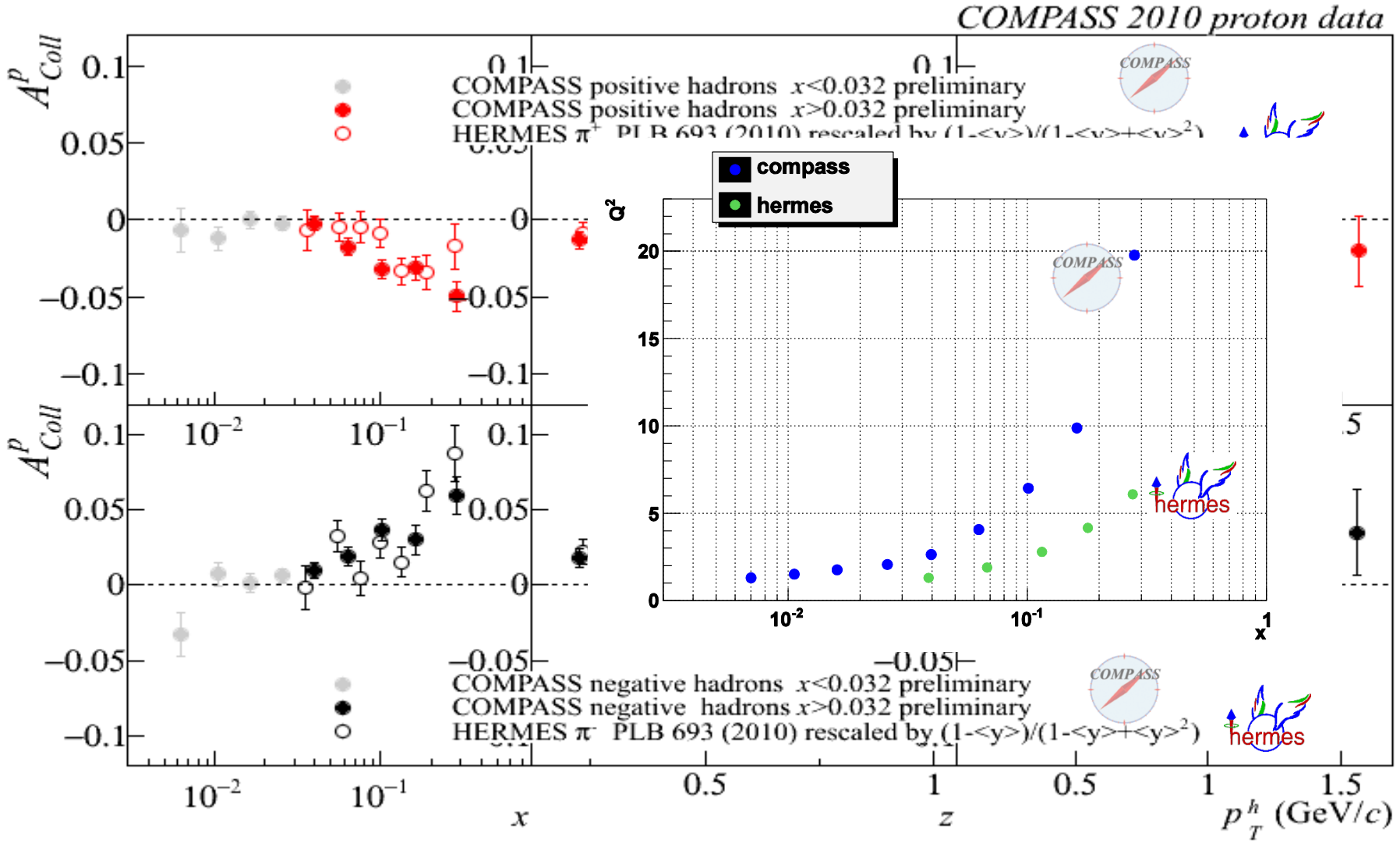
x > 0.032 region - comparison with HERMES results



- **agreement** with Hermes results in the overlap region→ **not obvious** result, **implies a negligible Q2 dependence for the Collins effect**

Collins asymmetry 2010 data

x > 0.032 region - comparison with HERMES results



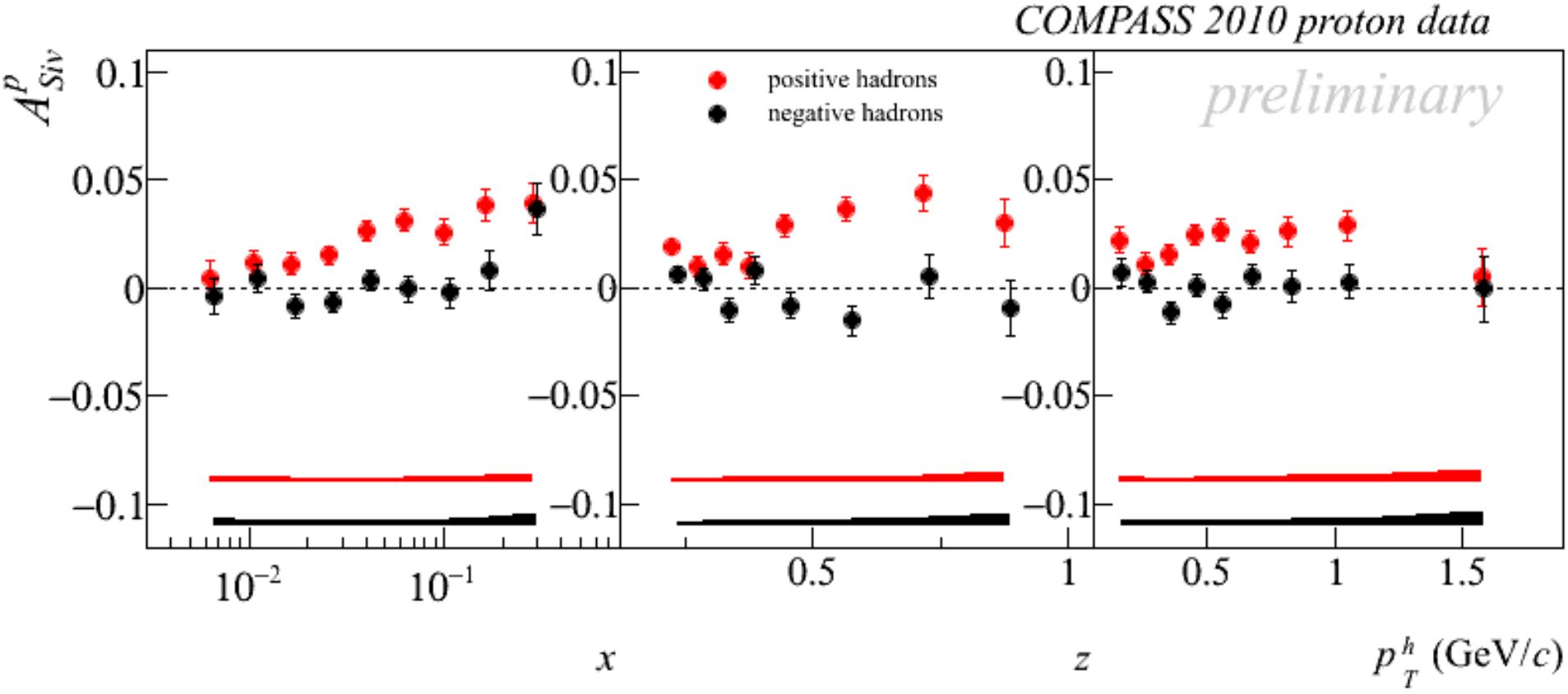
- **agreement** with Hermes results in the overlap region→ **not obvious** result, **implies a negligible Q2 dependence for the Collins effect**

the Sivers asymmetry 2010 data

$$N_h^{\pm}(\Phi_C) = N_h^0(1 \pm A_S^h \sin(\Phi_S))$$

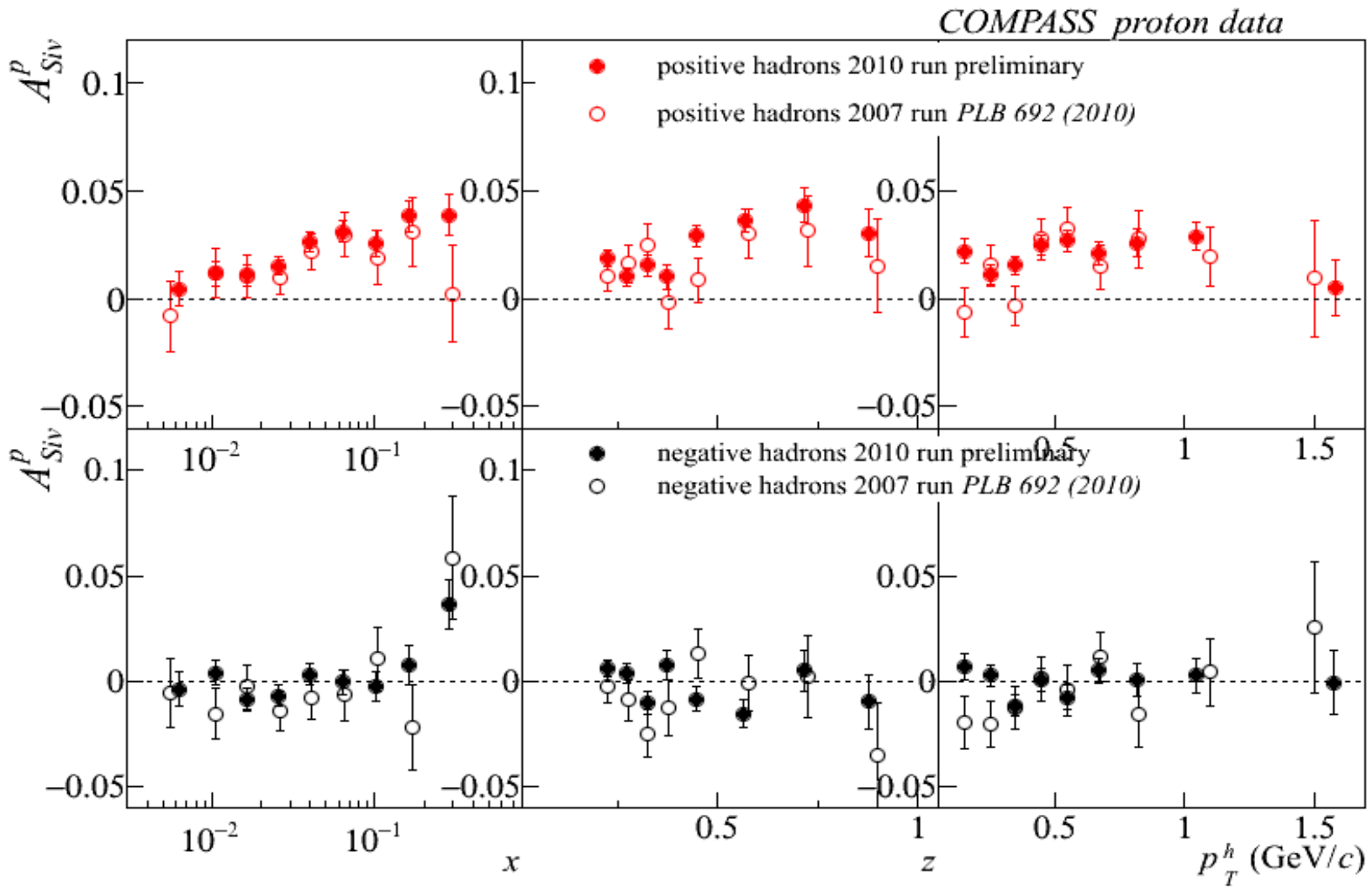
with $\Phi_S = \phi_h - \phi_s$

$$A_{Siv} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} \otimes D_1^q}{\sum_q e_q^2 f_1 \otimes D_1^q}$$



- **positive signal for the positive hadrons, larger in the valence region**

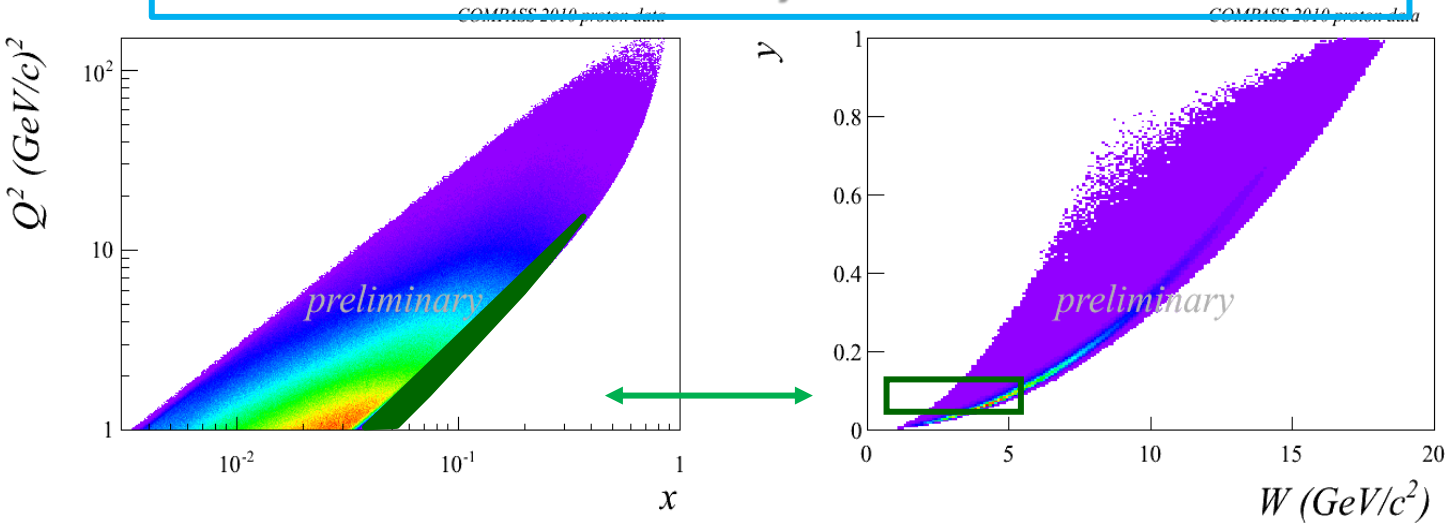
the Sivers asymmetry 2010 vs 2007 data

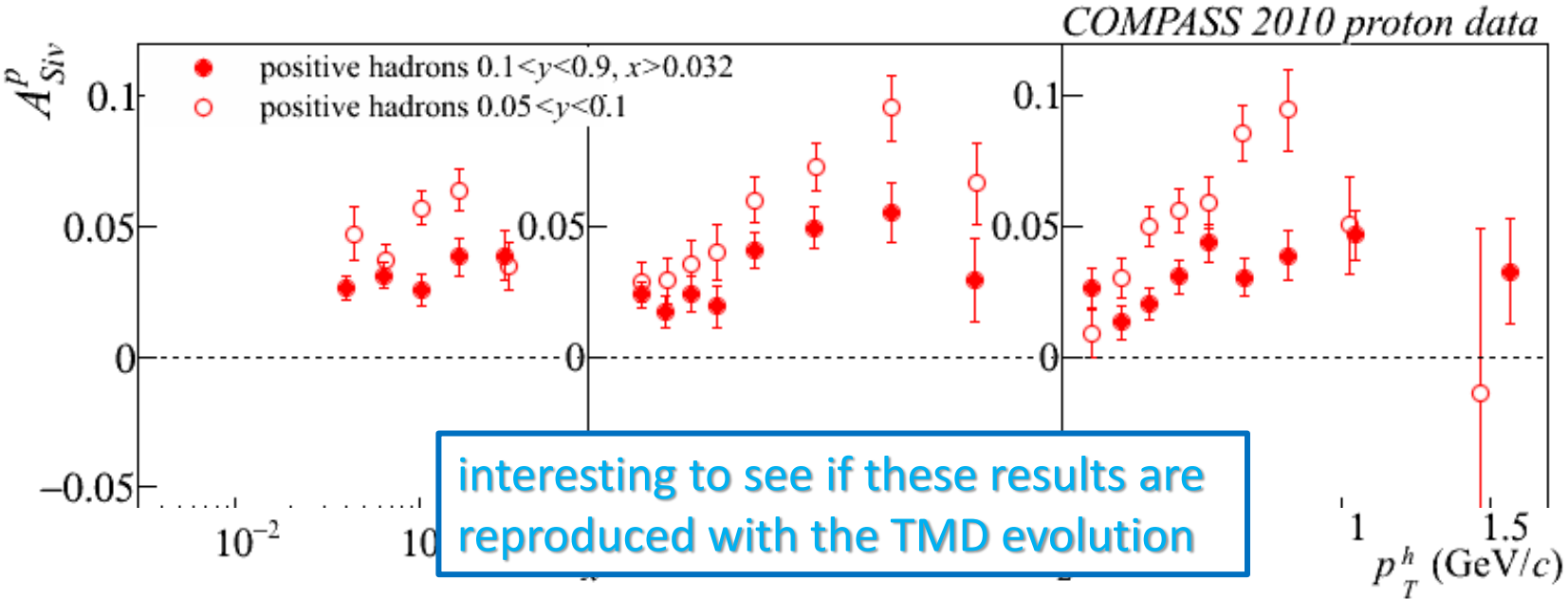


- again good agreement between 2007 and 2010 data

the **high statistic** and **quality** of the **2010 data** allow for **further investigation** of the **kinematic dependences** of the asymmetries:

0.05 < y < 0.1

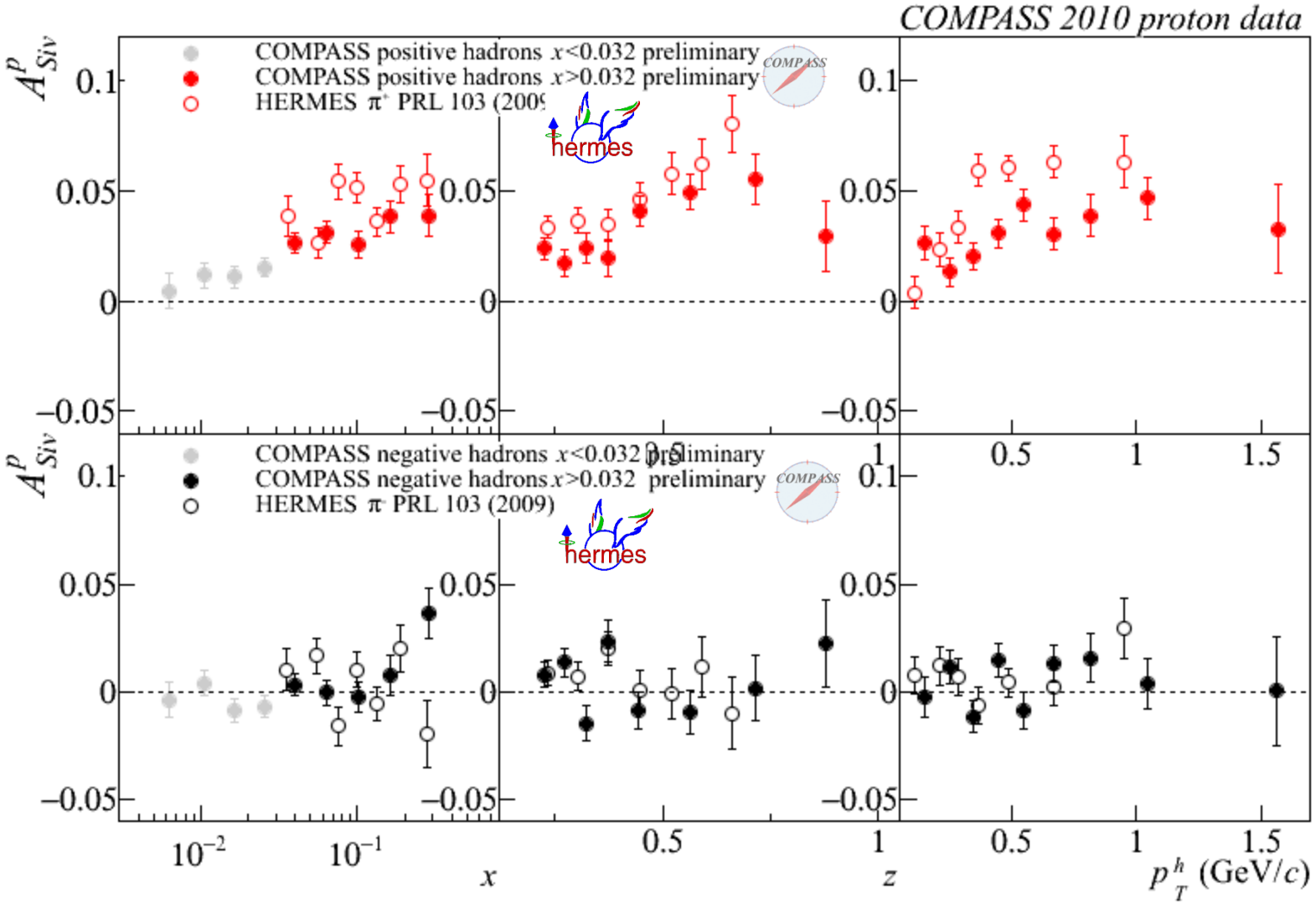




interesting to see if these results are reproduced with the TMD evolution

the Sivers asymmetry 2010 data

x > 0.032 region - comparison with HERMES results



- **smaller signal at COMPASS** *(not so evident from 2007 COMPASS data)*

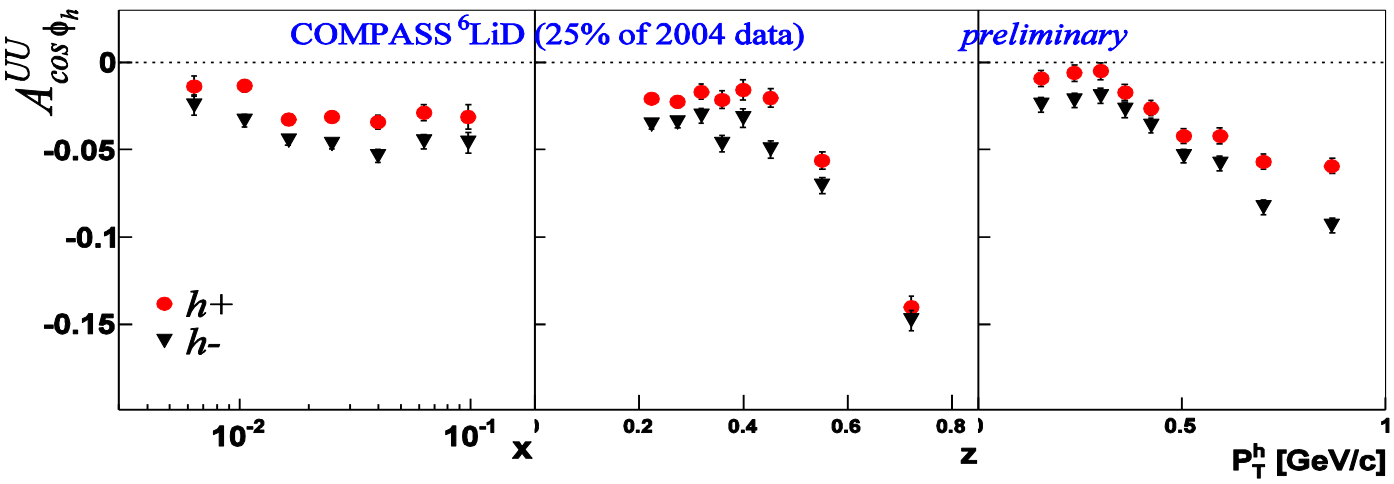
The measurement of the **Sivers effect**
(correlation between the quark intrinsic transverse momentum $k_\perp$ and the transverse polarization of the nucleon) confirms that
$k_\perp$ plays an important role in the nucleon description
(expected to be zero in the collinear description of the nucleon)

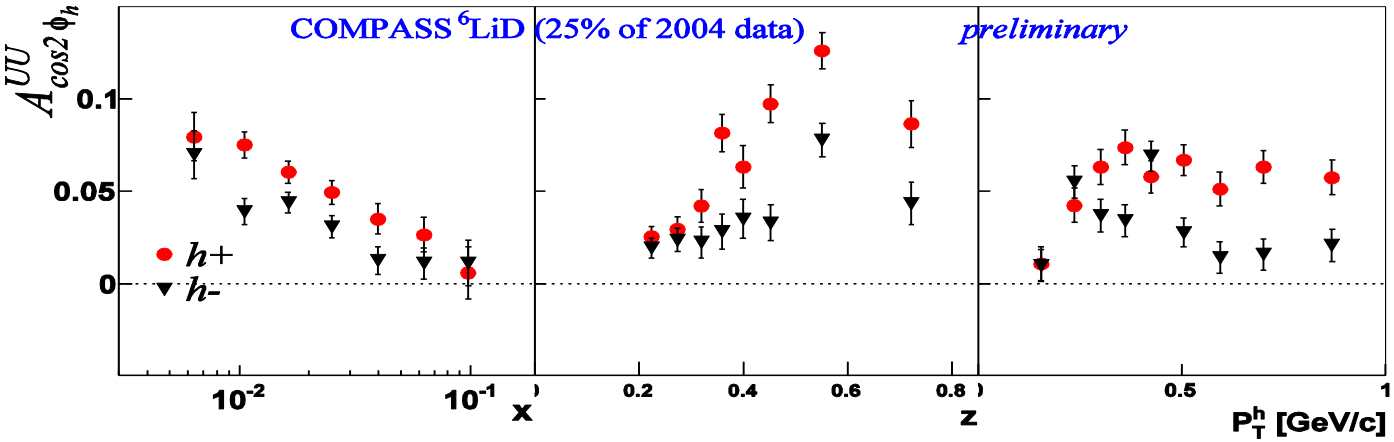
There are also **other TMD effects measured** to be significantly different from zero at **COMPASS:**

Azimuthal asymmetries on the **unpolarized deuteron** target
*(given by the **Cahn effect** and the **Boer-Mulders** TMD PDF)*

$$N(\phi_h) \propto N_0 \cdot (1 + \varepsilon_1 A^{UU}_{\cos\phi_h} \cos\phi_h + \varepsilon_2 A^{UU}_{\cos 2\phi_h} \cos 2\phi_h)$$

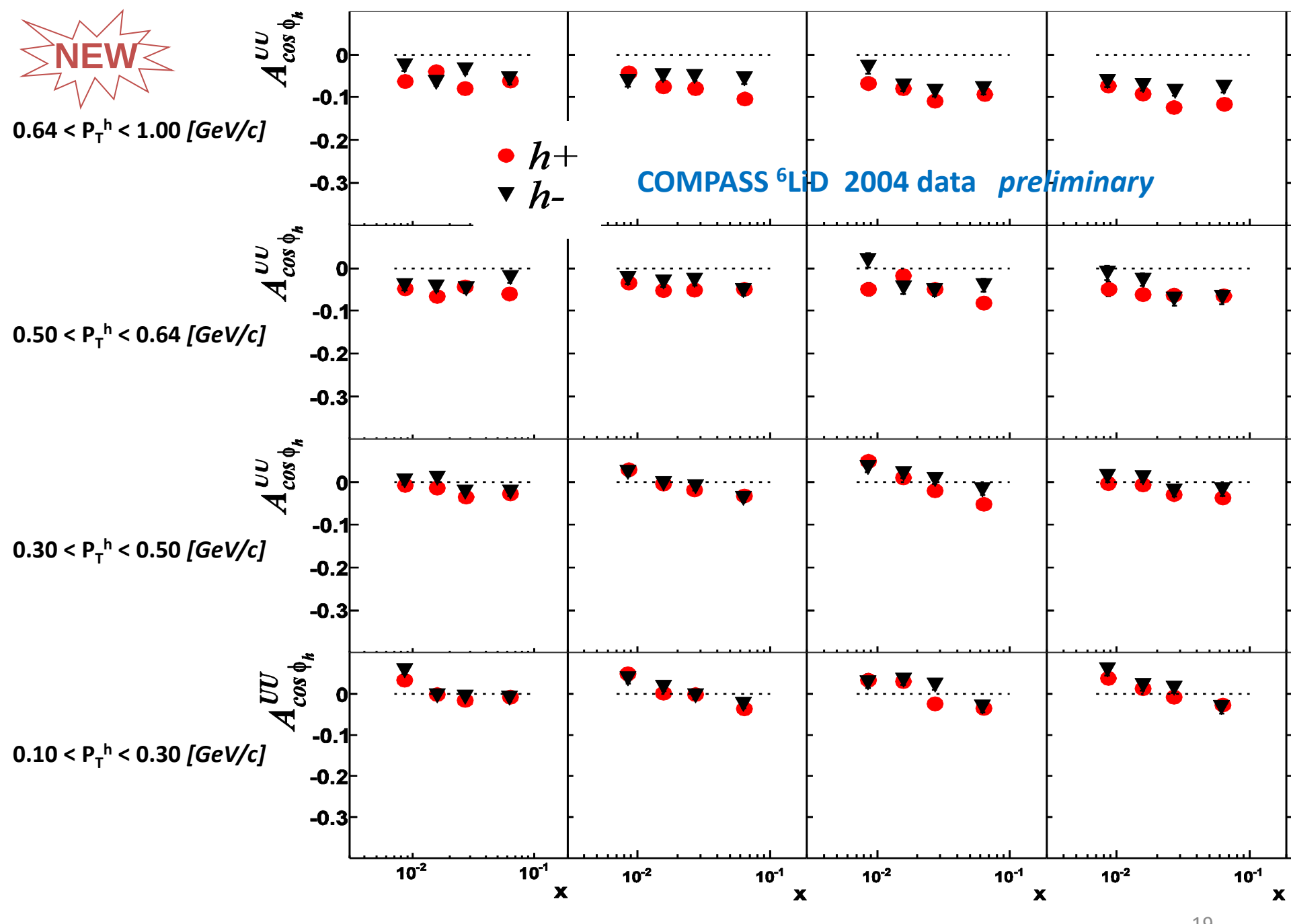
$$\langle \cos\phi_h \rangle = \frac{1}{Q}\,\text{Cahn} + \frac{1}{Q}\,\text{BM} \qquad \langle \cos 2\phi_h \rangle = \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$

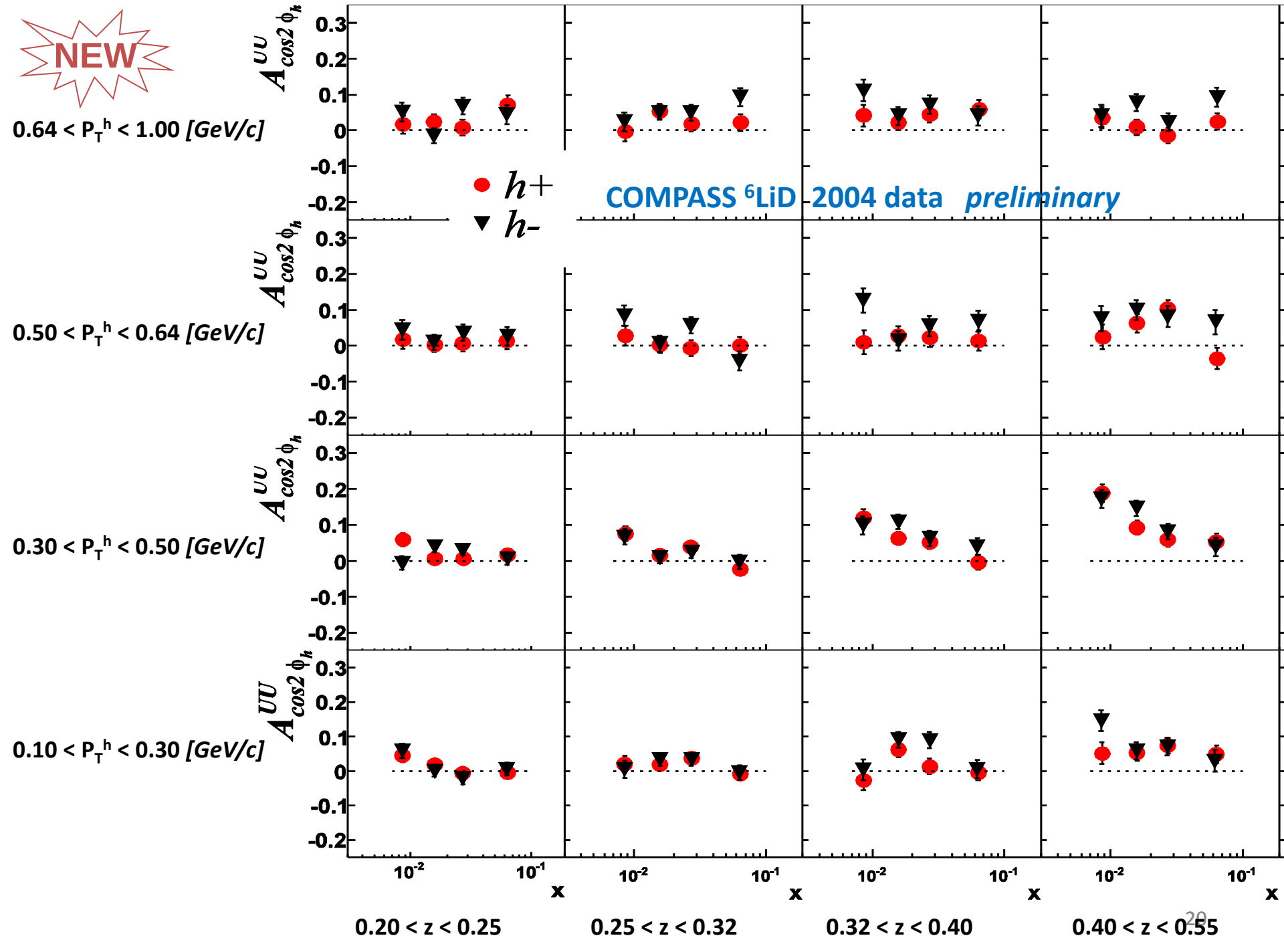




in order to **understand the strong kinematical dependencies** a **multi dimensional analysis** has been started.

as an example first results →


NEW
$A_{cos\,\phi_h}^{UU}$
h+
h-
COMPASS ^{6}LiD 2004 data preliminary
0.64 < P_T^h < 1.00 [GeV/c]
0.50 < P_T^h < 0.64 [GeV/c]
0.30 < P_T^h < 0.50 [GeV/c]
0.10 < P_T^h < 0.30 [GeV/c]
0 -0.1 -0.2 -0.3
10^{-2} 10^{-1}
x
0.20 < z < 0.25
0.25 < z < 0.32
0.32 < z < 0.40
0.40 < z < 0.55


NEW
$A^{UU}_{cos2\phi_h}$
$A^{UU}_{cos2\phi_h}$
$A^{UU}_{cos2\phi_h}$
$A^{UU}_{cos2\phi_h}$
h+
h-
COMPASS 6LiD 2004 data preliminary
0.64 < P_T^h < 1.00 [GeV/c]
0.50 < P_T^h < 0.64 [GeV/c]
0.30 < P_T^h < 0.50 [GeV/c]
0.10 < P_T^h < 0.30 [GeV/c]
0.3
0.2
0.1
0
-0.1
-0.2
10^-2
10^-1
x
0.20 < z < 0.25
0.25 < z < 0.32
0.32 < z < 0.40
0.40 < z < 0.55

Summary:

- very **interesting results** on **the transverse spin** and **transverse momentum effects** have been produced by the **COMPASS experiment**

- **new results** are expected from the collected data
  - measurement of the Collins and Sivers asymmetries for the **identified particles**
  - measurement of the **other transverse spin azimuthal asymmetries**
  - measurement of the **longitudinal spin asymmetries from proton** data
  - **further investigation** of the **kinematic dependencies** of the unpolarized and transverse spin asymmetries

- new measurements of the unpolarized azimuthal asymmetries at COMPASS II in parallel with DVCS, starting in 2015

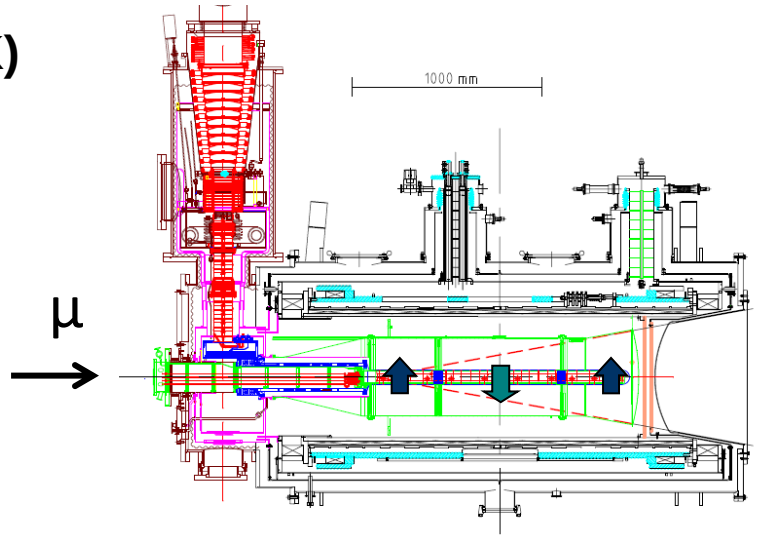
backup

the polarized target system (>2005)

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

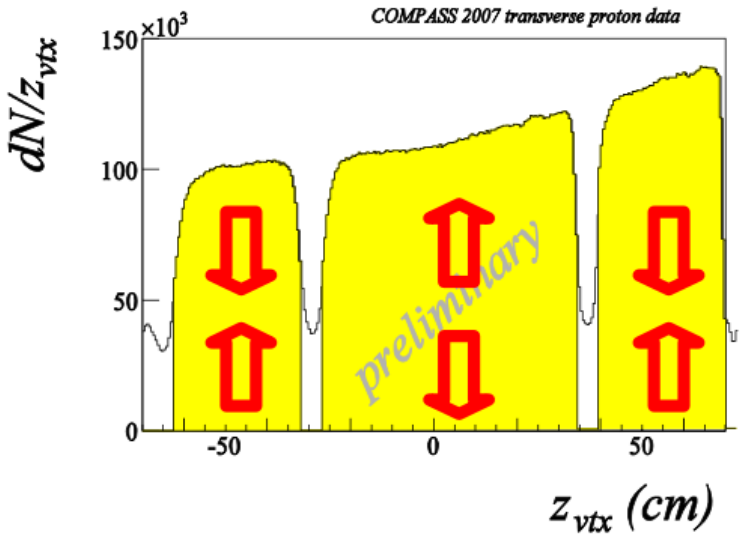
solenoid 2.5T
dipole magnet 0.6T

acceptance ± 180 mrad



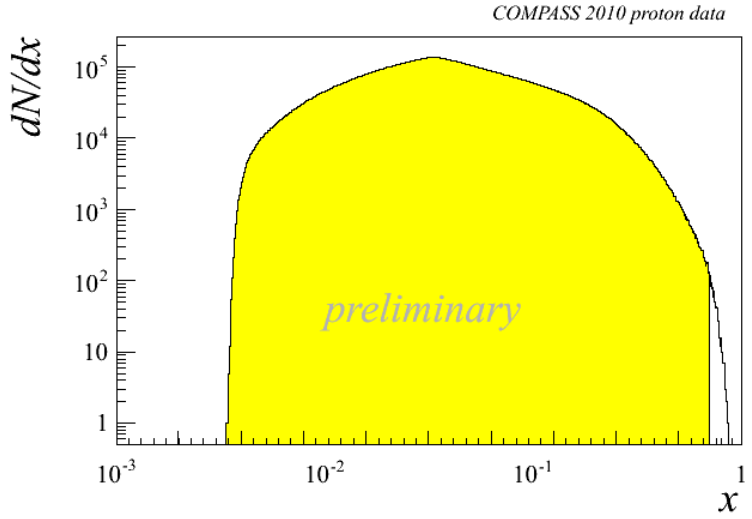
3 target cells 30, 60, 30 cm long
polarization reversed every week

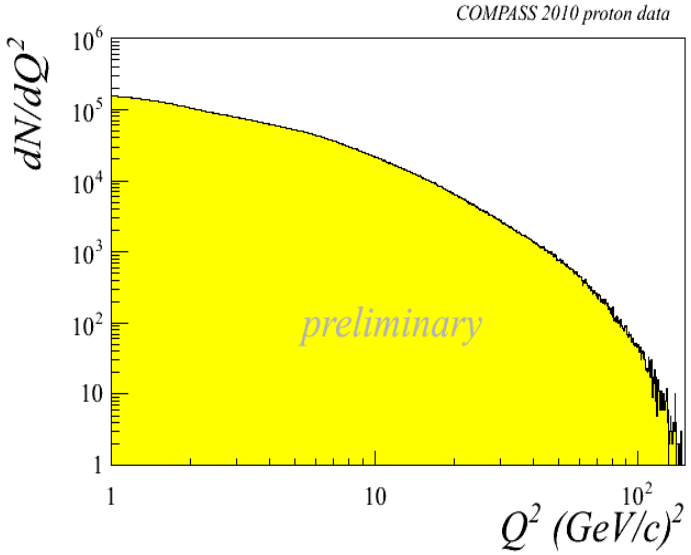
NH_3
polarization 90%
dilution factor 0.16

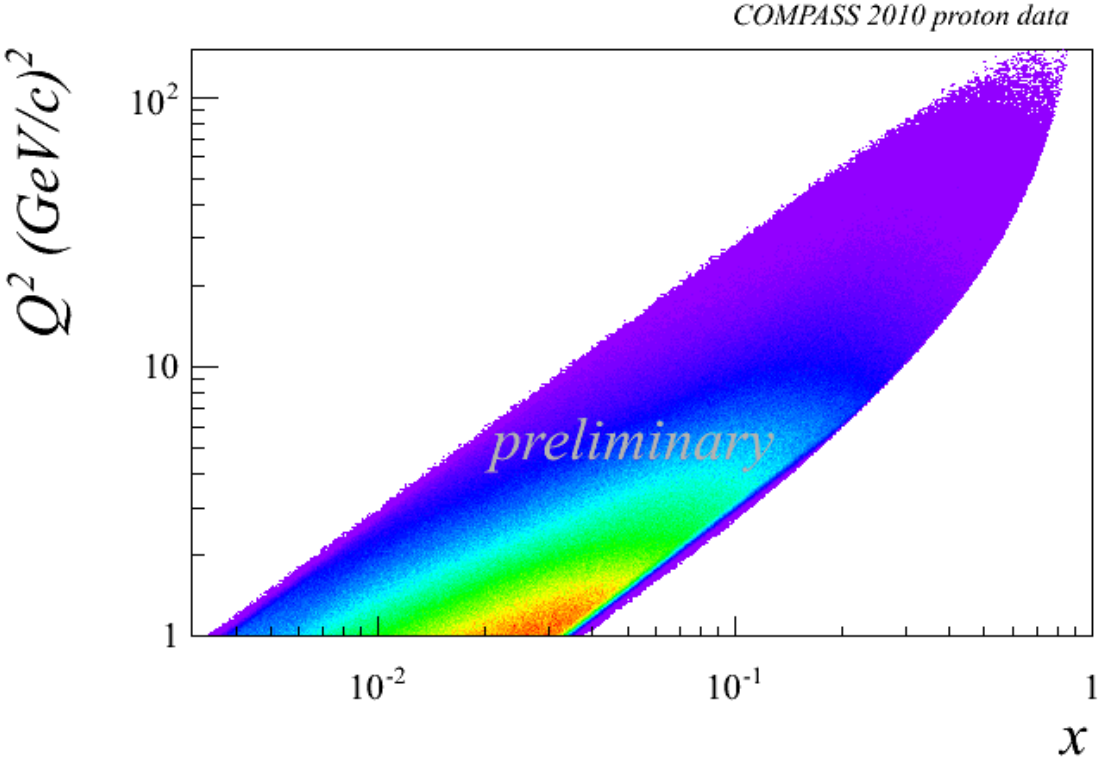


SIDIS event selection

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



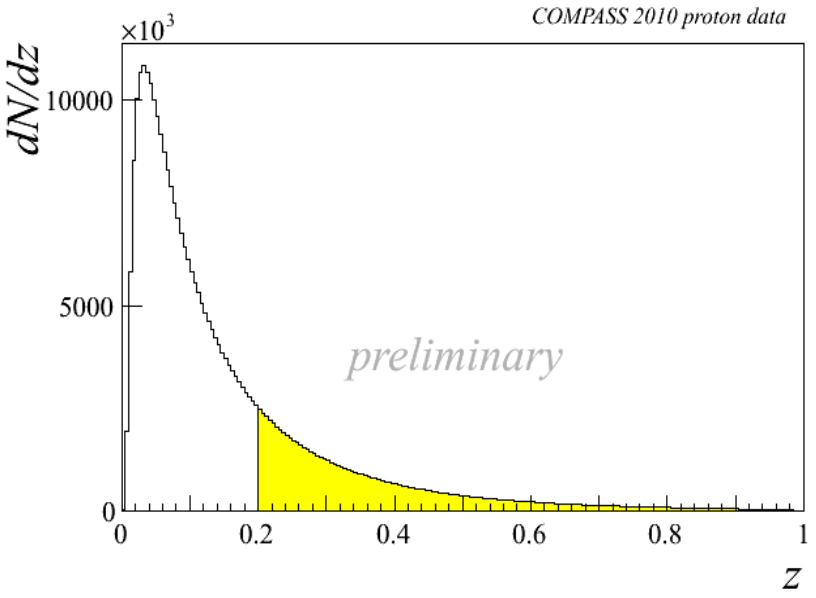


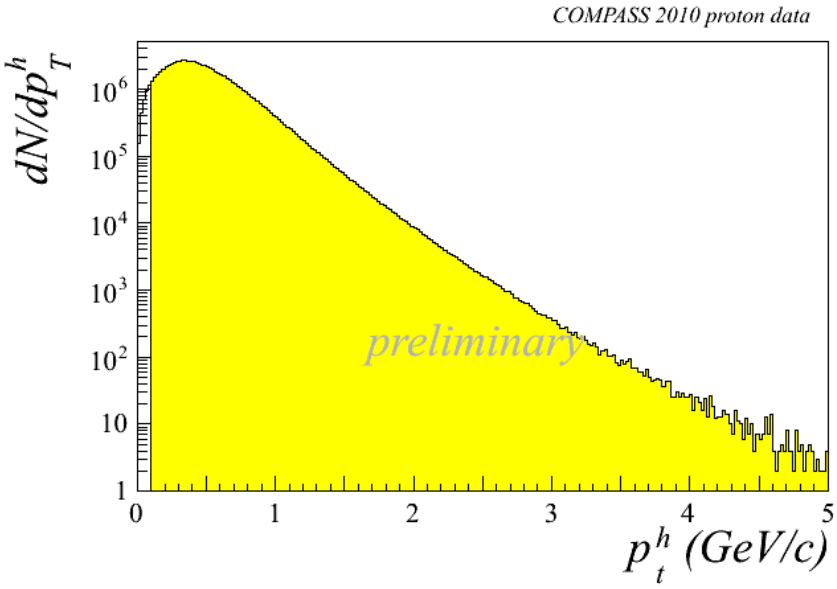


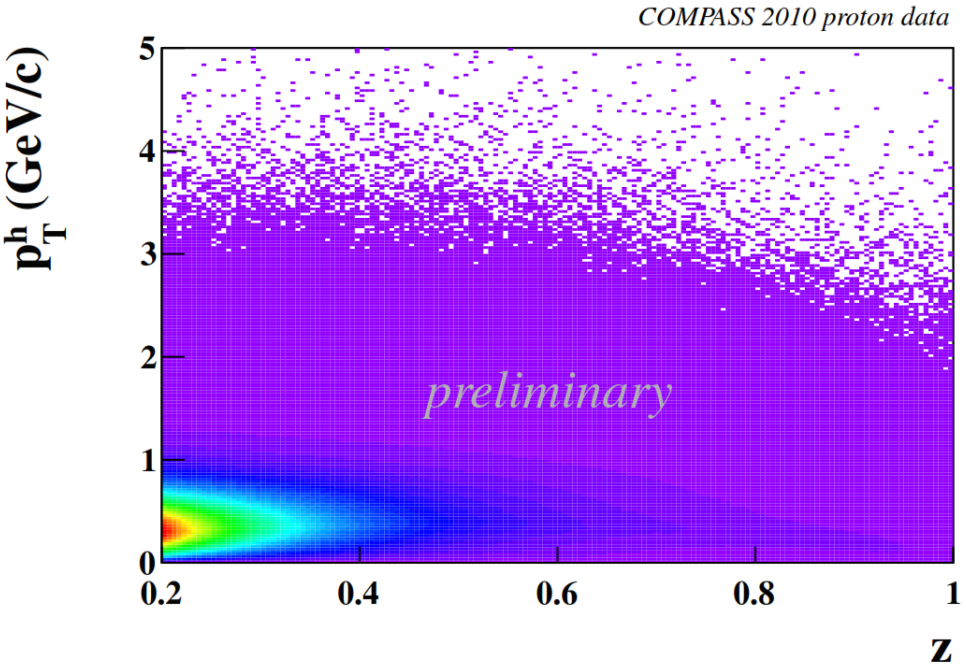
SIDIS event selection

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

hadron selection: $p_t^h > 0.1$ GeV/c
$z > 0.2$

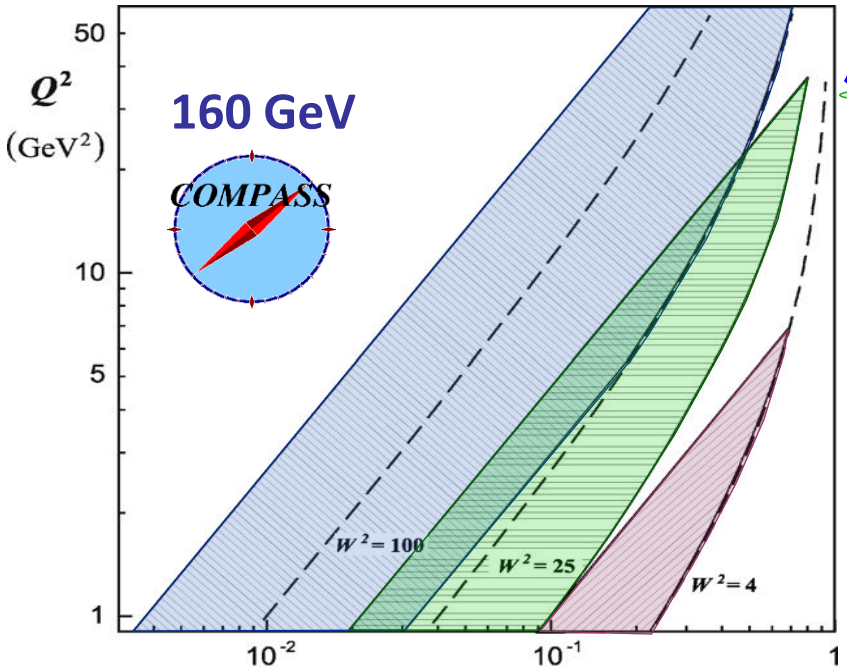






Phase space of different experiments

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



hermes

27.5 GeV

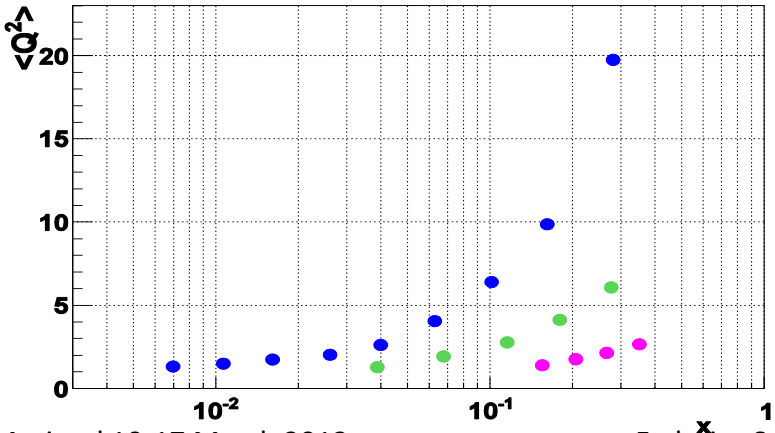
$0.004 < x < 0.3, \quad 25 < W^2 < 200 GeV^2$

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

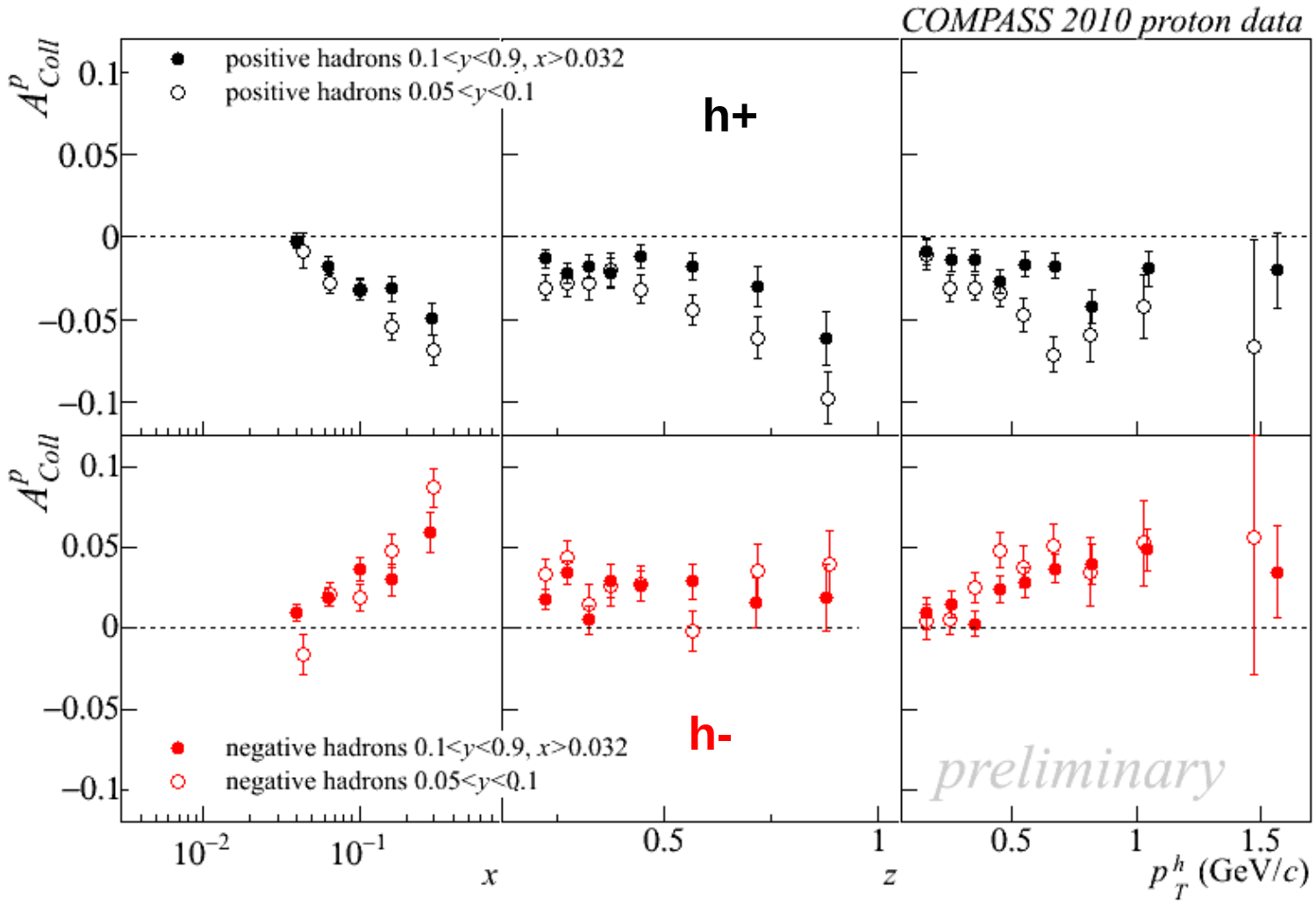
$0.14 < x < 0.34, \quad 4 < W^2 < 10$

(0.48)

JLab 6 GeV



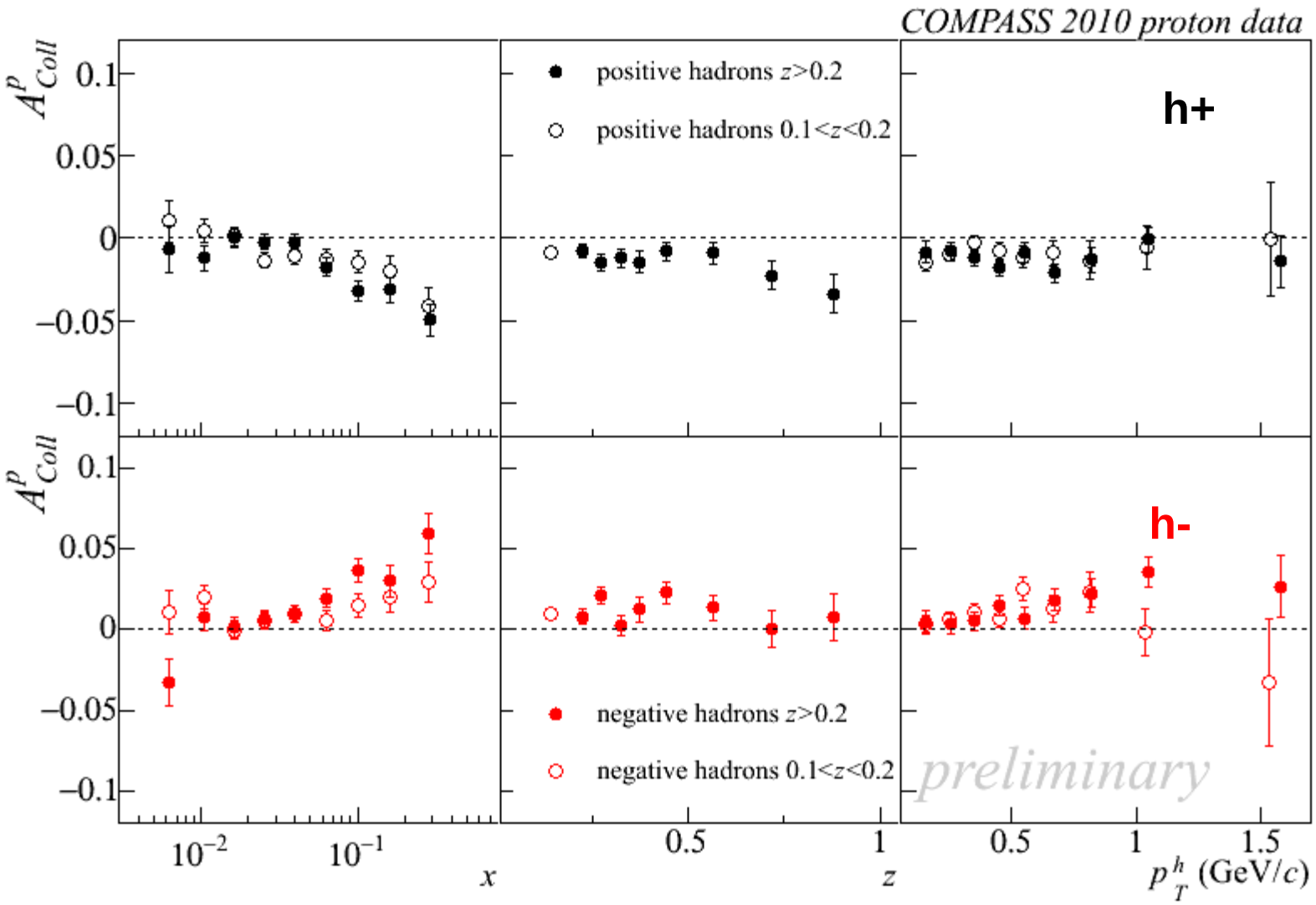
0.05 < y < 0.10 - Collins asymmetry



a small effect is visible for h+

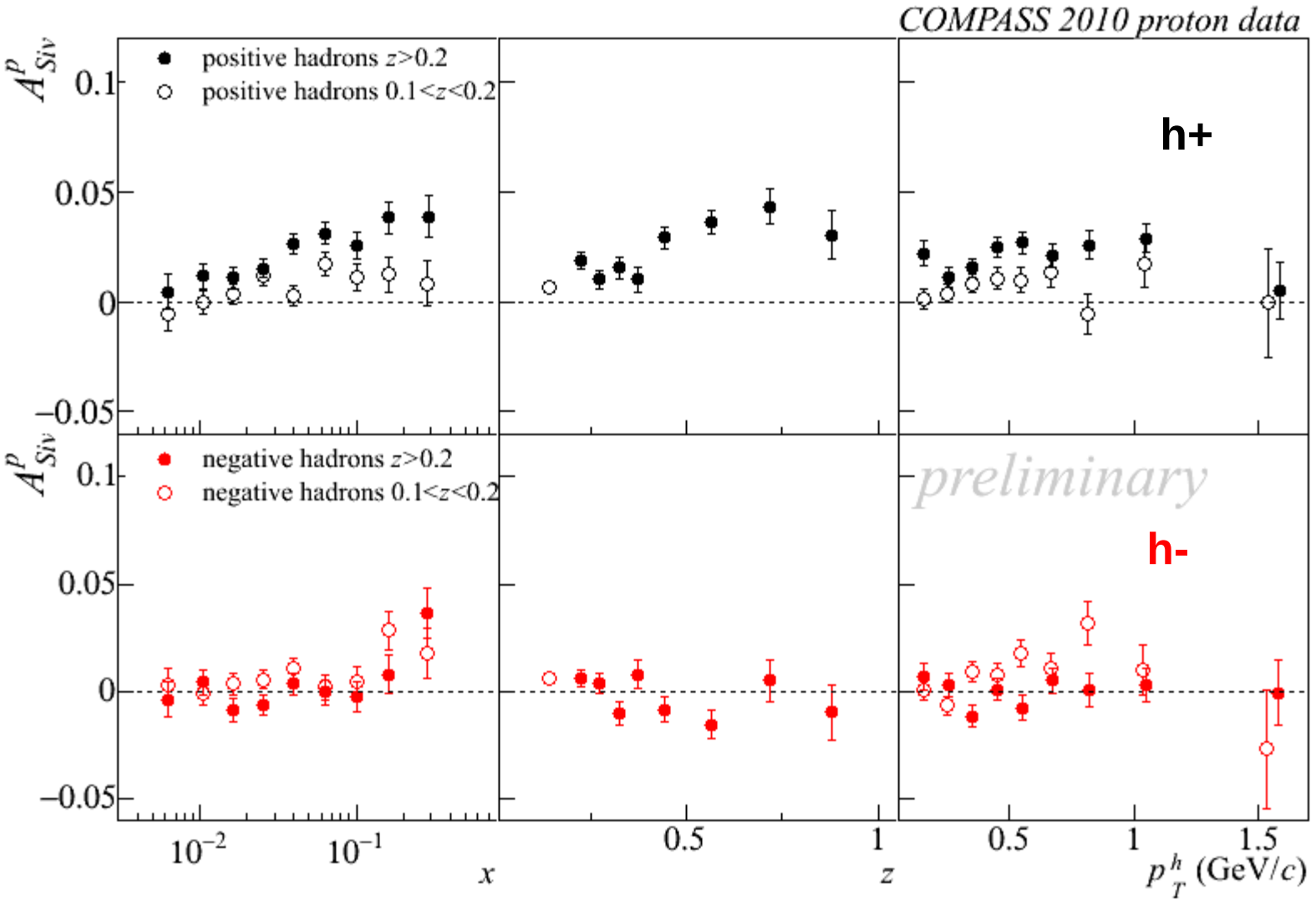
no effect splitting the "standard" sample in two bins (0.1 < y< 0.2; 0.2 < y < 0.9)

0.1 < z < 0.2 - Collins asymmetry



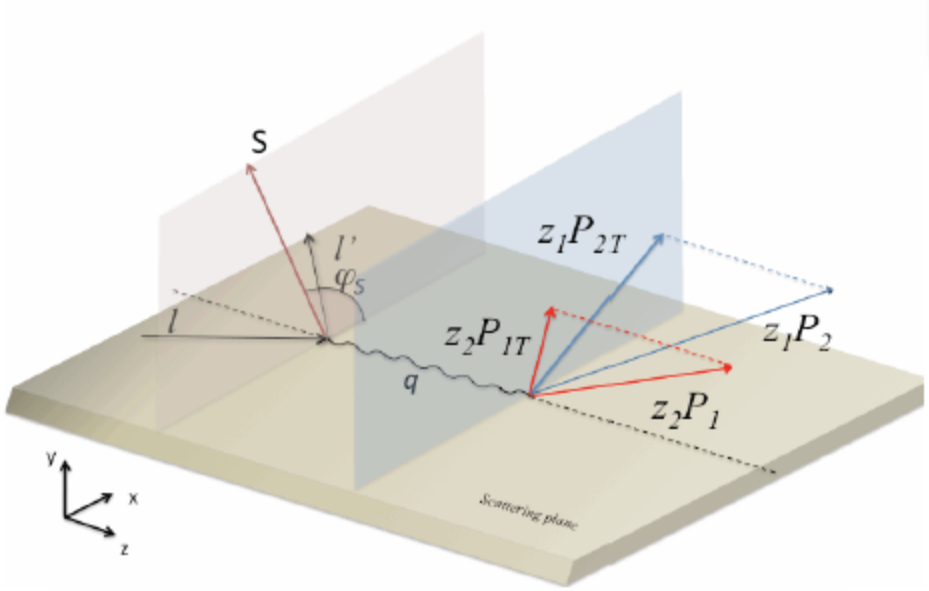
asymmetries somewhat smaller for 0.1<z<0.2 sample

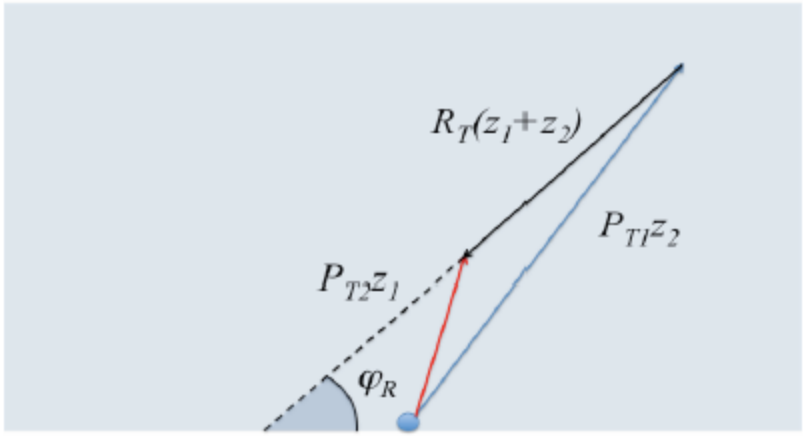
0.1 < z < 0.2 - Sivers asymmetry



clear decrease of the asymmetries for the 0.1<z<0.2 sample

Hadron pair angle definition





Definitions

$$z_i = \frac{E_i}{E_{Tot}}$$

$$z = z_1 + z_2$$

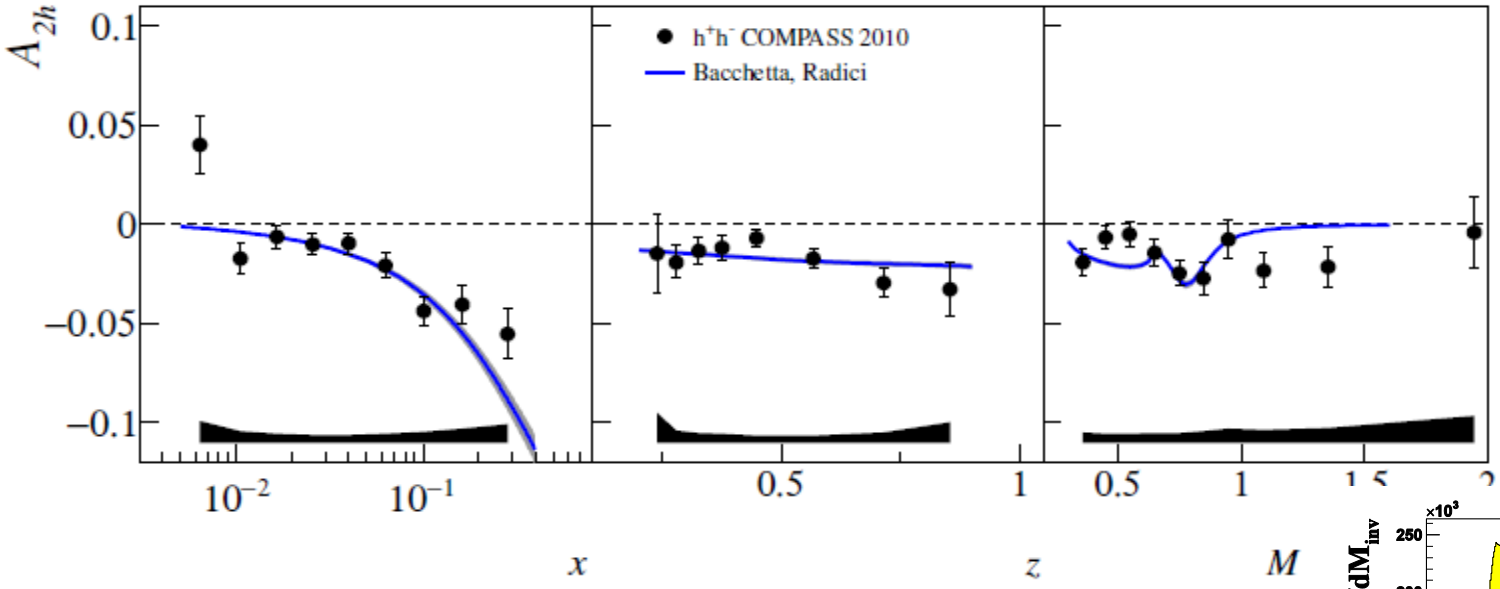
$$\xi = \frac{z_1}{z}$$

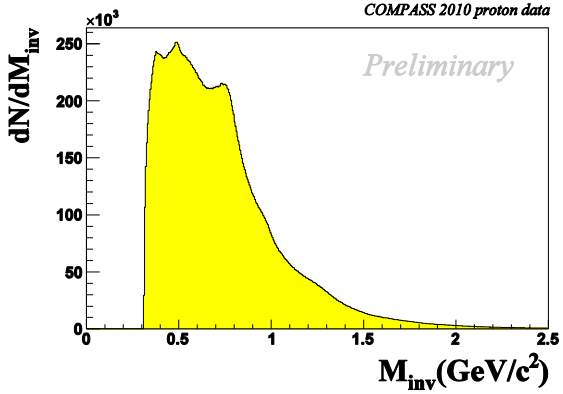
$$R_T = \frac{z_1 P_{2T} - z_2 P_{1T}}{z_1 + z_2}$$

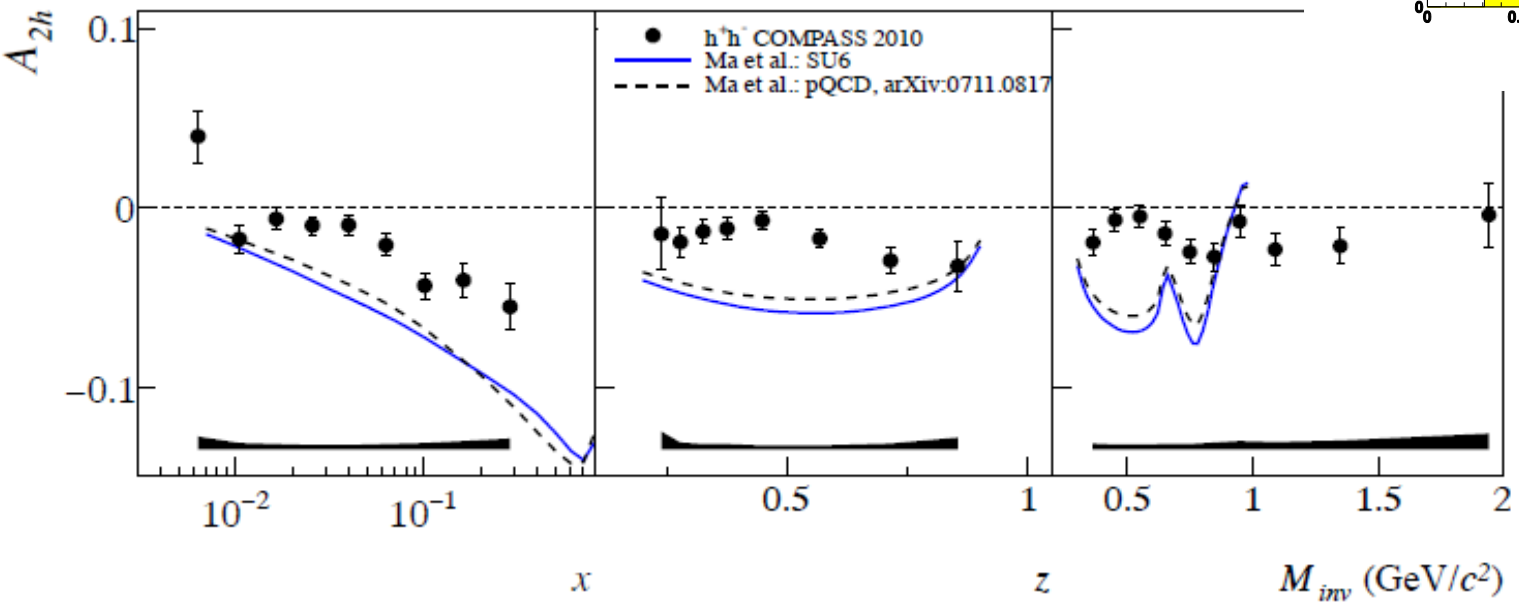
φ_S = azimuthal angle of the spin of the nucleon

φ_R = azimuthal angle of R_T

$$\varphi_{RS} = \varphi_R + \varphi_S - \pi$$


A_{2h}
0.1
0.05
0
−0.05
−0.1
10^{-2}
10^{-1}
0.5
1
0.5
1
1.5
2
h^+h^- COMPASS 2010
Bacchetta, Radici
x
z
M


COMPASS 2010 proton data
Preliminary
$\times 10^3$
dN/dM_{inv}
250
200
150
100
50
0
0.5
1
1.5
2
2.5
$M_{inv}(GeV/c^2)$


A_{2h}
0.1
0
−0.1
10^{-2}
10^{-1}
0.5
1
0.5
1
1.5
2
h^+h^- COMPASS 2010
Ma et al.: SU6
Ma et al.: pQCD, arXiv:0711.0817
x
z
M_{inv} (GeV/c^2)