COMPASS results on Collins and Sivers asymmetries for charged hadrons

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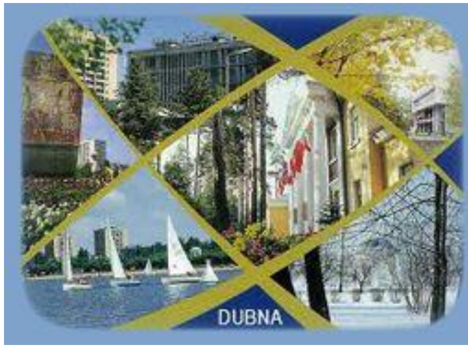
on behalf of the COMPASS Collaboration



SPIN2012
JINR, Dubna

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

fixed target experiment at the CERN SPS

physics programme:

hadron spectroscopy (p, π, K)

- light mesons, glue-balls, exotic mesons
- polarisability of pion and kaon

nucleon structure (μ)

- longitudinal spin structure
- transverse momentum and transverse spin structure

this session

the transverse spin and transverse momentum structure of the nucleon

the structure of the nucleon

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

transversity PDF

correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark

chiral odd

can not be measured in inclusive DIS, still poorly know

quark polarisation \ nucleon polarisation	U	L	T
U	f_1 *number density* q		
L		g_1 *helicity* Δq	
T			h_1 *transversity* $\Delta_T q$

the structure of the nucleon

taking into account the quark intrinsic transverse momentum k_T,
at leading order other 6 TMD PDFs are needed for a full description of the nucleon structure

transversity PDF

correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark

chiral odd

Sivers PDF

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

sensitive to orbital angular momentum

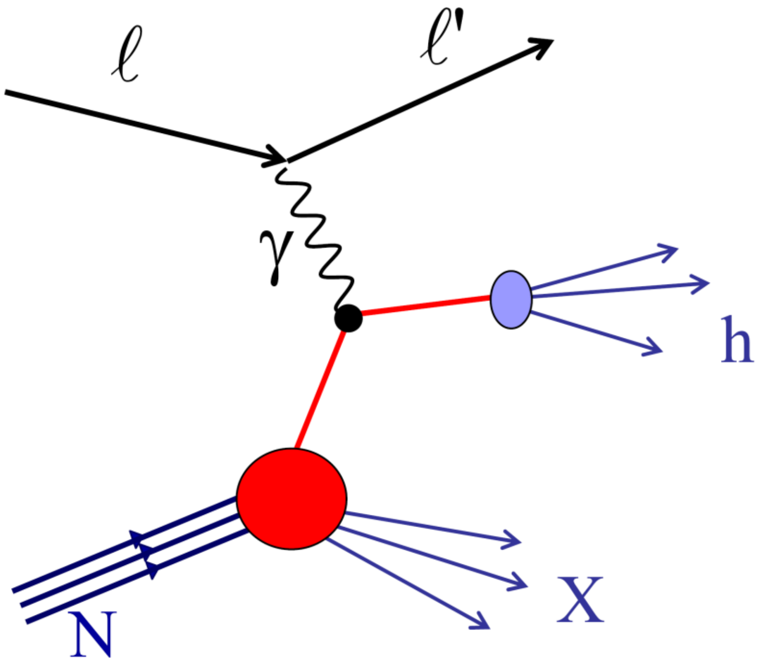
T-odd

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 gives access to all of them

Semi-Inclusive Deep Inelastic Scattering

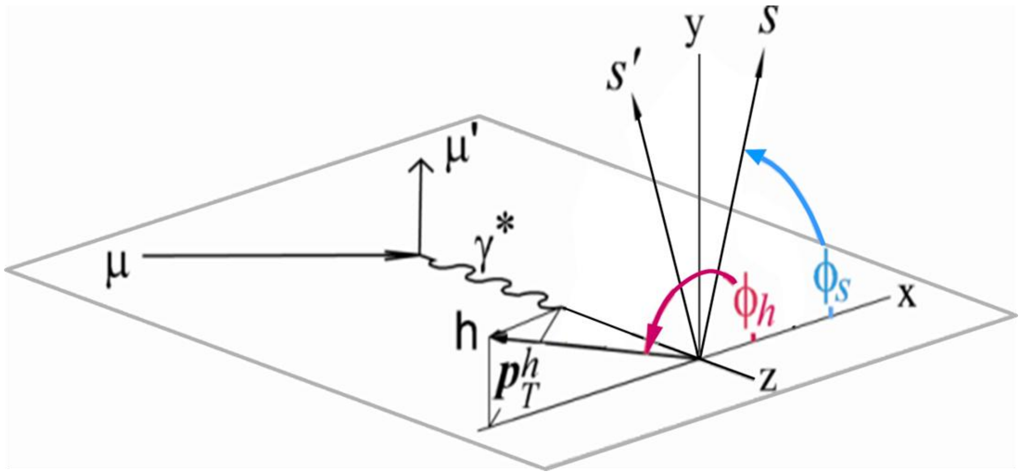


$$x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot \ell} =_{LAB} \frac{E-E'}{E}$$

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

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

$$\sigma^{\ell N\to \ell h X} \propto \sum_q q(x) \otimes \sigma^{\ell q\to \ell q} \otimes D_q^h(z)$$



Semi-Inclusive Deep Inelastic Scattering

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

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

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

unpol target

$\longrightarrow$ pol target

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

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

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

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

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

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

$\uparrow$ pol target

18 structure functions

Semi-Inclusive Deep Inelastic Scattering

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

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

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

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

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

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

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

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

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

$h_1^\perp H_1^\perp$

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

$f_{1T}^\perp D_1$

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

$h_1 H_1^\perp$

$g_{1T} D_1$

14 independent azimuthal modulations

amplitudes of the modulations → TMD PDFs

Semi-Inclusive Deep Inelastic Scattering

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

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

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

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

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

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

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

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

$h_1^\perp H_1^\perp$

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

$f_{1T}^\perp D_1$

$h_1 H_1^\perp$

$g_{1T} D_1$

14 independent azimuthal modulations

amplitudes of the modulations → TMD PDFs

SIDIS

- **allows to disentangle the effects related to the different TMD PDFs and to access all of them**
- **by identifying the final state hadrons and using different targets allows for flavour separation**

→ ***very powerful tool***

all the amplitudes (AA) **have been measured in COMPASS**

Semi-Inclusive Deep Inelastic Scattering

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

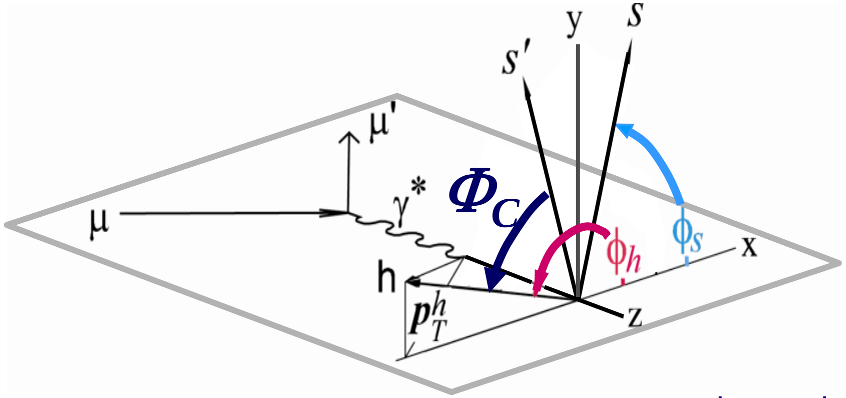
Sivers $f_{1T}^{\perp} D_1$

Collins $h_1 H_1^{\perp}$

this talk

Collins asymmetry in SIDIS

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



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

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

transversity

"Collins FF"

$$A_{Coll} \approx \frac{\sum_q e_q^2 \, h_{1q} \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 \, f_{1q} \otimes D_{1q}^h}$$

BELLE, BaBar

today the most promising way to access transversity, together with 2h asymmetry (→ C. Braun)

Sivers asymmetry

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

$\Phi_S = \phi_h - \phi_s$

$$N_h^{\pm}(\Phi_S) = N_h^0 \left[1 \pm P_T \cdot A_{Siv} \cdot \sin \Phi_S \right]$$

Sivers PDF

$$A_{Siv} \approx \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2 \, f_1^q \otimes D_{1q}^h}$$

the COMPASS experiment

data taking

with transversely polarised targets

2002, 2003, 2004:

160 GeV μ beam, deuteron (^{6}LiD) **target**

2007, 2010:

160 GeV μ beam, proton (NH_3) **target**

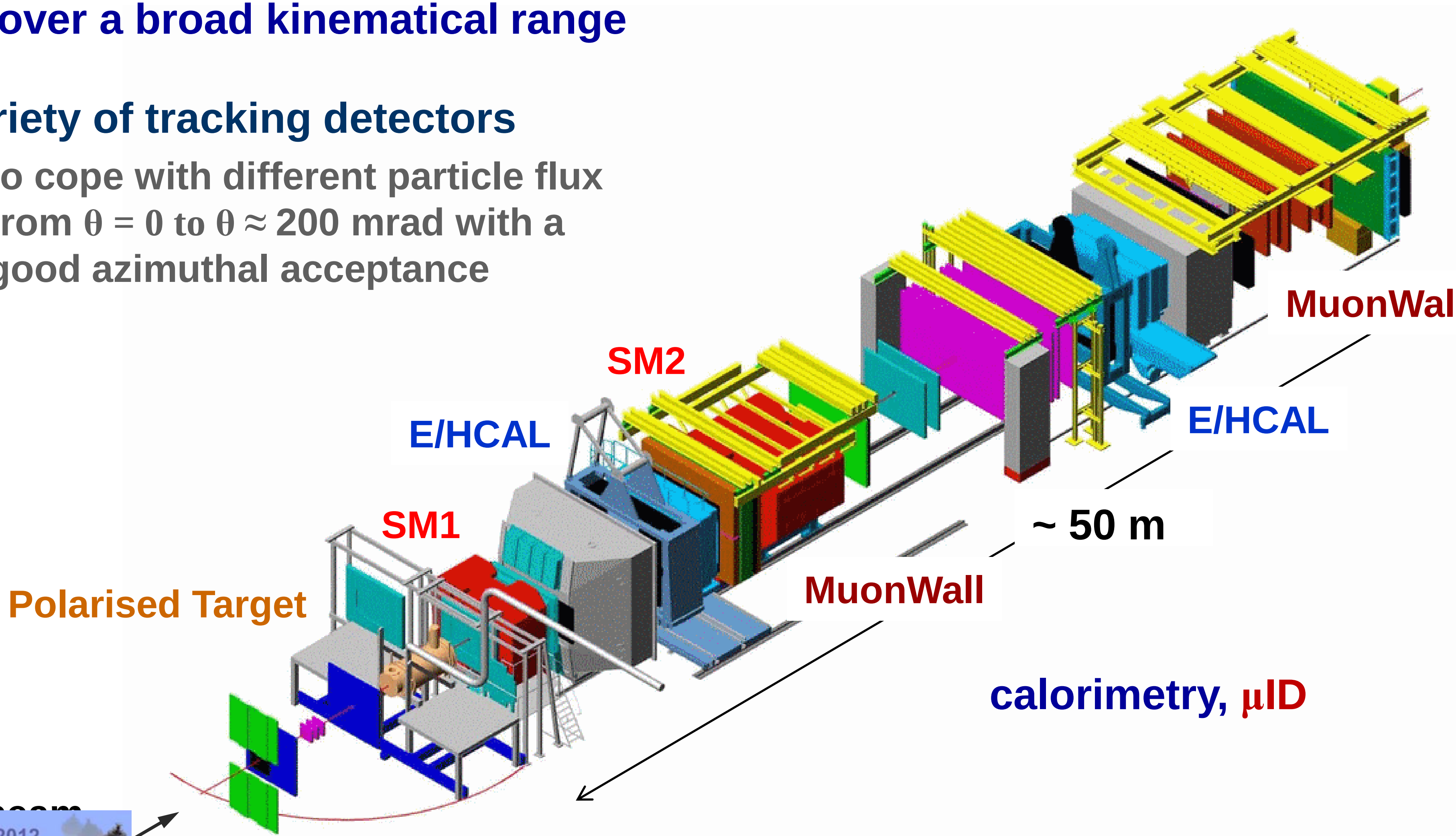
COMPASS spectrometer

designed to
- use high energy beams
- have large angular acceptance
- cover a 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

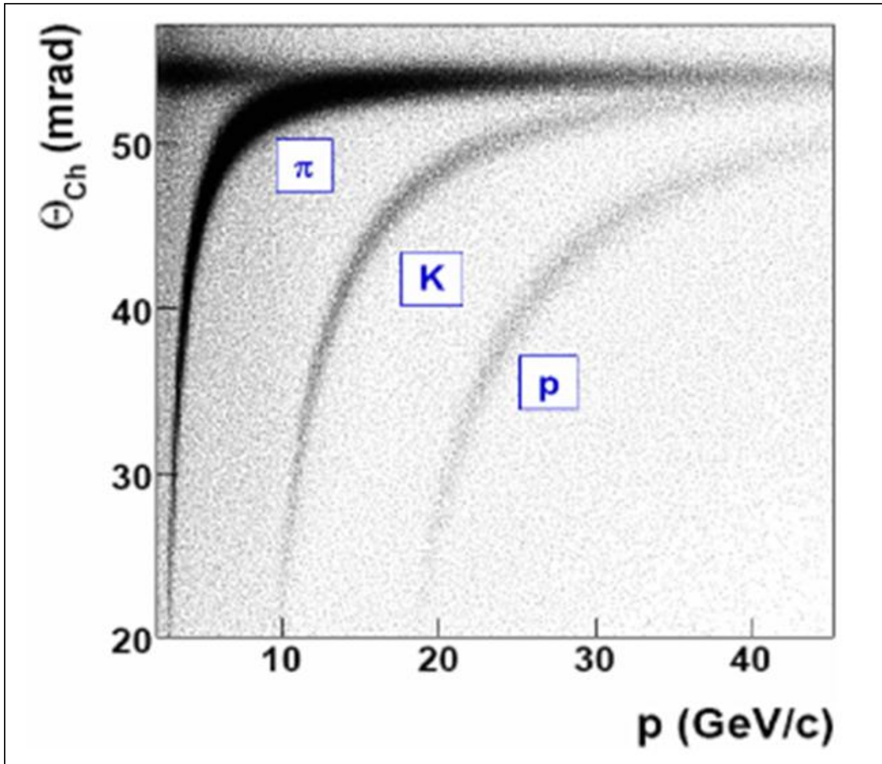


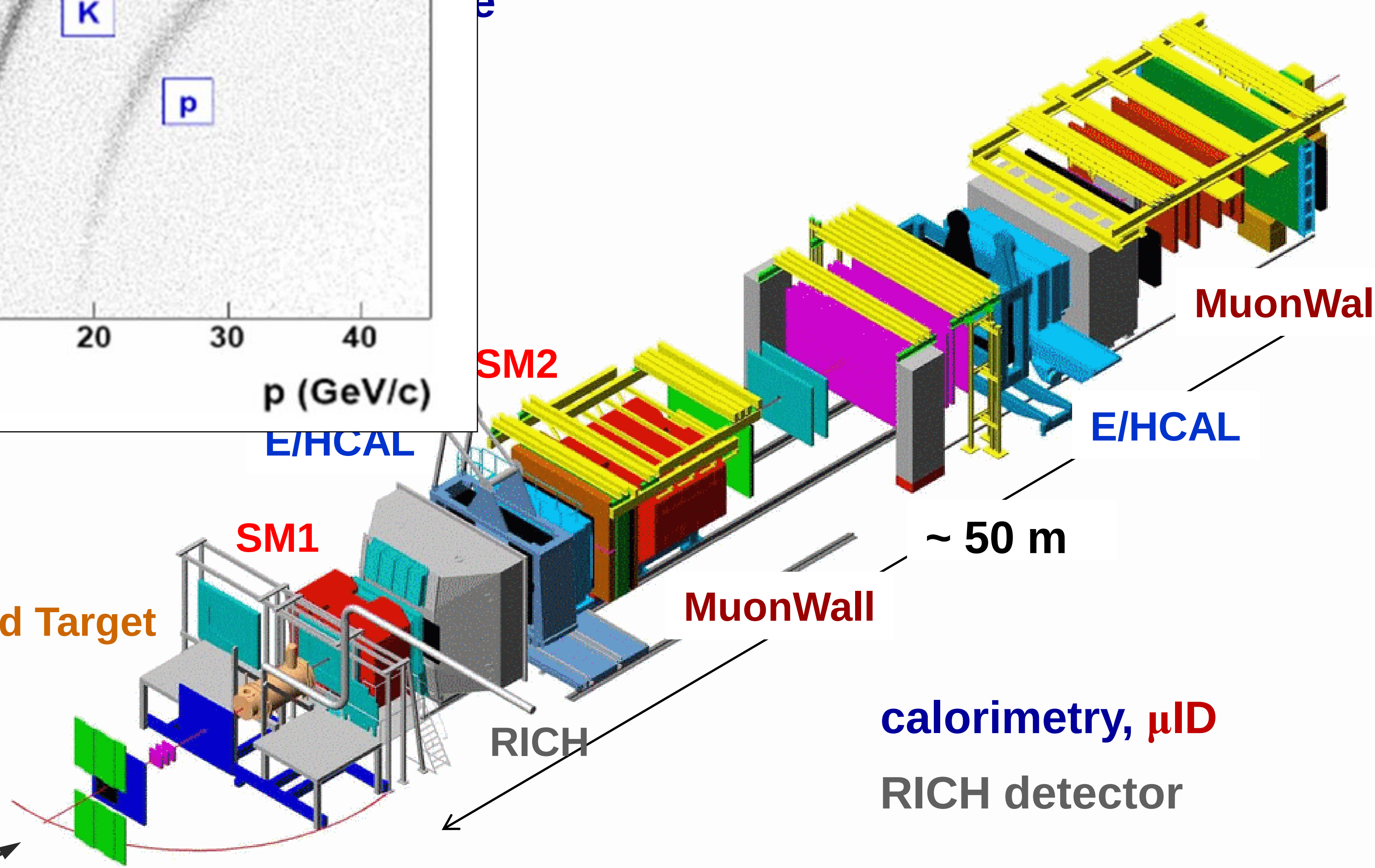
calorimetry, μID

COMPASS spectrometer

two stages spectrometer

- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)





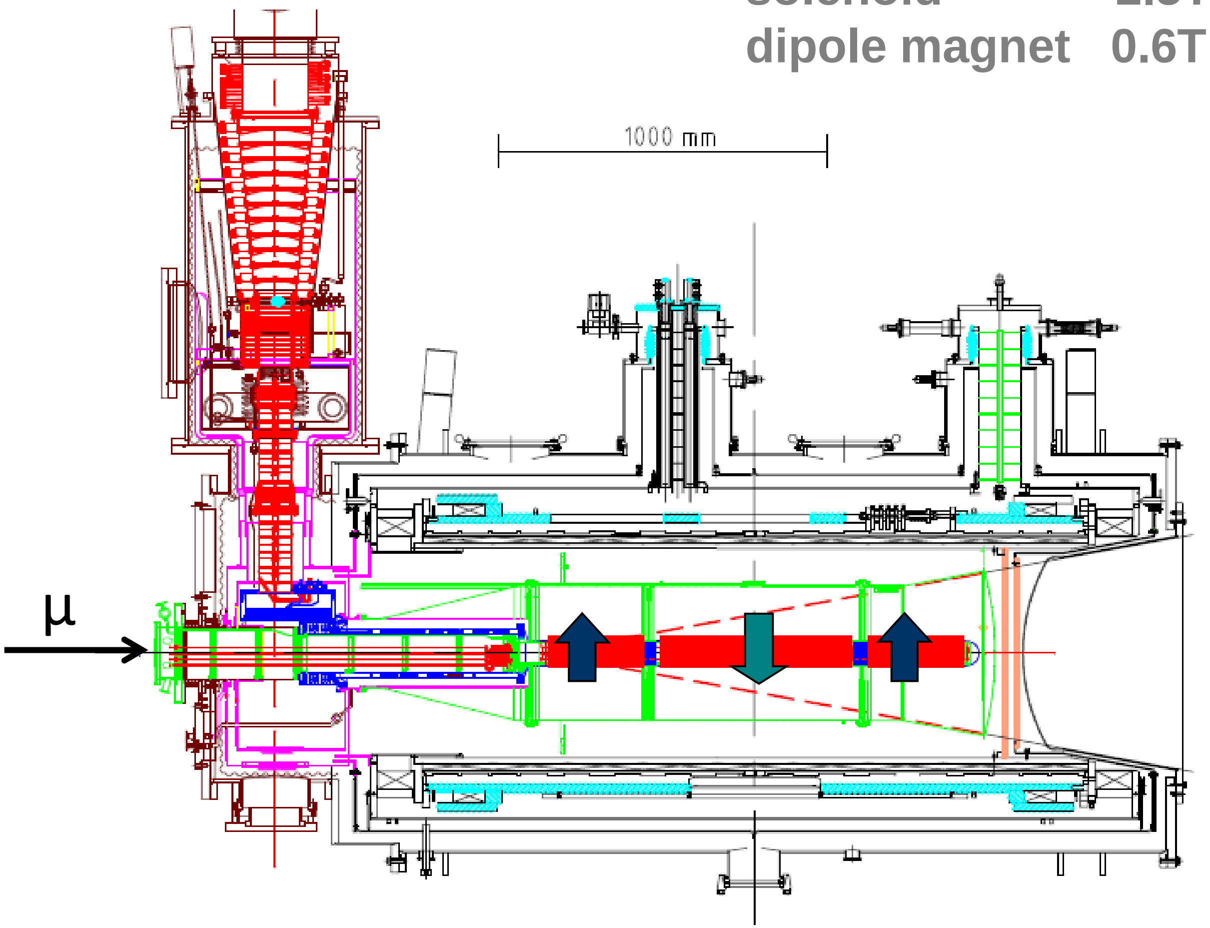
calorimetry, μID

RICH detector

the polarized target system (>2005)

^3He – ^4He 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

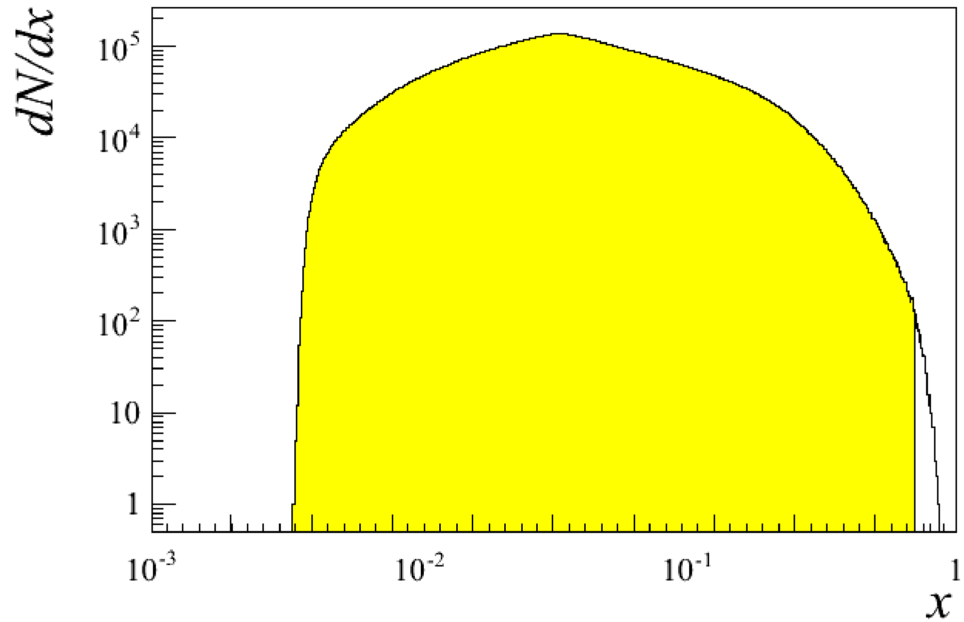
	d (^6LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

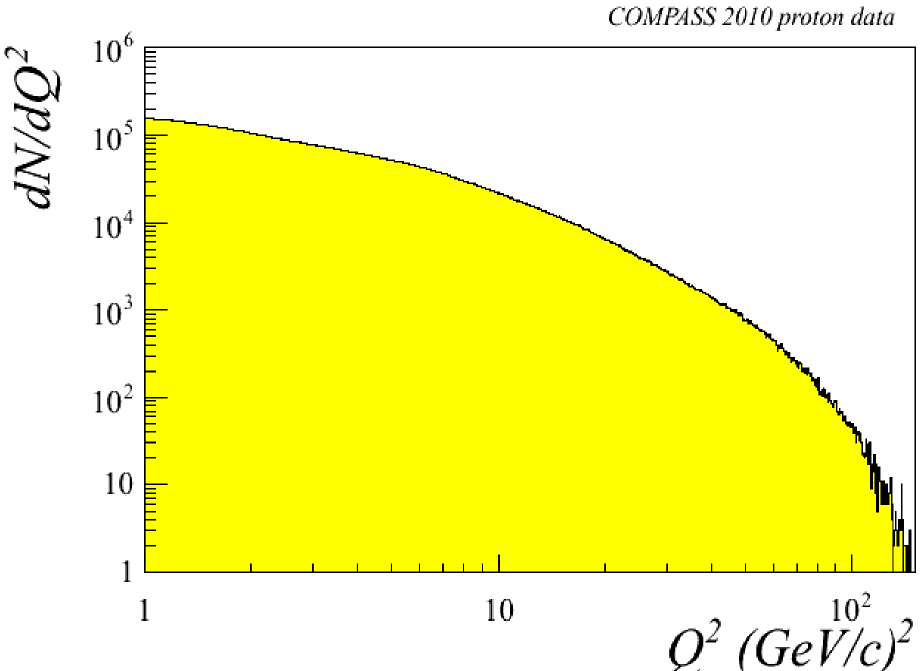
no evidence for relevant nuclear effects *(160 GeV)*

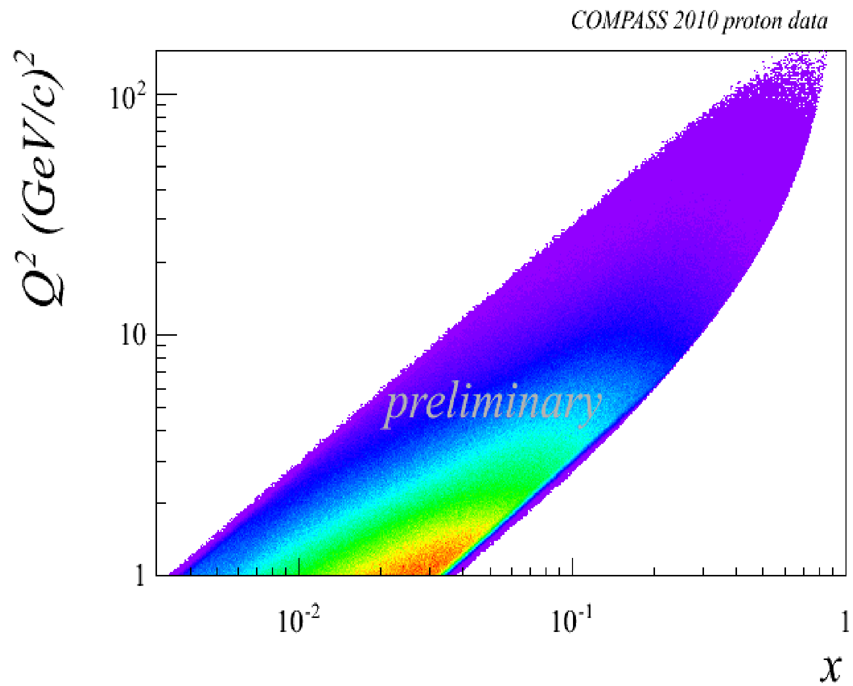
SIDIS event selection

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

hadron selection: $p_t^h > 0.1\ \mathrm{GeV}/c$
$z > 0.2$







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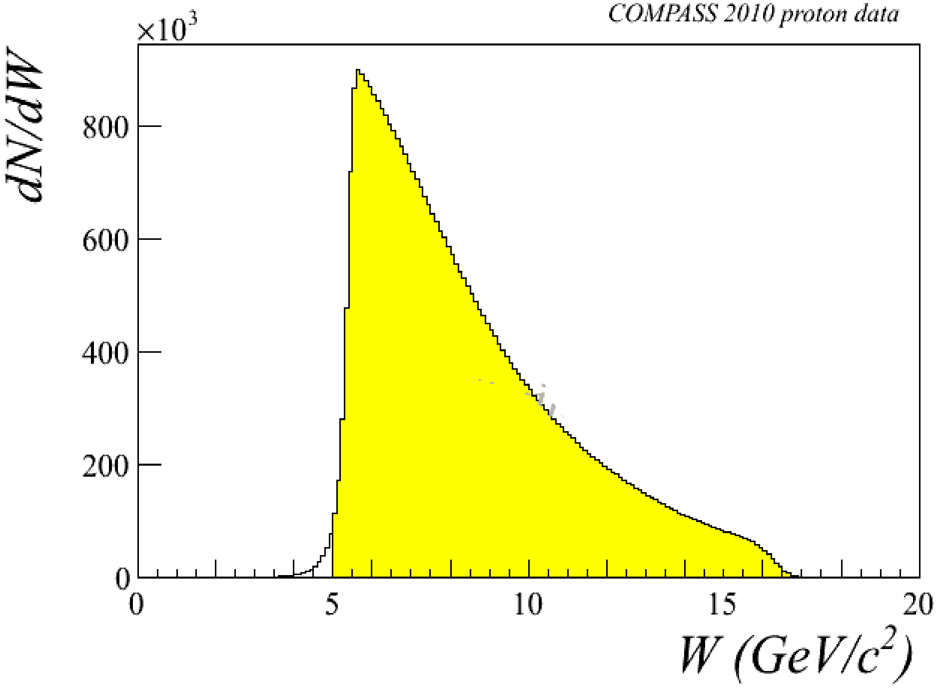
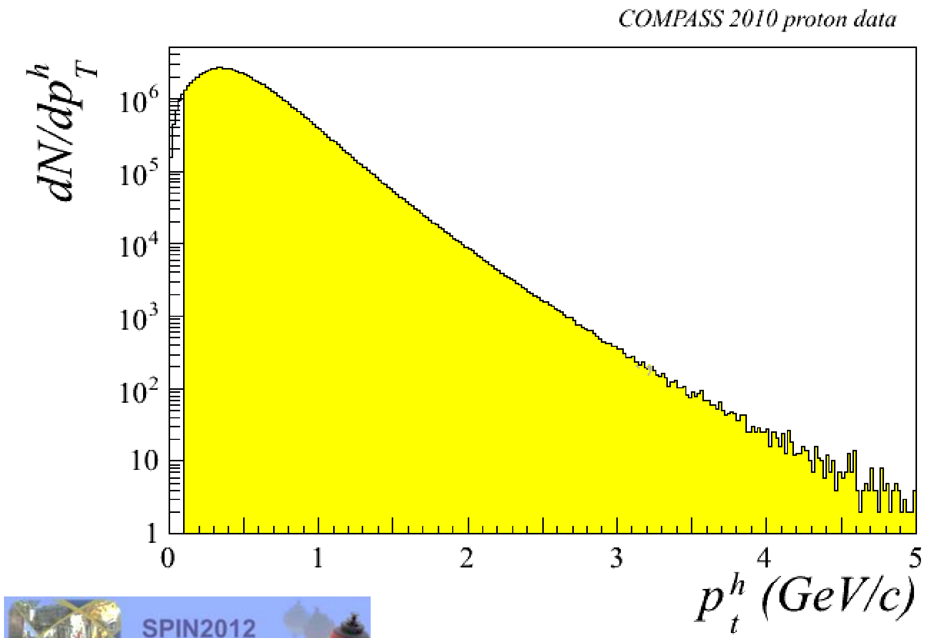
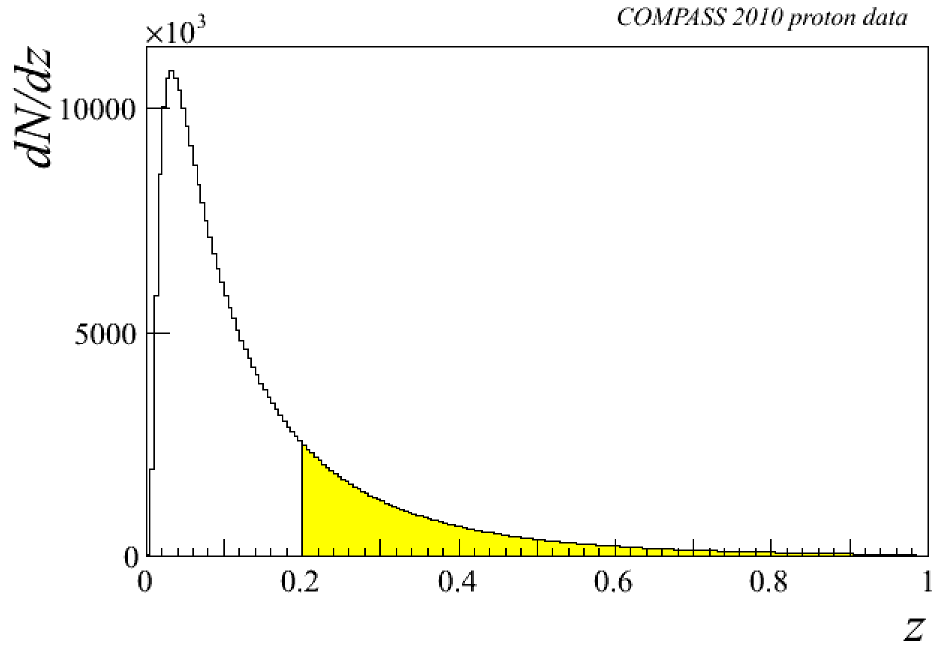






Collins and Sivers asymmetries: results

data taking

with transversely polarised targets

2002, 2003, 2004:

160 GeV μ beam, deuteron (^{6}LiD) **target**

published results for charged hadrons, kaons and charged pions

NPB765 (2007) 31, PLB 673 (2009) 127

2007, 2010:

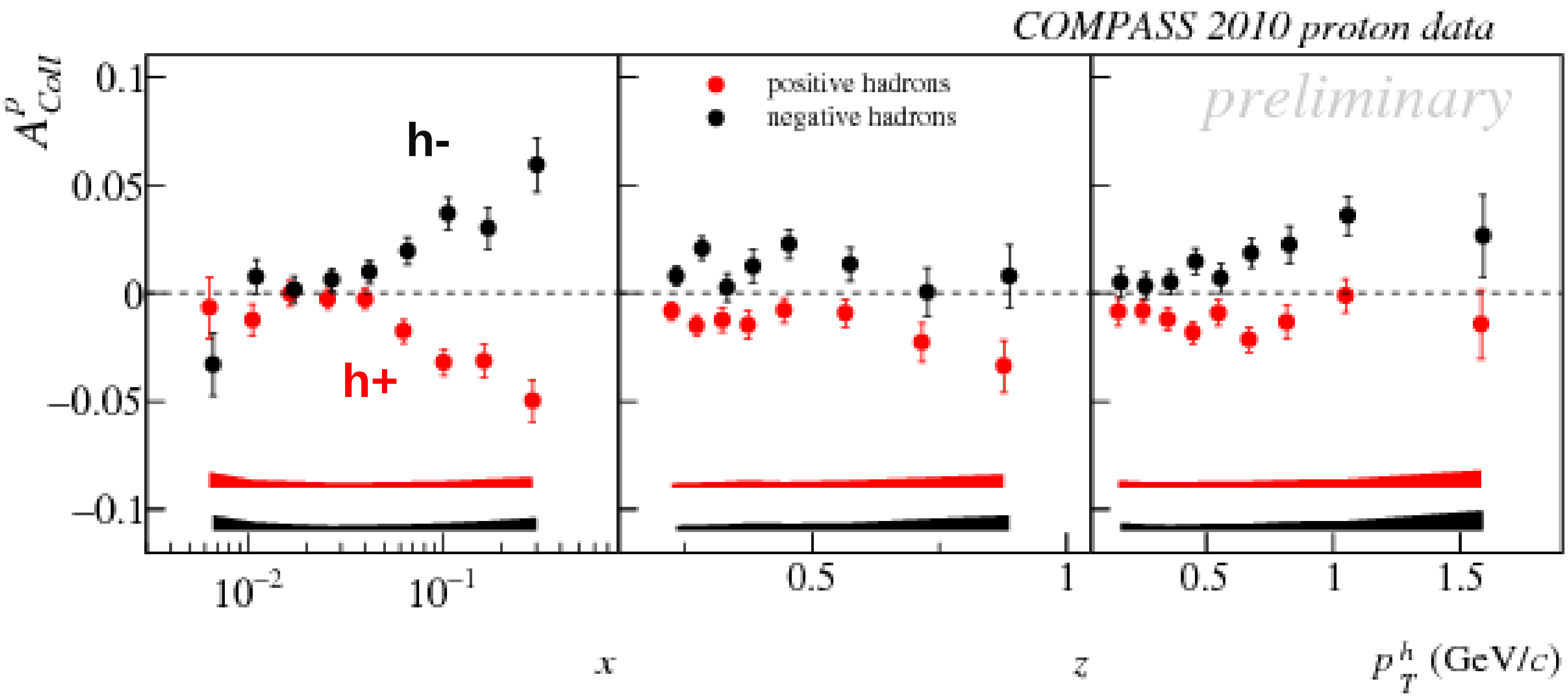
160 GeV μ beam, proton (NH_3) **target**

charged hadrons
- **2007: published** PLB 692 (2010) 240
- **2010: sent for publication** arXiv:1205.5121 / 2

charged pions and charged kaons
- **2007: preliminary results** (G. Pesaro, SPIN2010)
- **2010: preliminary results NEW**

Collins asymmetry on proton

charged hadrons
2010 data

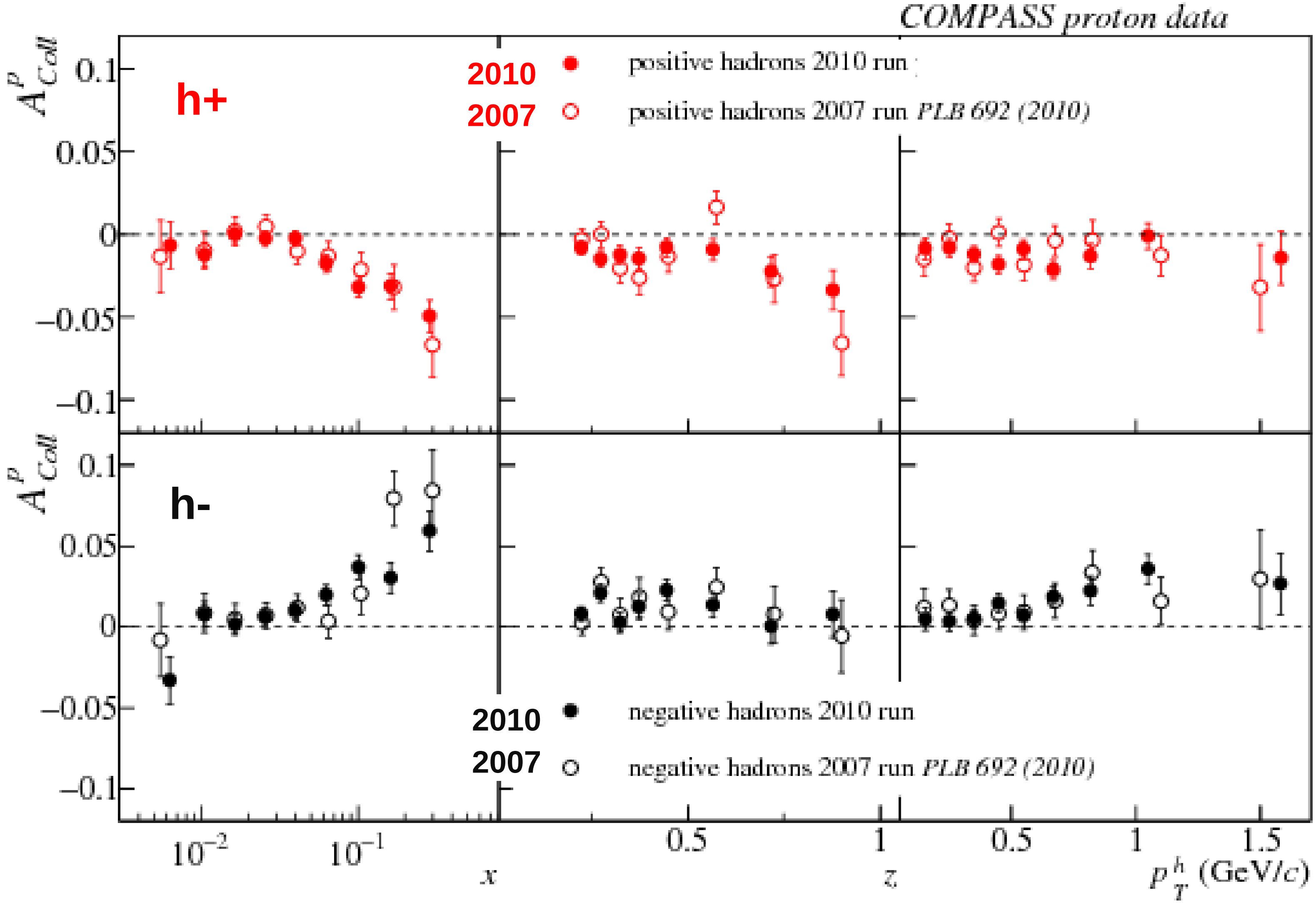


$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

Collins asymmetry on proton

charged hadrons

2010 vs 2007 data

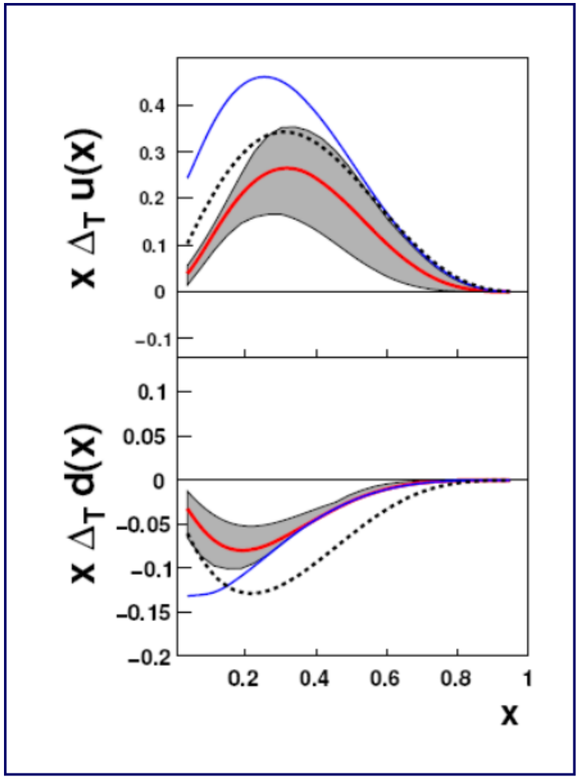


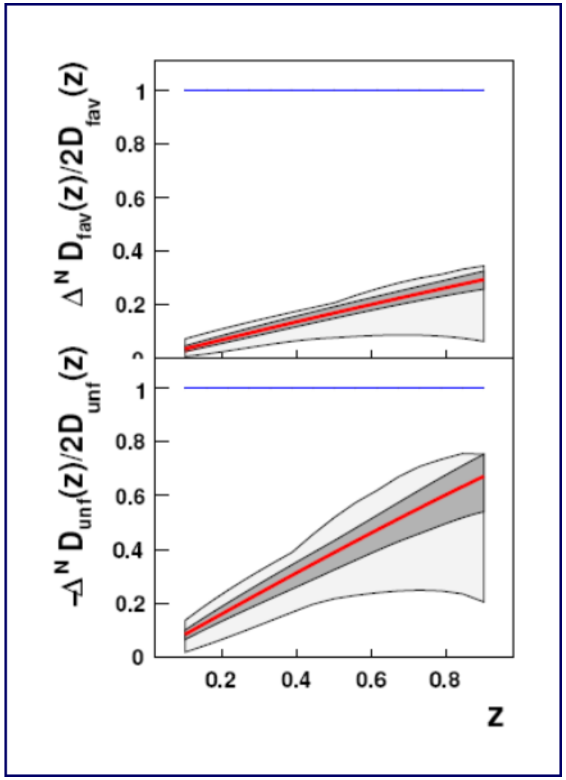
nice confirmation, with better statistics

Collins asymmetry on proton

M. Anselmino et al., Nucl. Phys. Proc. Suppl. 2009

fit to HERMES p, COMPASS d, Belle e+e- data





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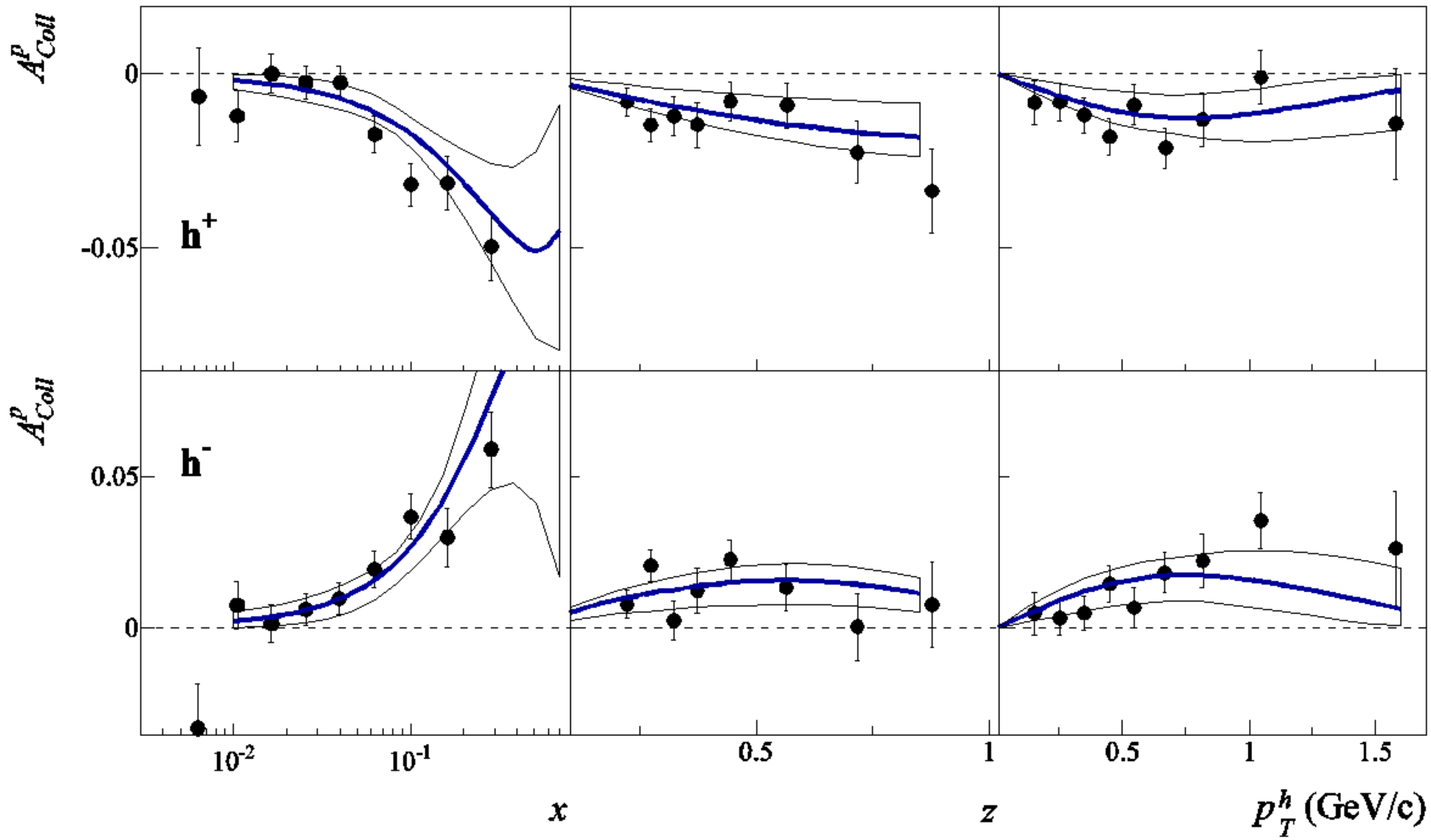
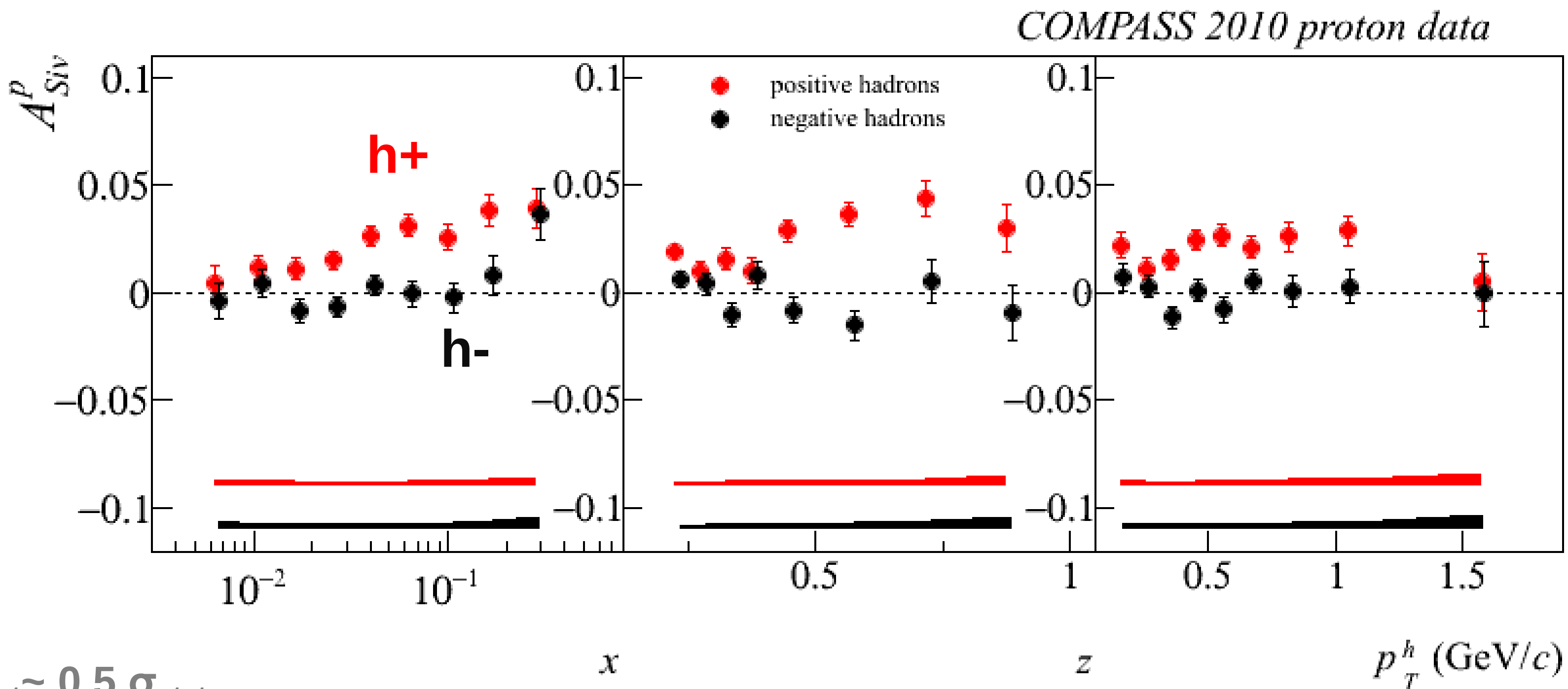


2010 p data

Sivers asymmetry on proton

charged hadrons

2010 data



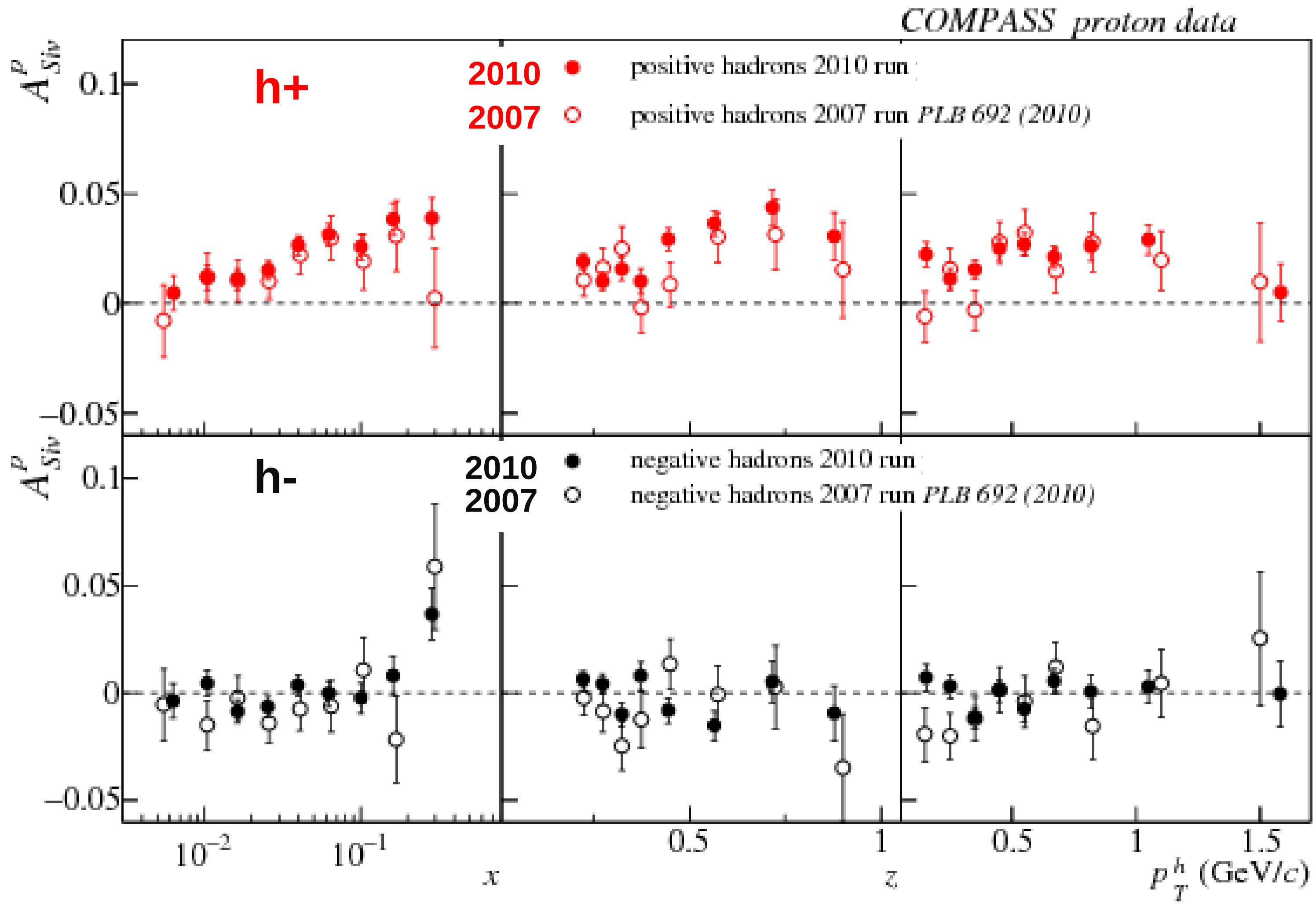
$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

clear evidence for a positive signal for h^+, which extends to small x

Sivers asymmetry on proton

charged hadrons

2010 vs 2007 data



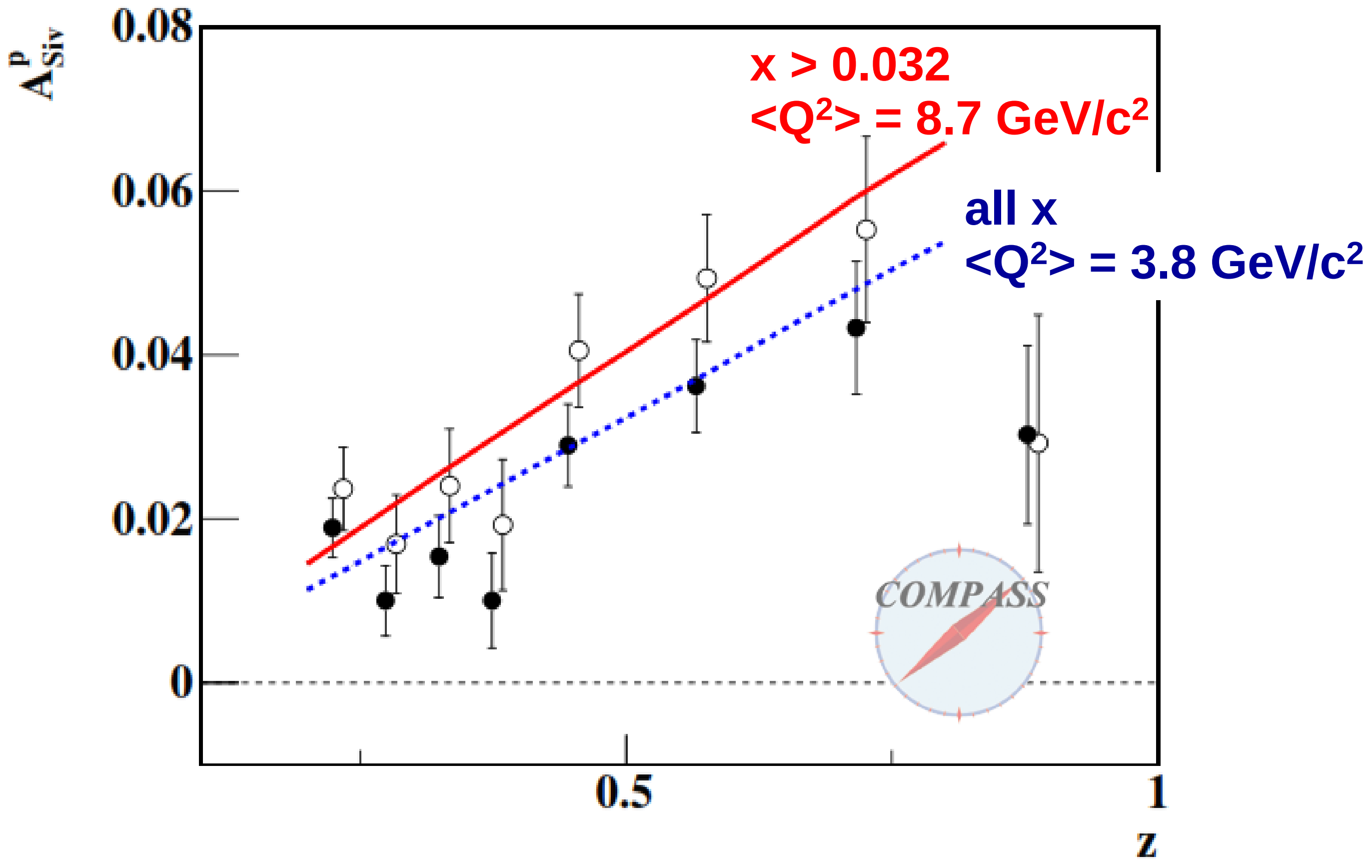
nice confirmation, with much higher precision

Sivers asymmetry on proton

charged hadrons, 2010 data - Q^2 evolution

comparison with

S. M. Aybat, A. Prokudin and T. C. Rogers calculations PRL 108 (2012) 242003

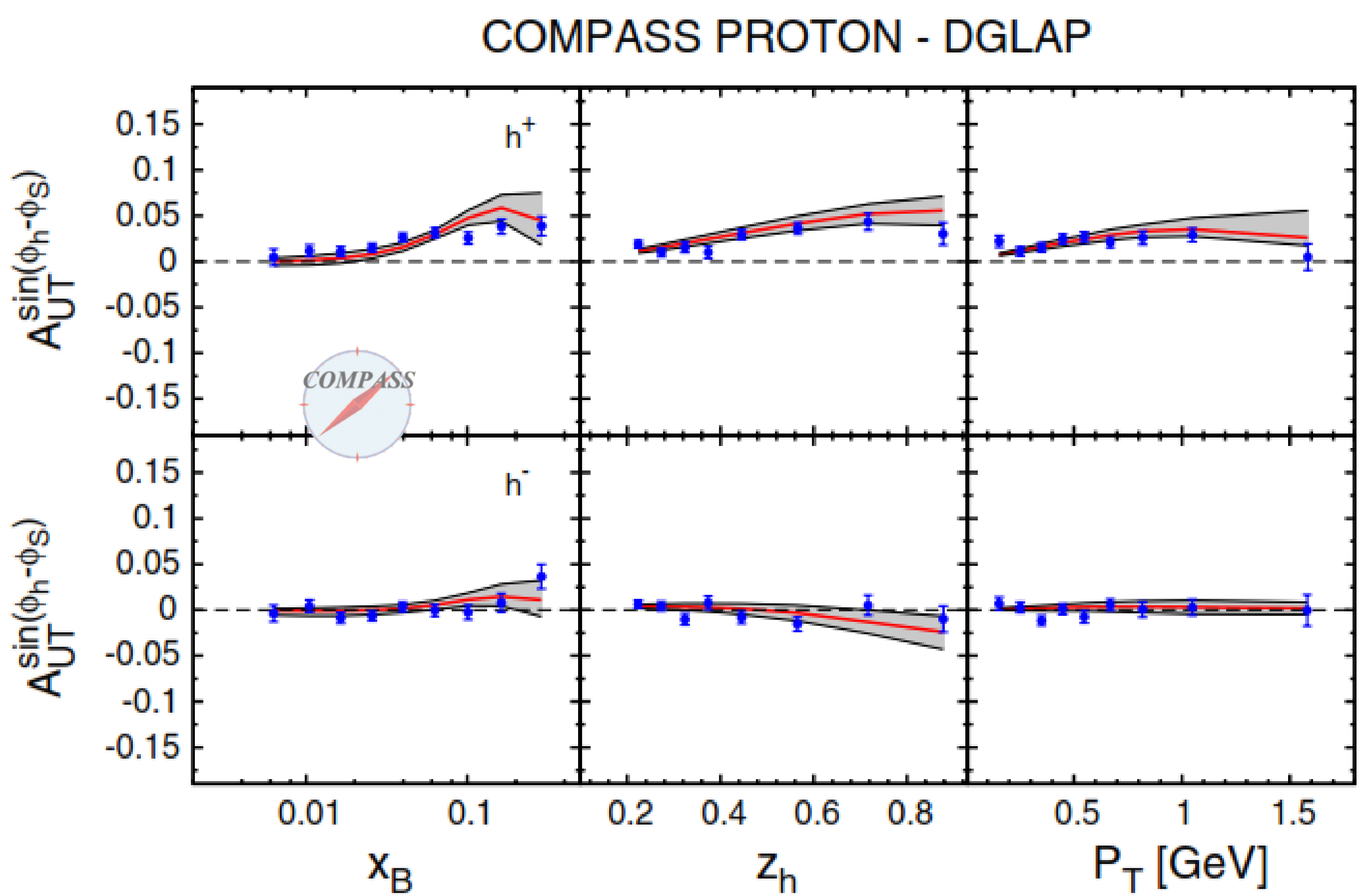


Sivers asymmetry on proton

charged hadrons, 2010 data - Q^2 evolution

M. Anselmino, M. Boglione, S. Melis PRD86 (2012) 014028

fit to HERMES p and COMPASS d and p 2010 data



Sivers asymmetry on proton

charged hadrons, 2010 data - Q^2 evolution

M. Anselmino, M. Boglione, S. Melis PRD86 (2012) 014028

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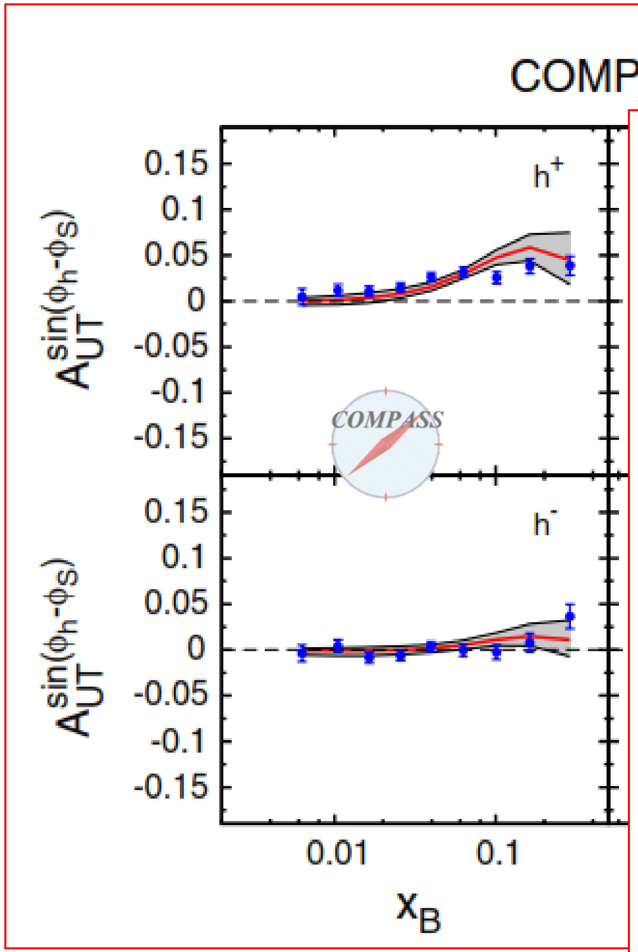
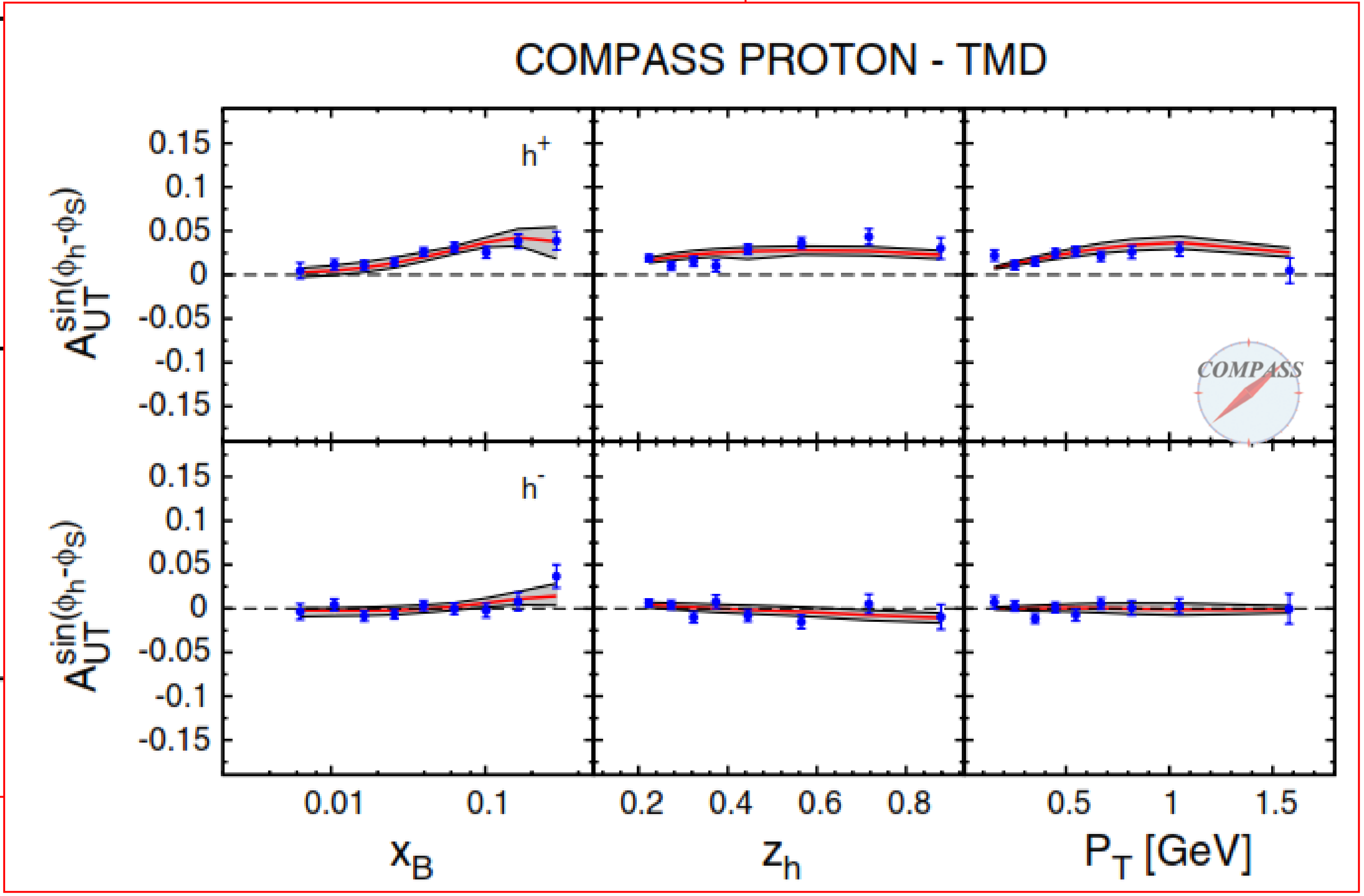
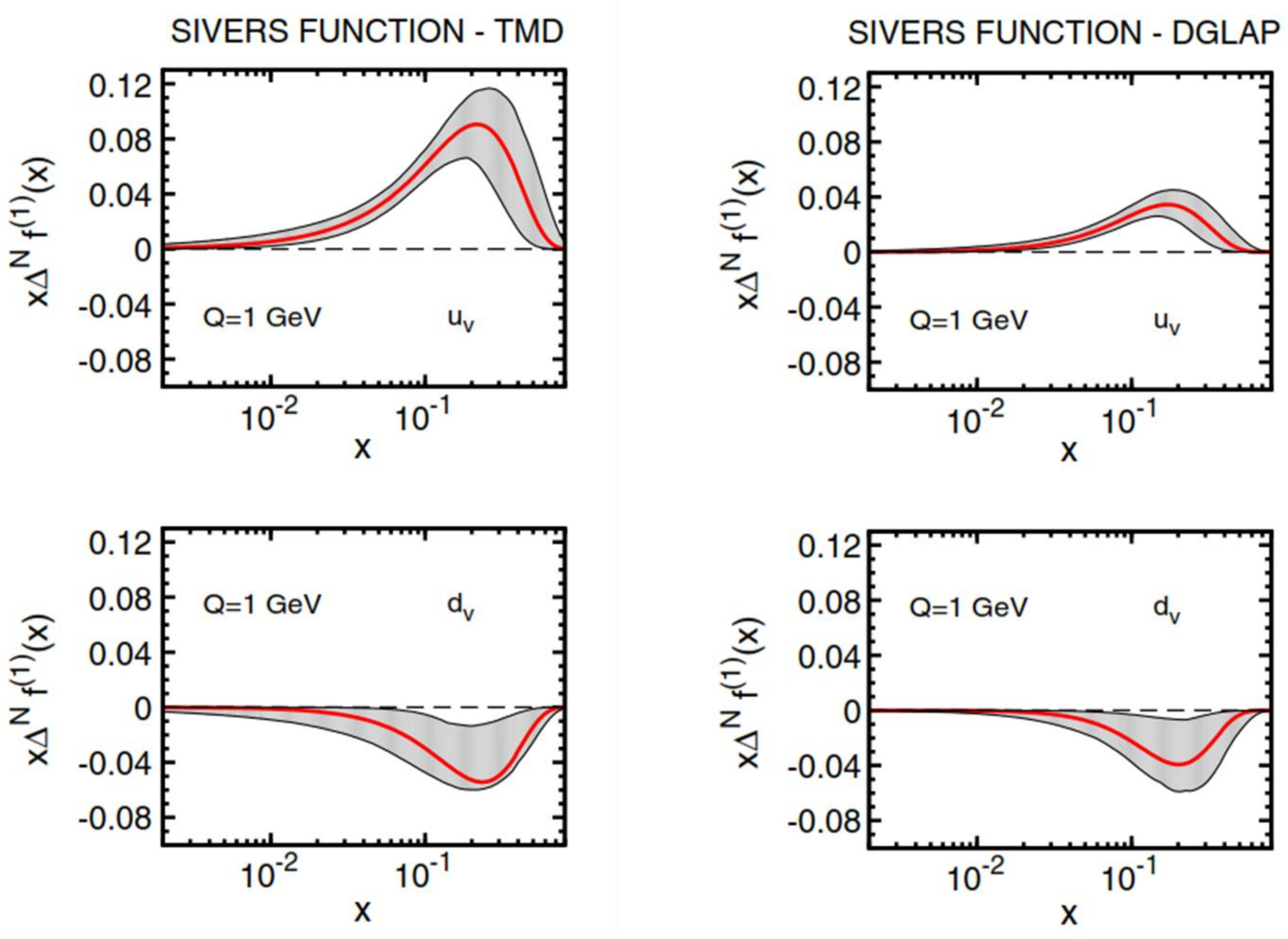




Sivers asymmetry on proton

charged hadrons, 2010 data and Q^2 evolution

M. Anselmino, M. Boglione, S. Melis PRD86 (2012) 014028



Collins and Sivers asymmetries
on proton
for charged pions and kaons

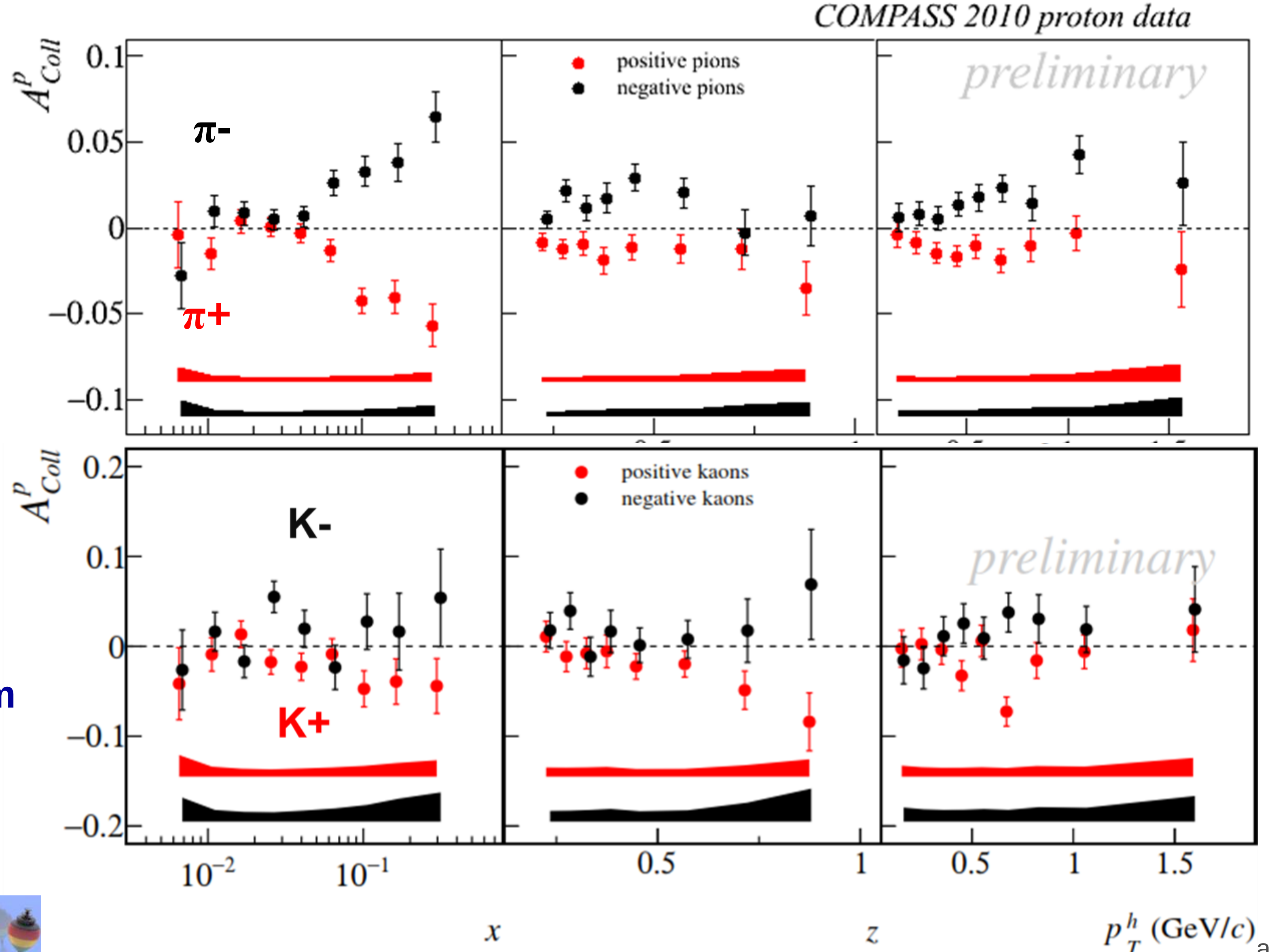
NEW

Collins asymmetry on proton

charged pions and kaons

2010 data **NEW**

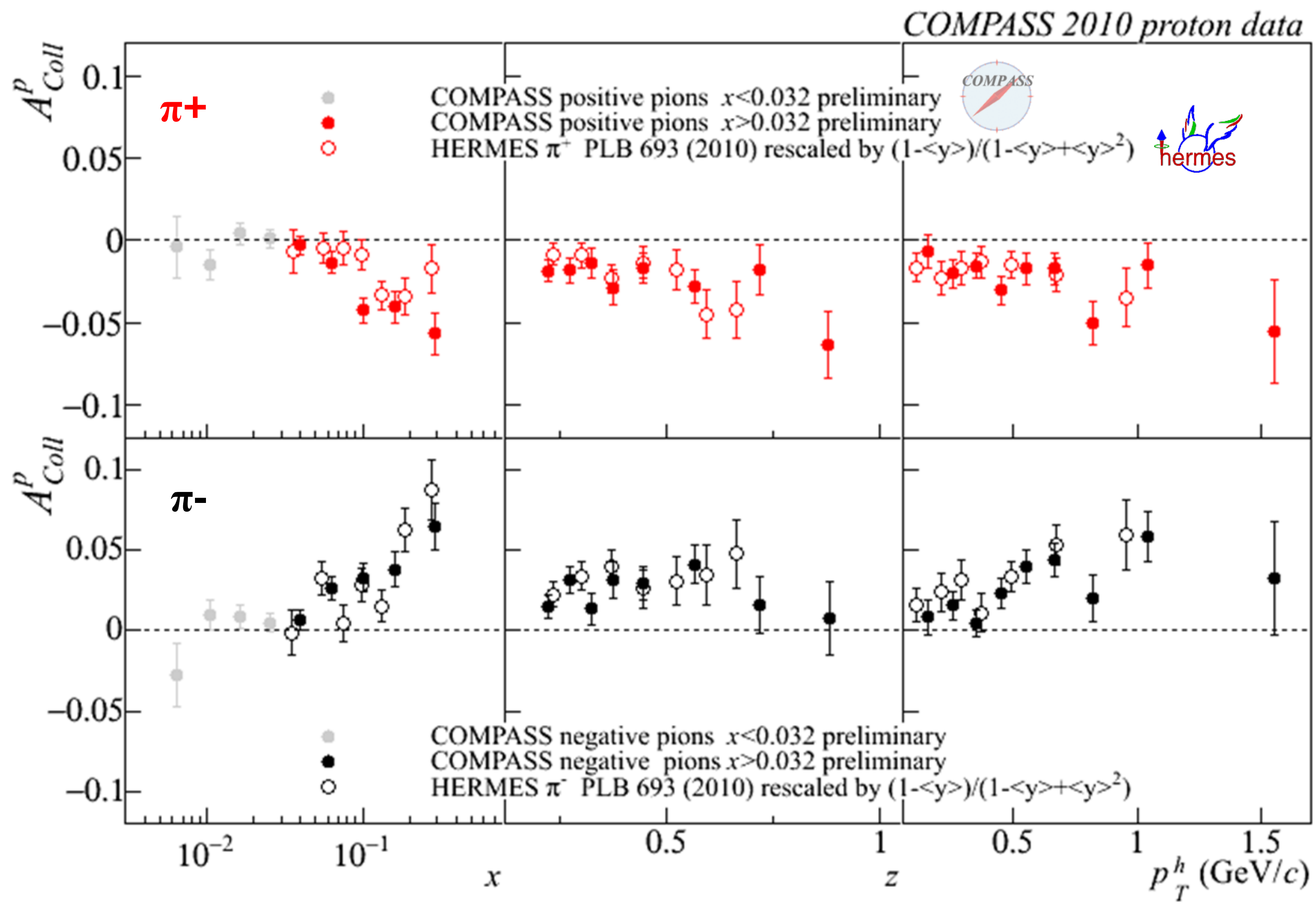
$\sigma_{syst} \sim 0.6\, \sigma_{stat}$



different from zero …

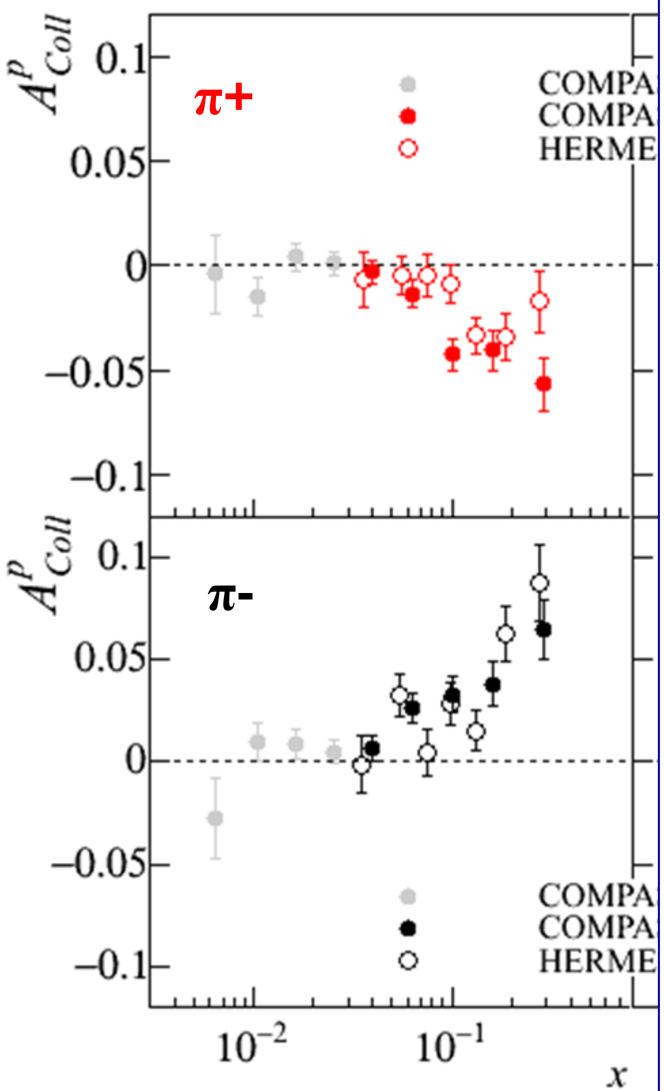
Collins asymmetry on proton

2010 data, charged pions, x > 0.032

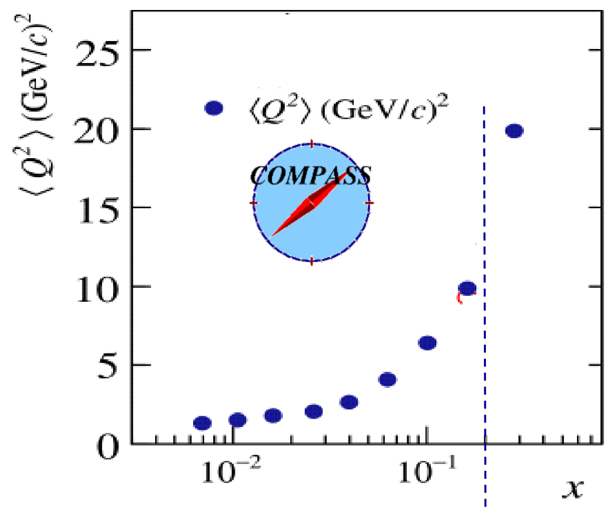


Collins asymmetry on proton

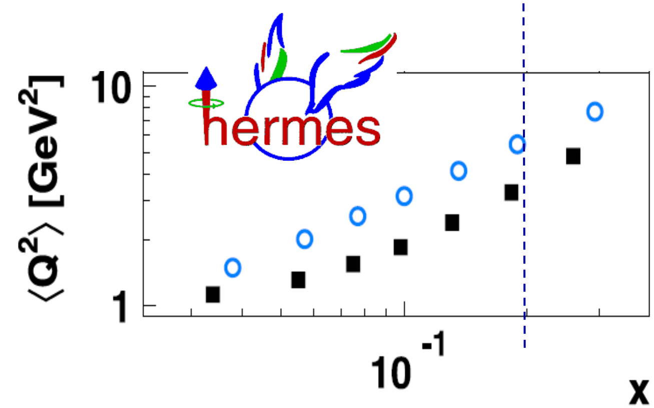
2010 data, charged pions, x > 0.03



as for charged hadrons, same strength:
a very important, not obvious result!



~12



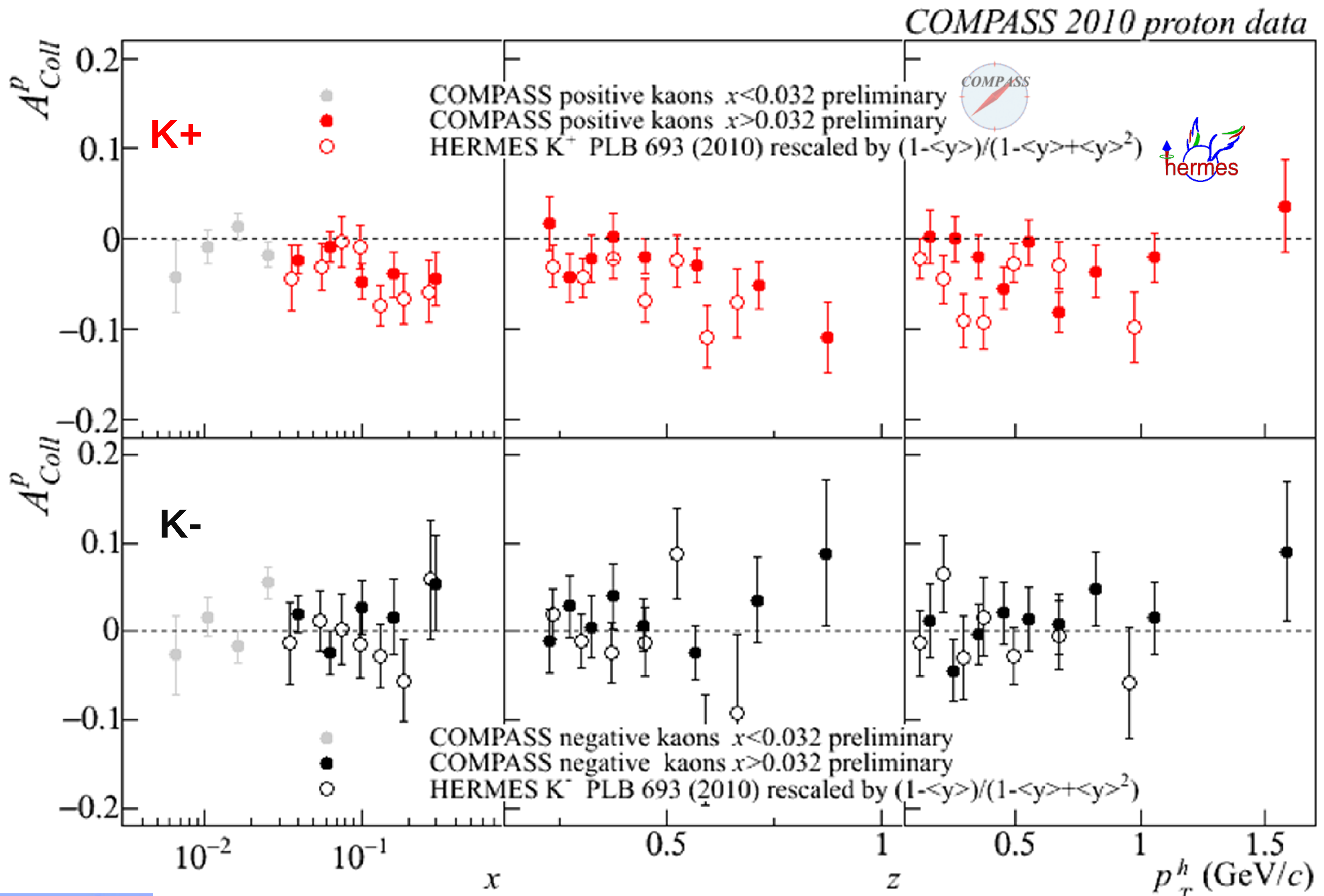
~ 4

indication for not a higher twist effect,

no strong Q^2 dependence of the Collins FF

Collins asymmetry on proton

2010 data, charged kaons, x > 0.032

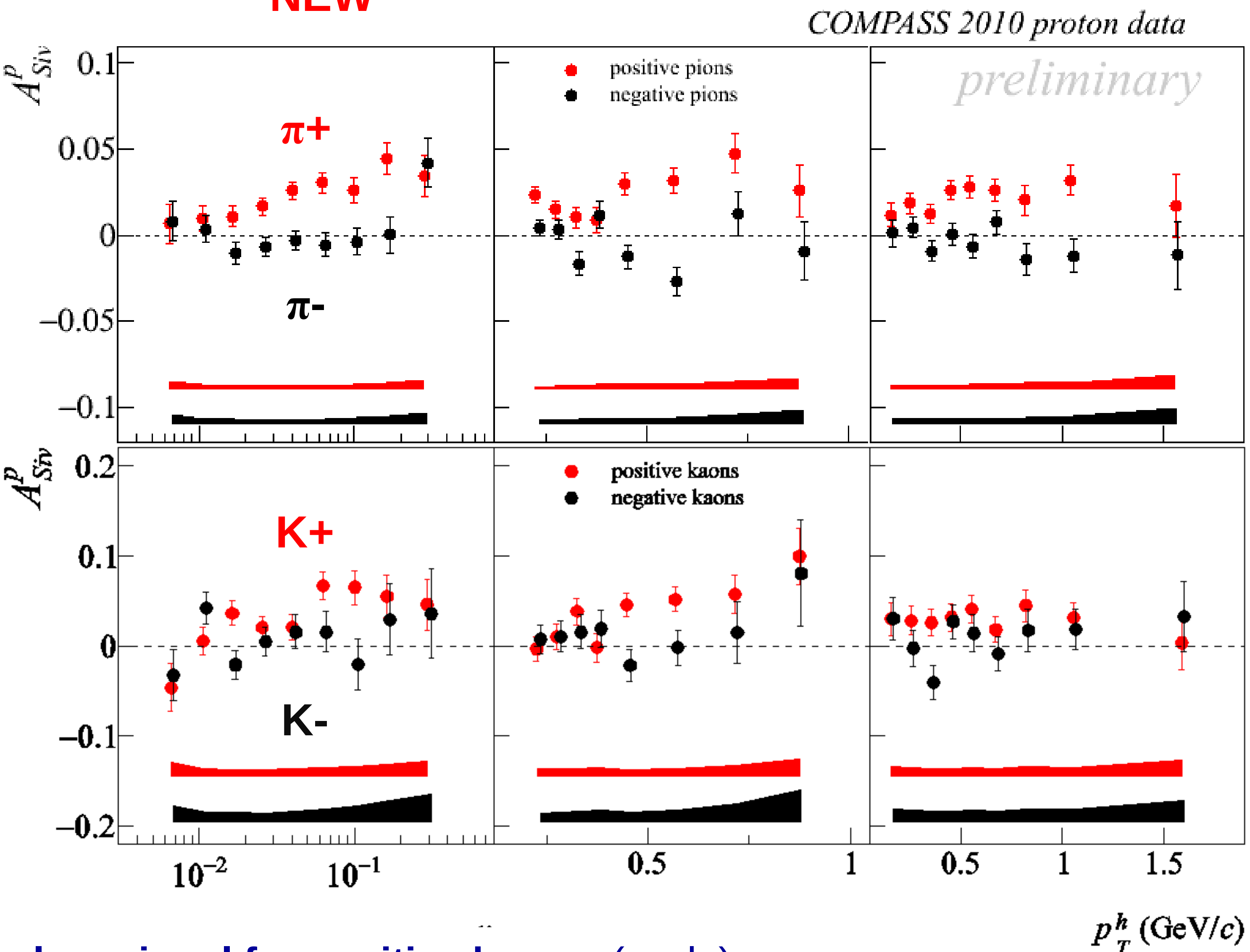


Anna Martin

Sivers asymmetry on proton

charged pions and kaons

2010 data NEW

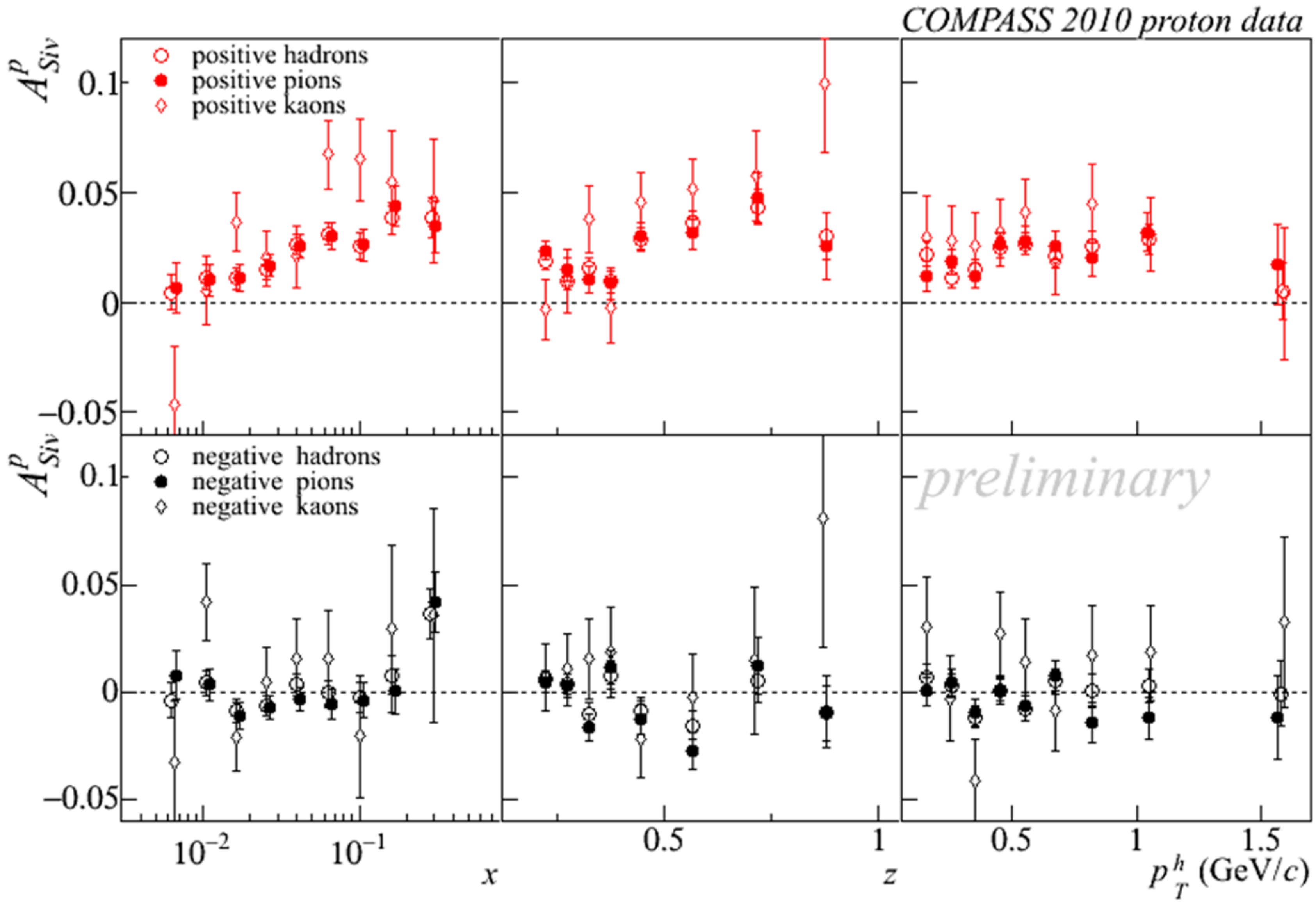


$\sigma_{syst} \sim 0.6\ \sigma_{stat}$

clear signal for positive kaons (scale)

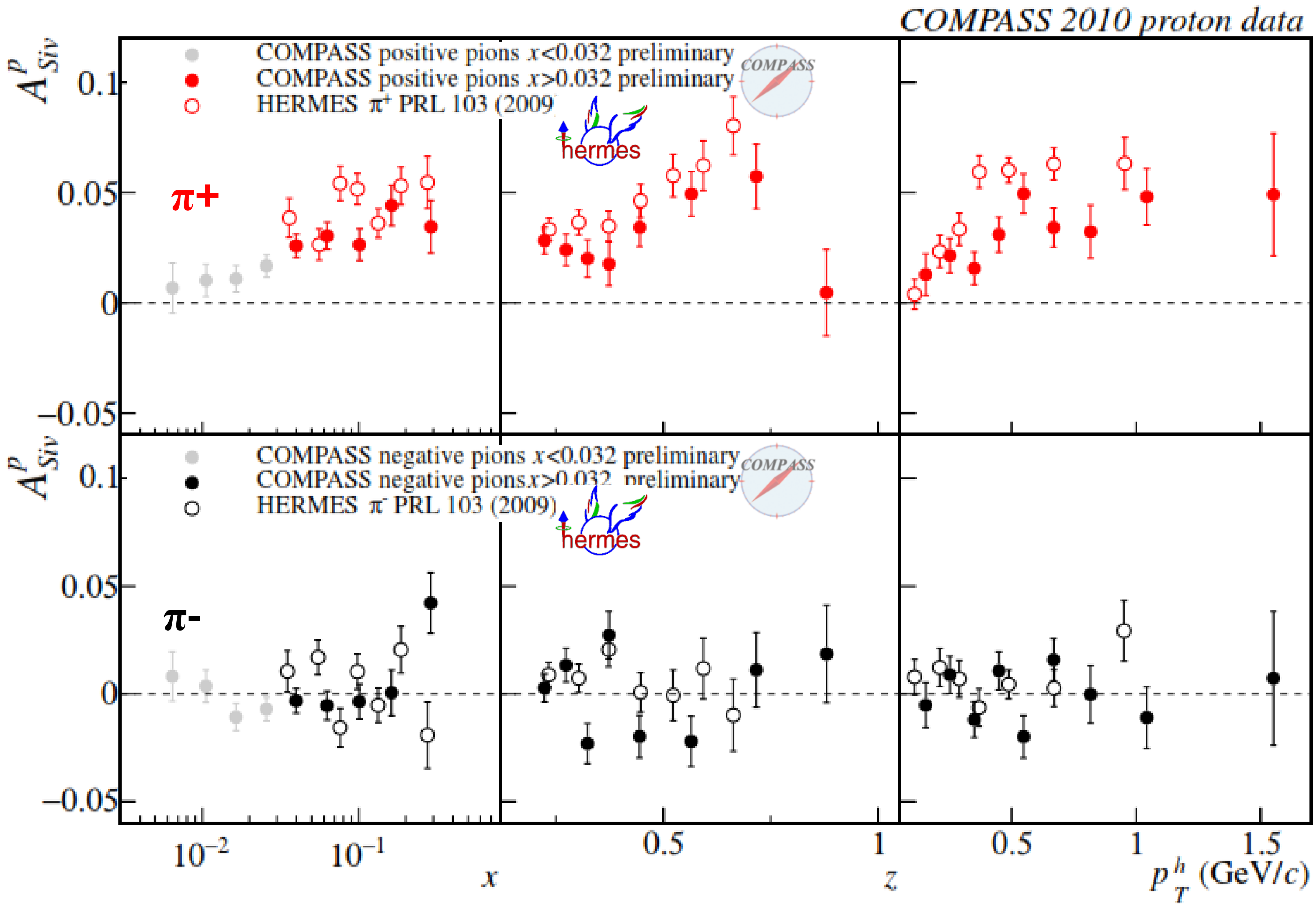
Sivers asymmetry on proton

2010 data



Sivers asymmetry on proton

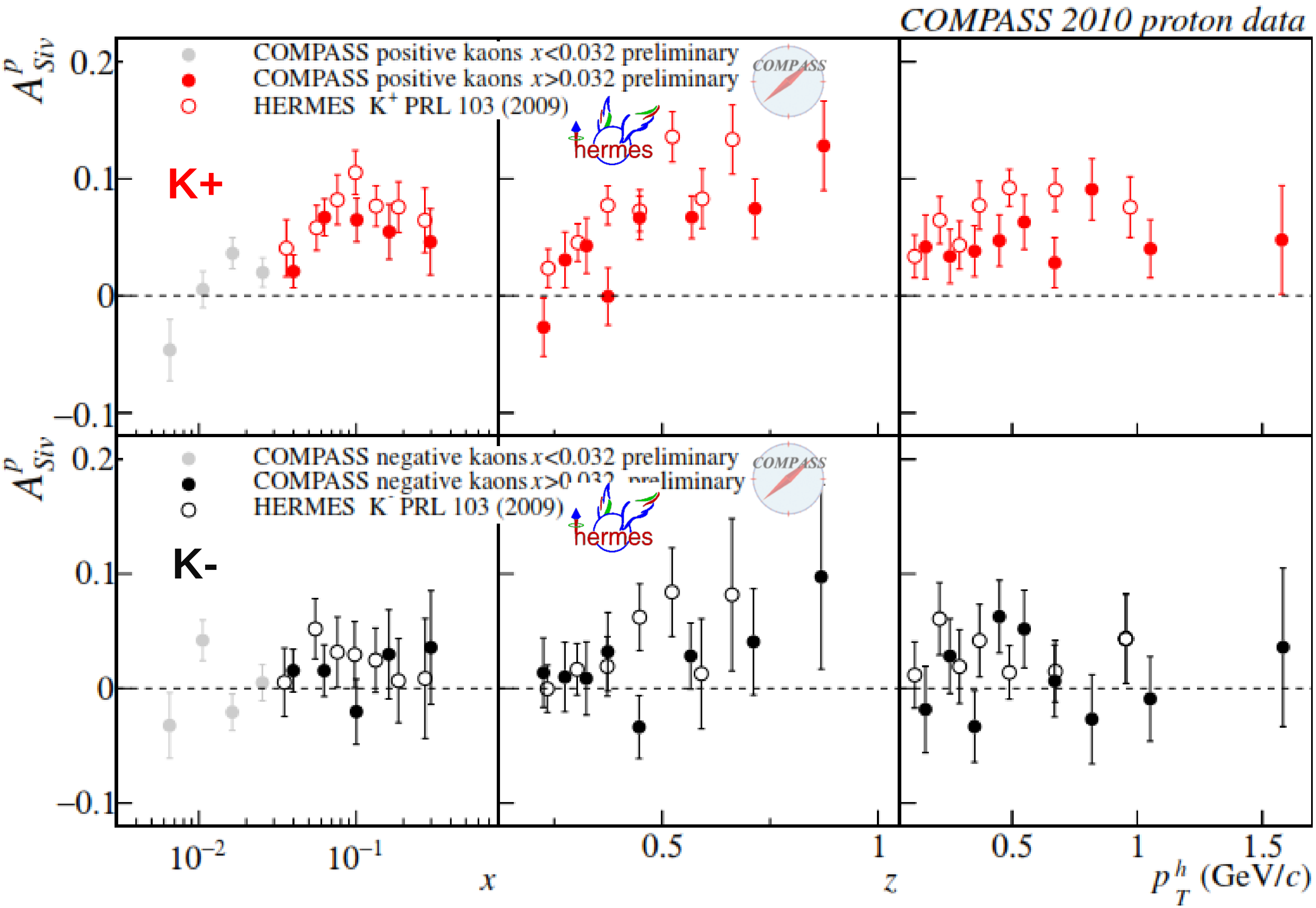
2010 data, charged pions, x > 0.032



smaller

Sivers asymmetry on proton

2010 data, charged kaons, x > 0.032

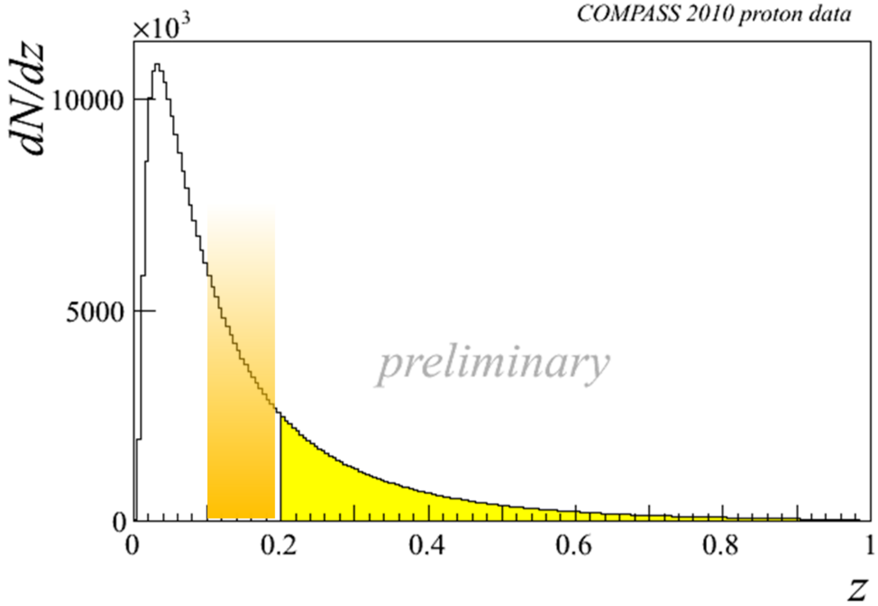


more on Collins and Sivers asymmetries

**thanks to the high beam momentum,
we have enlarged the usual COMPASS phase space
still remaining in the DIS CF regime**

- **low z** → **(0.1,0.2)** (0.2,0.3) (0.3,1.0)

for charged and identified hadrons

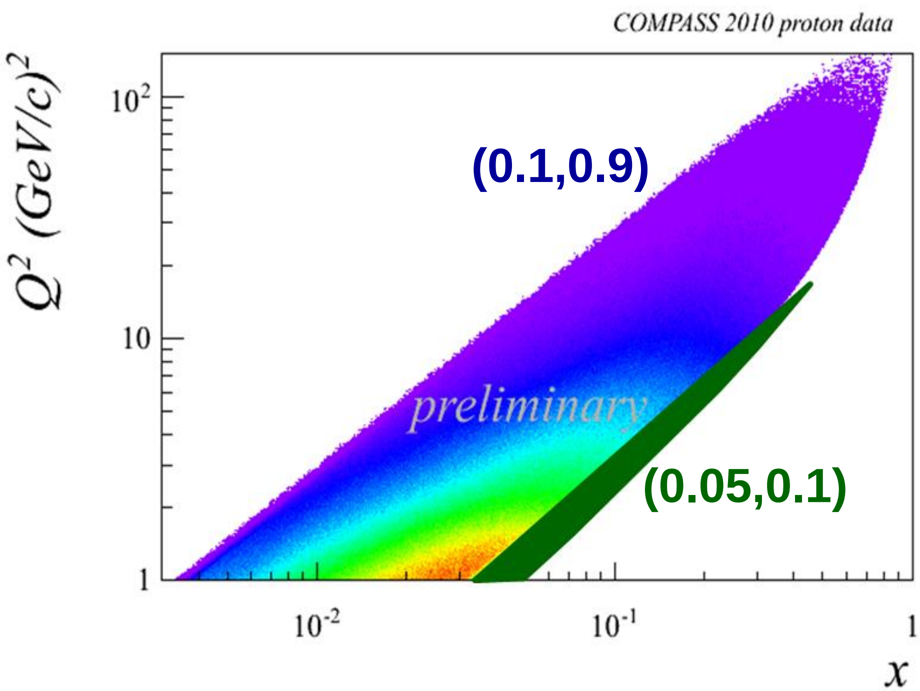


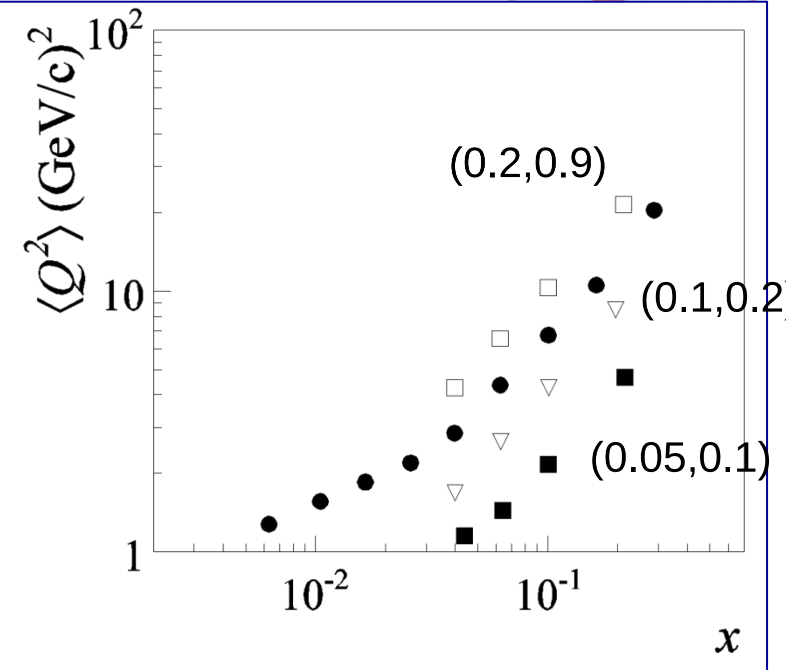
more on Collins and Sivers asymmetries

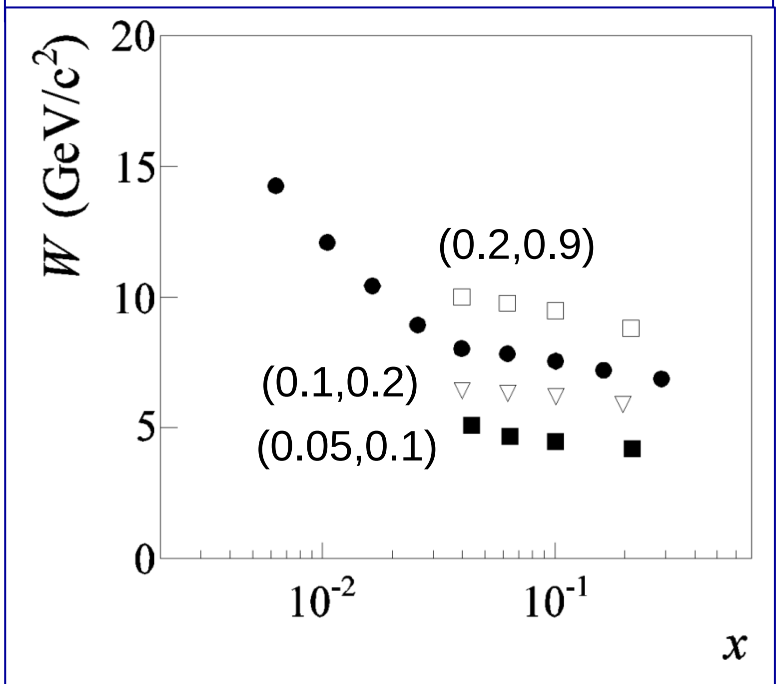
thanks to the high beam momentum,
we have enlarged the usual COMPASS phase
still remaining in the DIS CF regime

- **low z** → **(0.1,0.2)** (0.2,0.3) (0.3,1.0)
- **low y** → **(0.05,0.1)** (0.1,0.2) (0.2,0.9)

for charged and identified hadrons

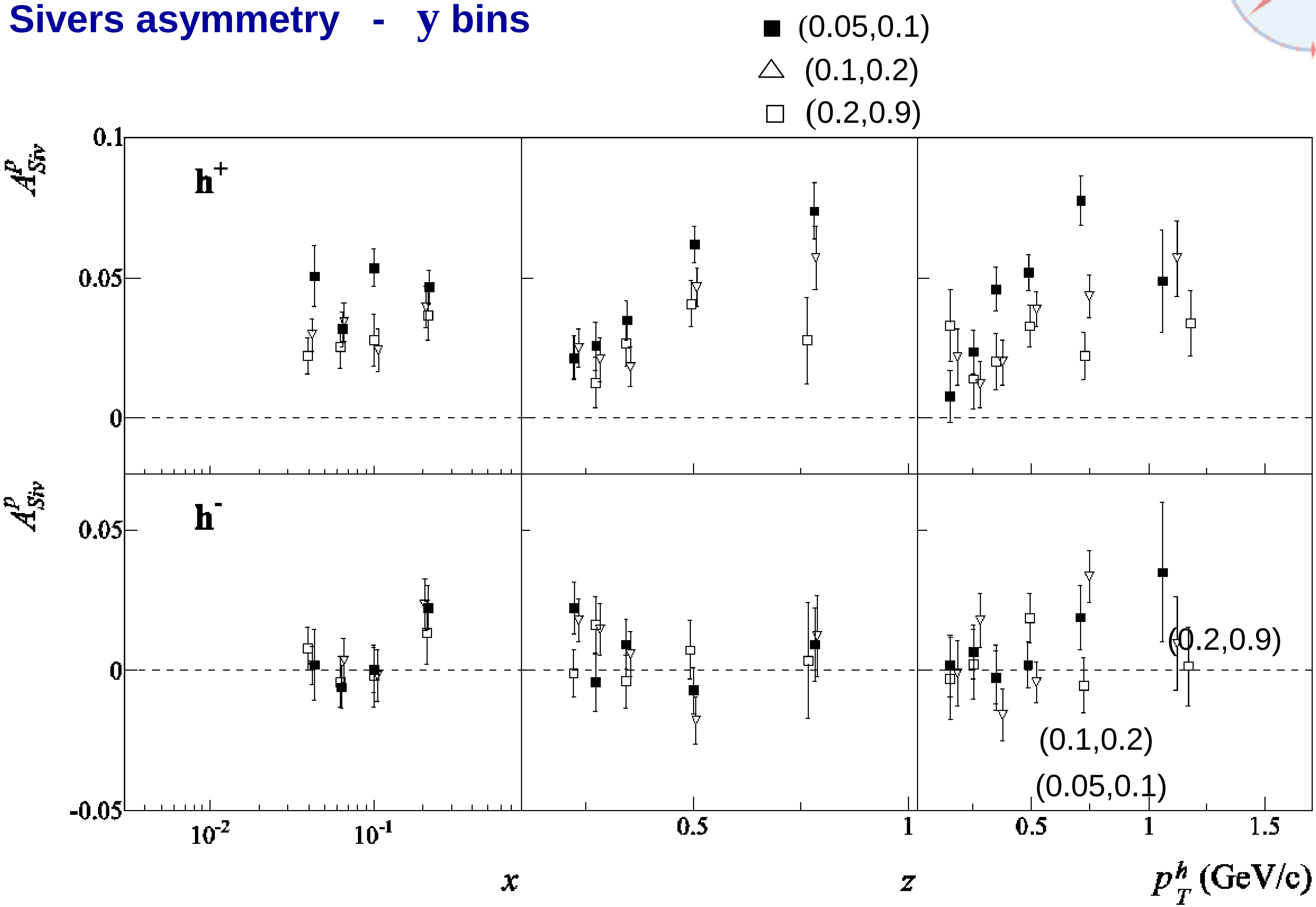






more on Collins and Sivers asymmetries

Sivers asymmetry - y bins



arXiv:1205.5121 / 2

conclusion

COMPASS
has produced results on the Collins and Sivers asymmtries
on d and on p
for charged and identified hadrons
using a 160 GeV muon beam

clear signals on p have been measured,
with interesting kinematical dependences

new inputs to study Q^2 evolution
for the extraction of transversity and Sivers PDFs

***next*: multidimensional analysis (x, Q^2, z, p_t) using p data**

on a longer time scale:
possible measurements with **transversely polarised p at 100 GeV**
to further investigate Q^2 evolution
possible measurements with **transversely polarised d**
to improve the extraction of u and d quarks PDFs
(EPSG)