



COMPASS measurements
of **Collins** and **Sivers**
asymmetries

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(on behalf of the COMPASS Collaboration)





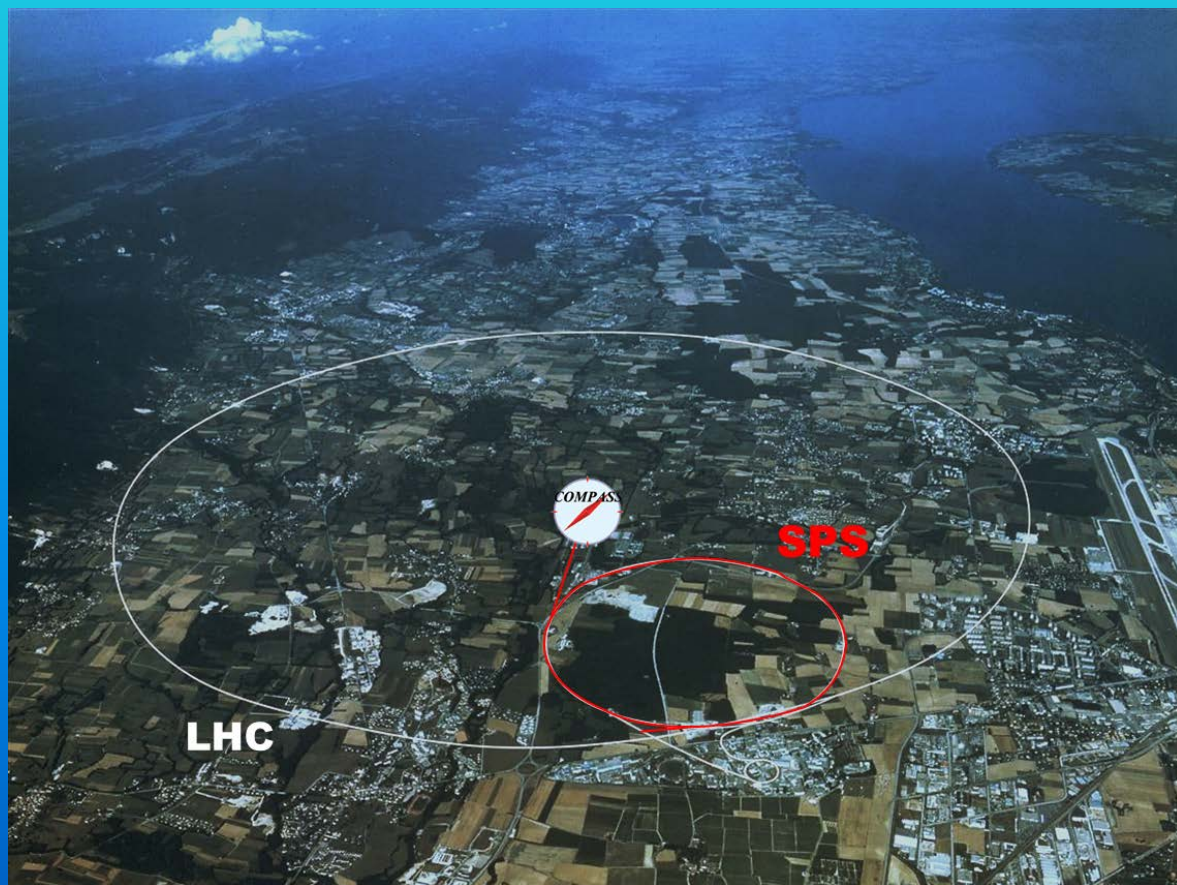
COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Collaboration

~ 250 physicists
from 24 Institutions
of 13 Countries

- fixed target
- experiment
- at the CERN SPS

data taking: since 2002





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physics programme:

hadron spectroscopy (p, π, K beams)

nucleon structure (with μ beam)

- longitudinal spin structure
- **transverse momentum and transverse spin structure**
 - results on the **Collins and Sivers transverse spin asymmetries in SIDIS**

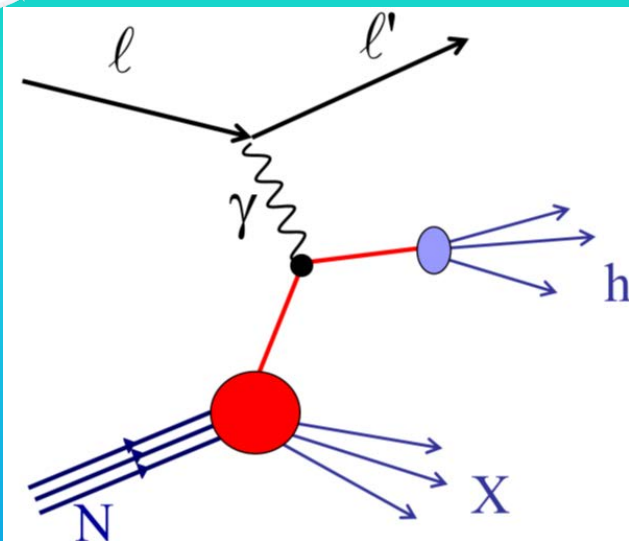


COMPASS data taking

muon beam	deuteron (${}^6\text{LiD}$) polarised target	2002 2003 2004	L/T target polarisation
		2006	L target polarisation
	proton (NH_3) polarised target	2007	L/T target polarisation
hadron	LH target	2008 2009	
muon beam	proton (NH_3) polarised target	2010	T target polarisation
		2011	L target polarisation
Hadron	Ni target	2012	
muon beam	LH2 target	2012	Pilot DVCS & unpol. SIDIS
<p>muon beam: 160 GeV/c longitudinal polarisation -80% intensity $2 \cdot 10^8 \mu^+/\text{spill}$ (4.8s/16.2s)</p>			



Semi-Inclusive Deep Inelastic Scattering



$$x = \frac{Q^2}{2P \cdot q}$$

$$Q^2 = -q^2$$

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

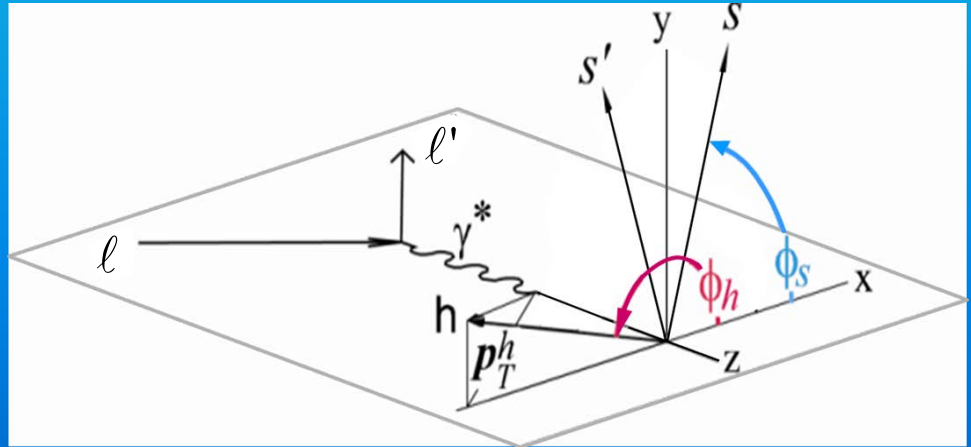
$$W^2 = (P + q)^2$$

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

p_T^h

ϕ_h

ϕ_S





Semi-Inclusive Deep Inelastic Scattering

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

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

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

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

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

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

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

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

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

Sivers asymmetry

$\sin(\phi_h - \phi_S)$

$\sin(\phi_h + \phi_S)$

Collins asymmetry

18 structure functions

14 independent azimuthal modulations

all the 14 amplitudes are been measured in COMPASS



SIDIS off transversely polarised nucleons

azimuthal distribution of the inclusively produced hadrons

$$N_h^\pm(\phi_h, \phi_S) = N_h^0(\phi_h) \left[1 \pm P_T D_{NN} A_{Coll} \sin(\phi_h + \phi_S + \pi) \pm P_T A_{Siv} \sin(\phi_h - \phi_S) \pm \dots \right]$$

polarisation direction

nucleon transverse polarisation

spin transfer coefficient

Collins angle

Sivers angle



A_{Coll} and A_{Siv} and the other 6 transverse spin asymmetries are measured by fitting the (ϕ_h, ϕ_S) distributions in the different x, z, p_T^h bins



SIDIS off transversely polarised nucleons

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$$A_{Coll} \approx \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 f_1^q \otimes D_{1q}^h}$$

Collins FF

BELLE, BaBar

transversity PDF

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

quark structure of the nucleon in the collinear case

		nucleon polarisation		
		U	L	T
quark polarisation	U	f_1 number density \mathbf{q}		
	L		g_1 helicity $\Delta\mathbf{q}$	
	T			h_1 transversity $\Delta_T\mathbf{q}$

it is chiral odd



SIDIS off transversely polarised nucleons

azimuthal distribution of the inclusively produced hadrons

$$N_h^\pm(\phi_h, \phi_S) = N_h^0(\phi_h) \left[1 \pm P_T D_{NN} A_{Coll} \sin(\phi_h + \phi_S + \pi) \pm P_T A_{Siv} \sin(\phi_h - \phi_S) \pm \dots \right]$$

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

Sivers PDF

correlation between the transverse spin of the nucleon and the transverse momentum of the quark sensitive to orbital angular momentum

the quark structure of the nucleon at LO with quark intrinsic transverse momentum k_T

		nucleon polarisation			
		U	L	T	
quark polarisation	U	f_1 number density \mathbf{q}		f_{1T}^\perp - Sivers	$\Delta_0^T \mathbf{q}$
	L		g_1 - helicity $\Delta \mathbf{q}$	g_{1T} -	
	T	h_1^\perp - Boer Mulders	h_{1L}^\perp -	h_1 - transversity h_{1T}^\perp -	$\Delta_T \mathbf{q}$

T-odd



SIDIS off transversely polarised nucleons

azimuthal distribution of the inclusively produced hadrons

$$N_h^\pm(\phi_h, \phi_S) = N_h^0(\phi_h) \left[1 \pm P_T D_{NN} A_{Coll} \sin(\phi_h + \phi_S + \pi) \pm P_T A_{Siv} \sin(\phi_h - \phi_S) \pm \dots \right]$$

transversity PDF

$$A_{Coll} \approx \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 f_1^q \otimes D_{1q}^h}$$

and 2h transverse spin asymmetry

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 most promising experimental way to access the transversity PDFs and the Sivers PDFs

different targets and PID
→ flavor separation

COMPASS

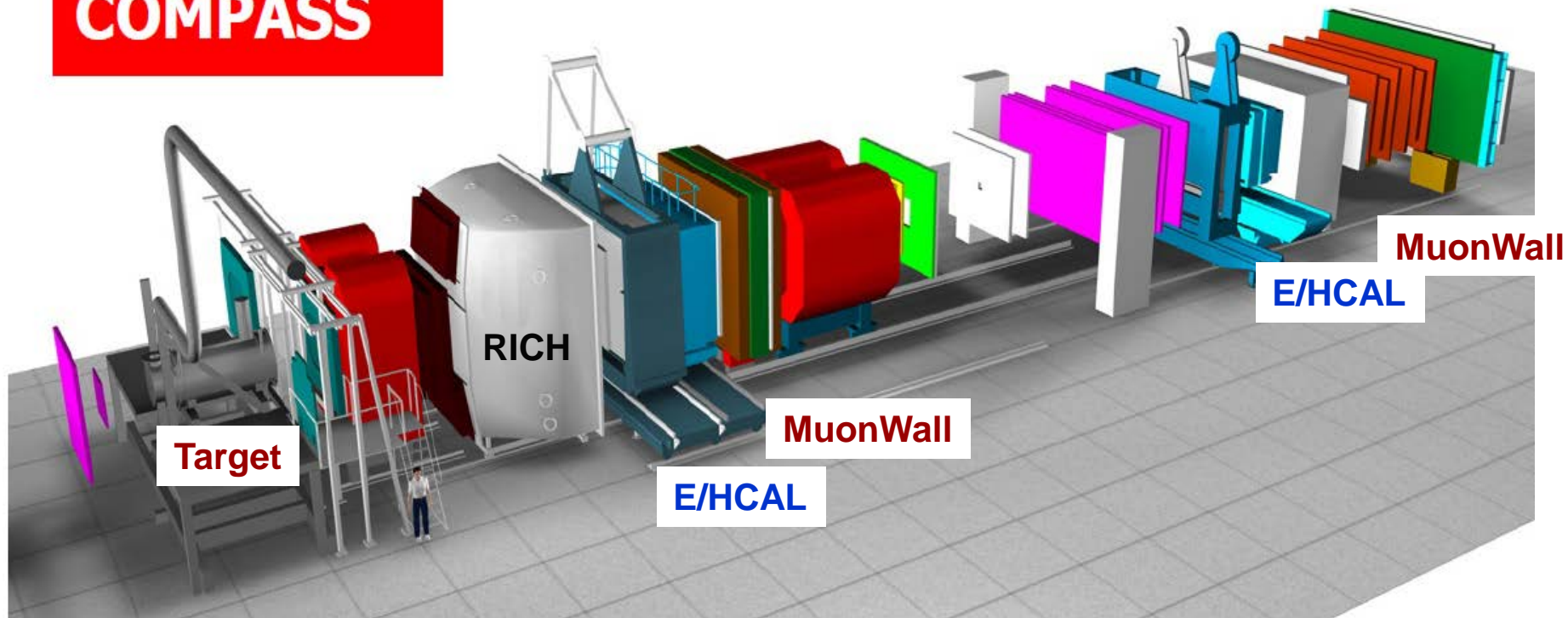
- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

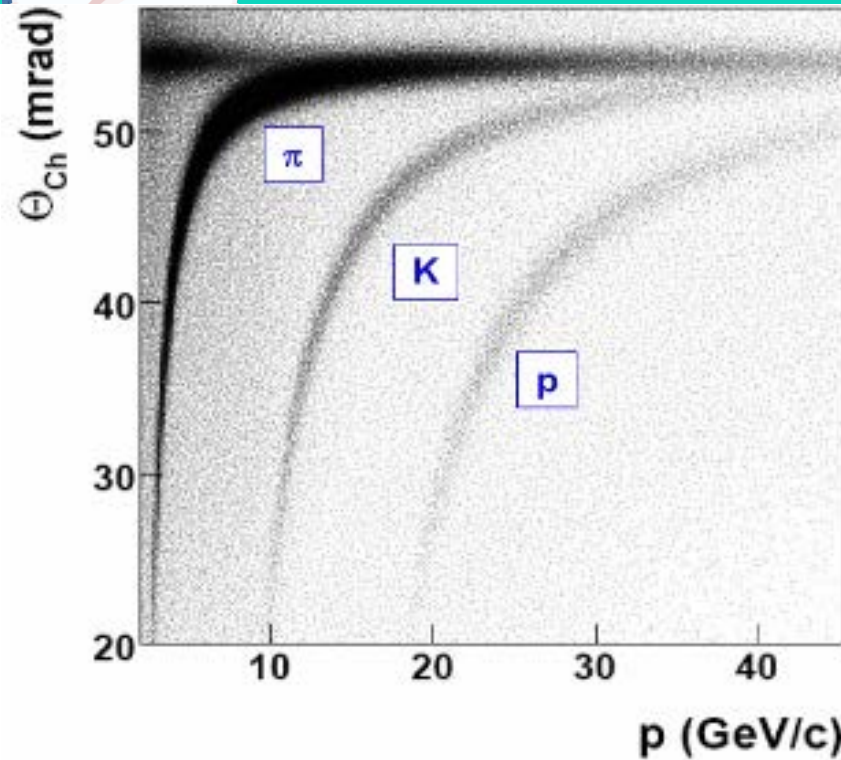
COMPASS



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

SciFi *Straws*
Silicon *DC*
Micromegas *MWPC*
GEMs

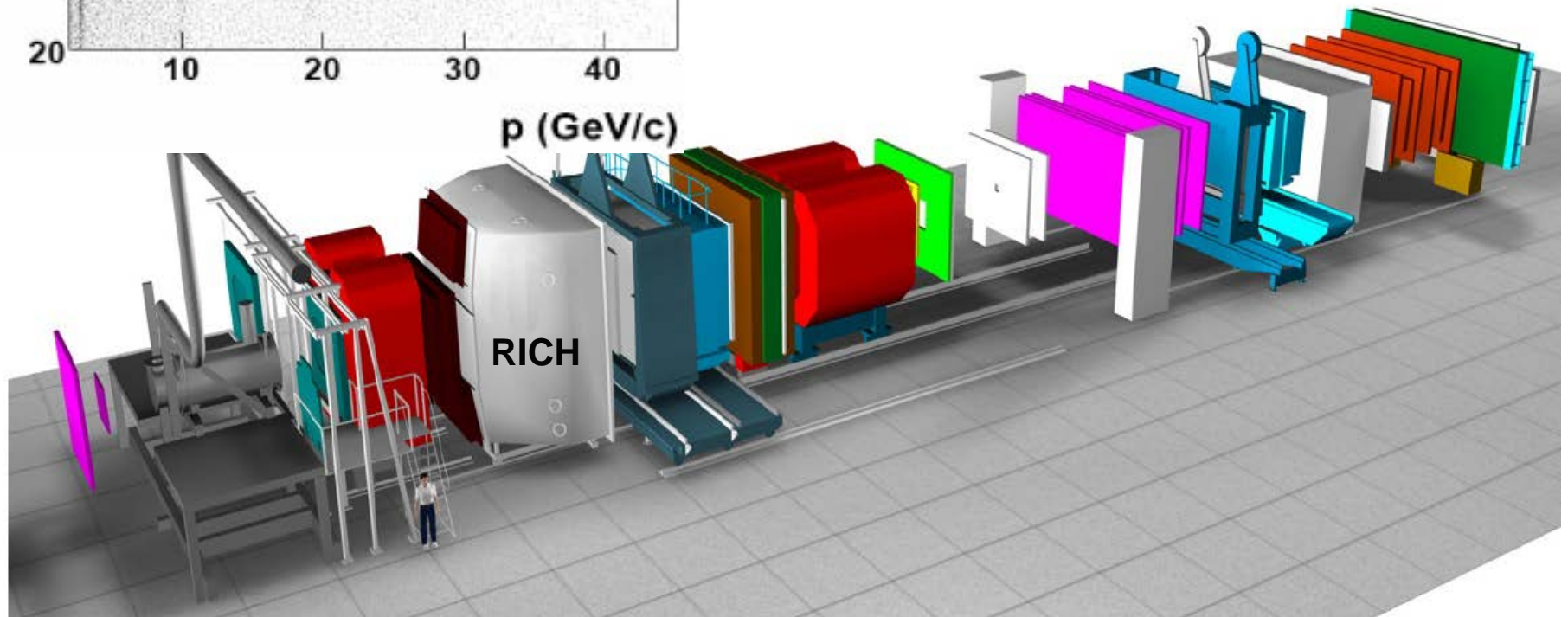
COMPASS



radiator C_4F_{10}

threshold: $\pi \sim 2 \text{ GeV/c}$

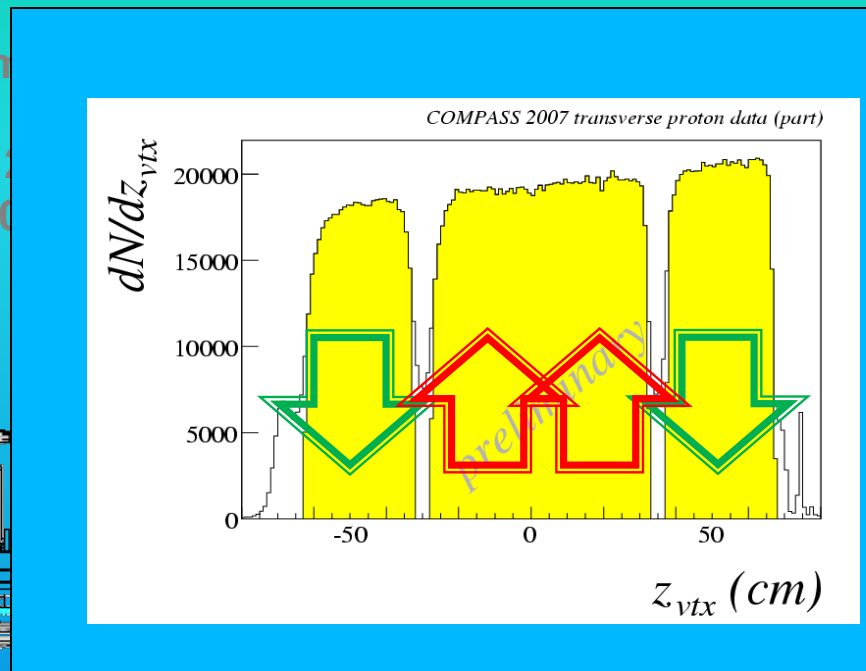
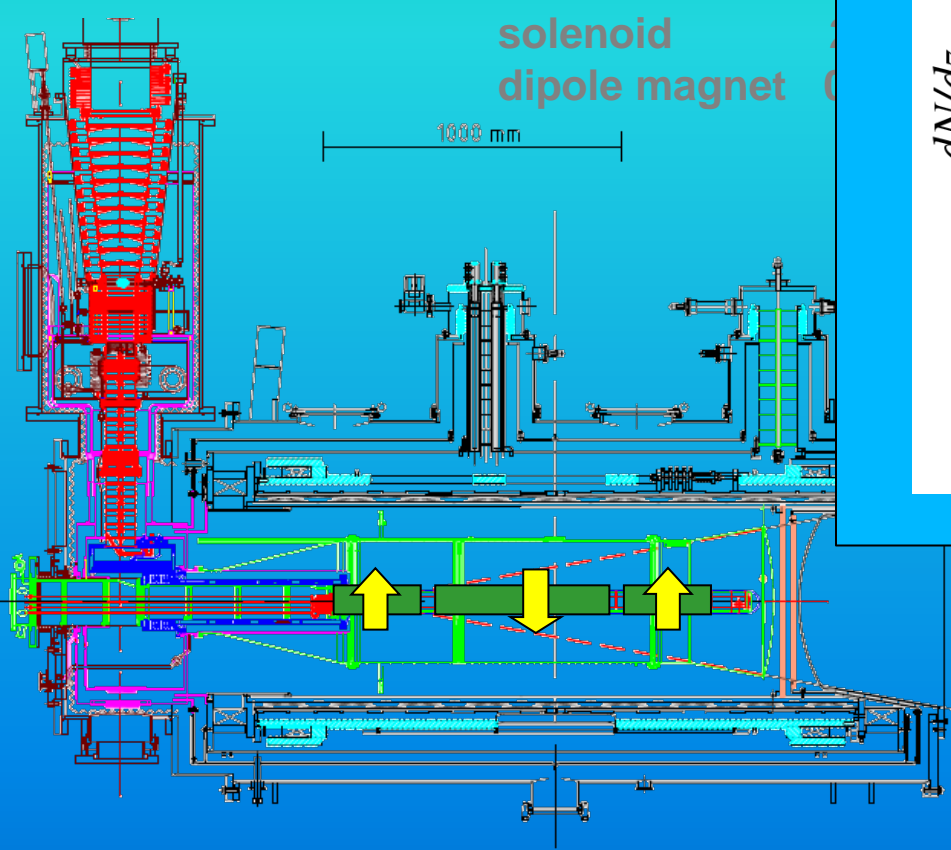
$K \sim 10 \text{ GeV/c}$





the polarized target system (>2005)

$^3\text{He} - ^4\text{He}$ dilution refrigerator (T~50mK)



opposite polarisation

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

no evidence for relevant nuclear effects (160 GeV)



SIDIS event and hadron selection

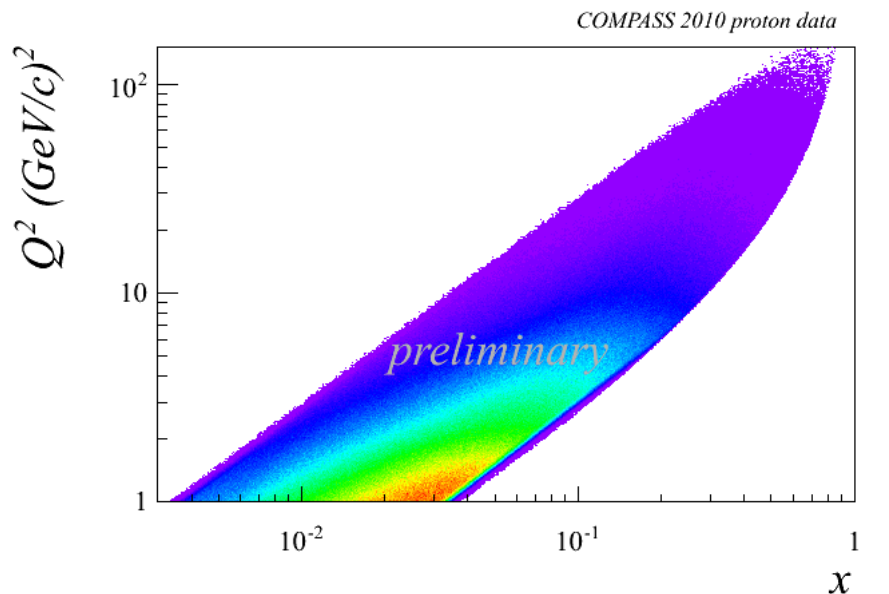
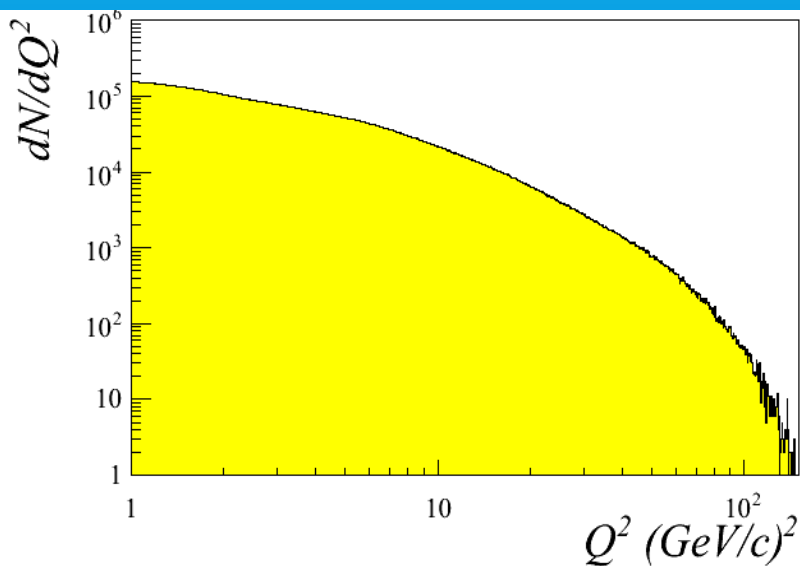
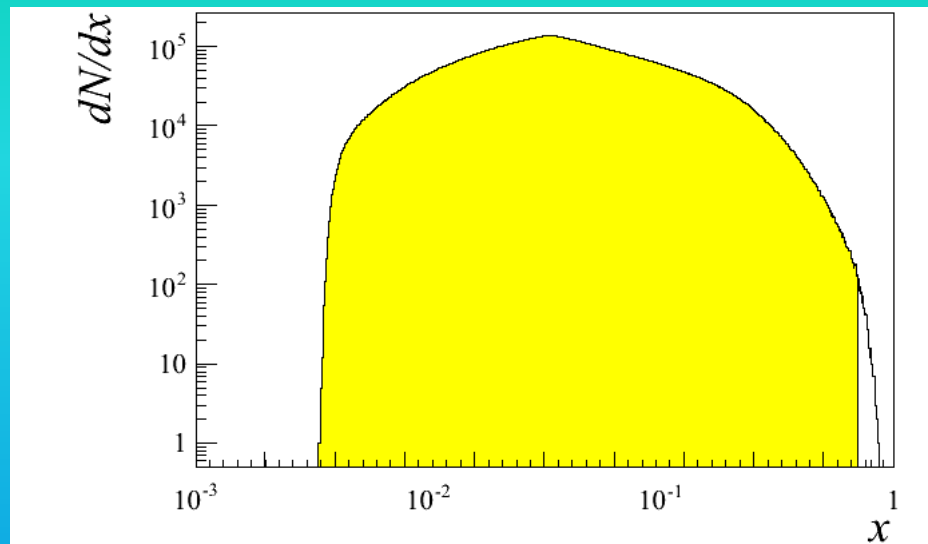


SIDIS event selection

$p_\mu = 160 \text{ GeV}/c$

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

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





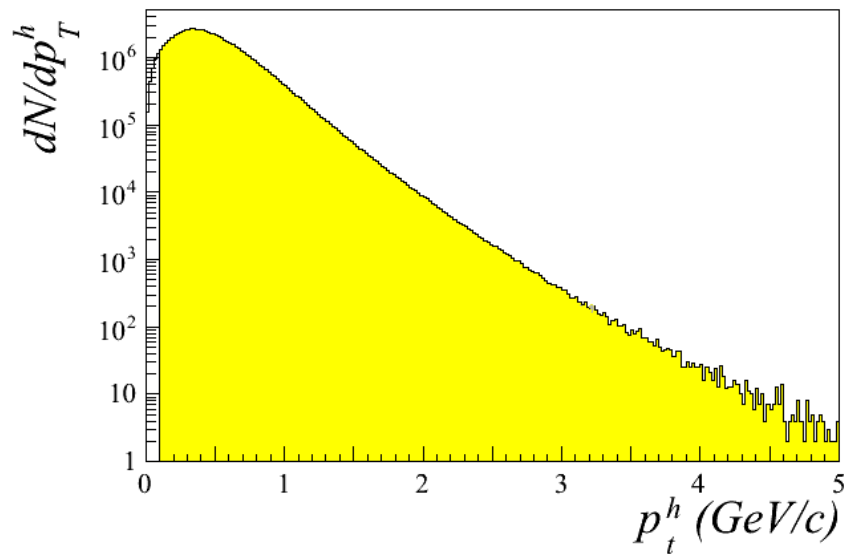
SIDIS event selection

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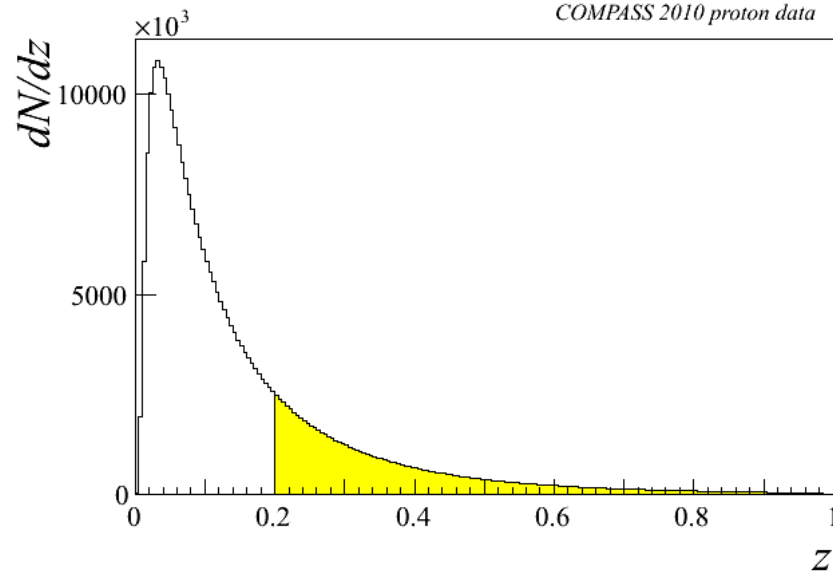
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COMPASS 2010 proton data



COMPASS 2010 proton data





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PID: π^{\pm} $1.5 < p^{\pi} < 50 \text{ GeV}/c$
 K^{\pm} $9.5 < p^K < 50 \text{ GeV}/c$



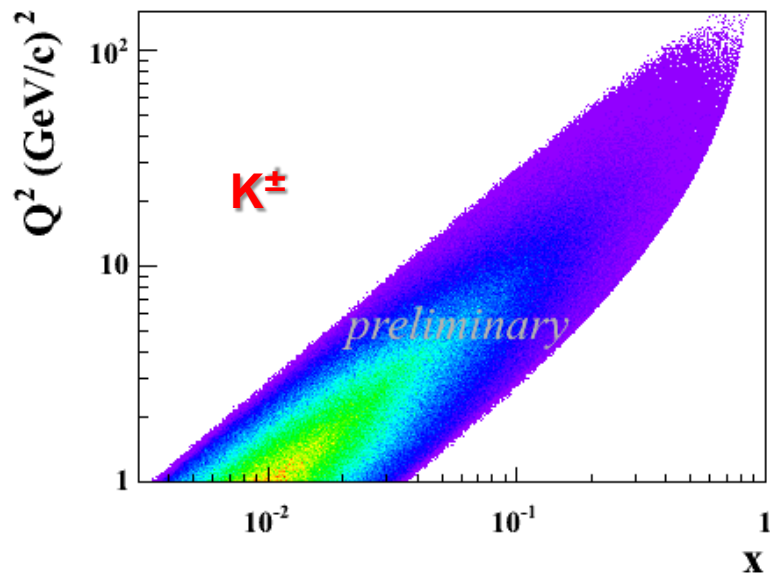
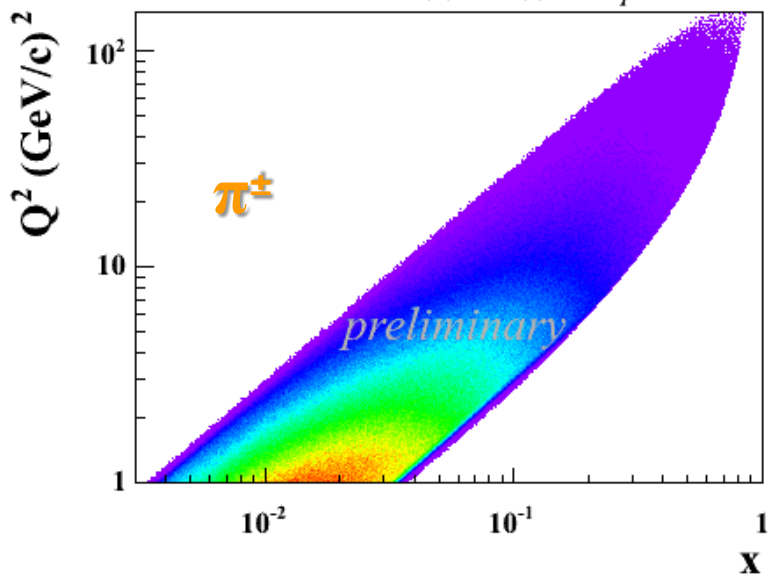
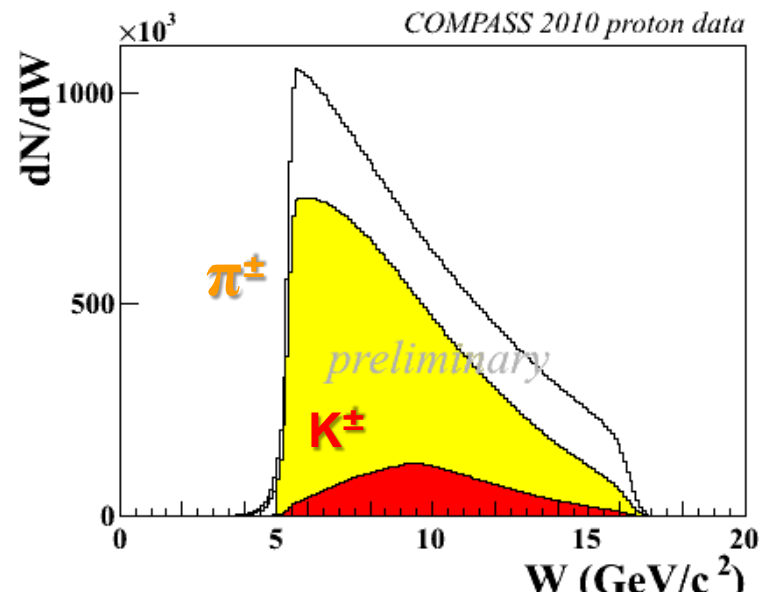
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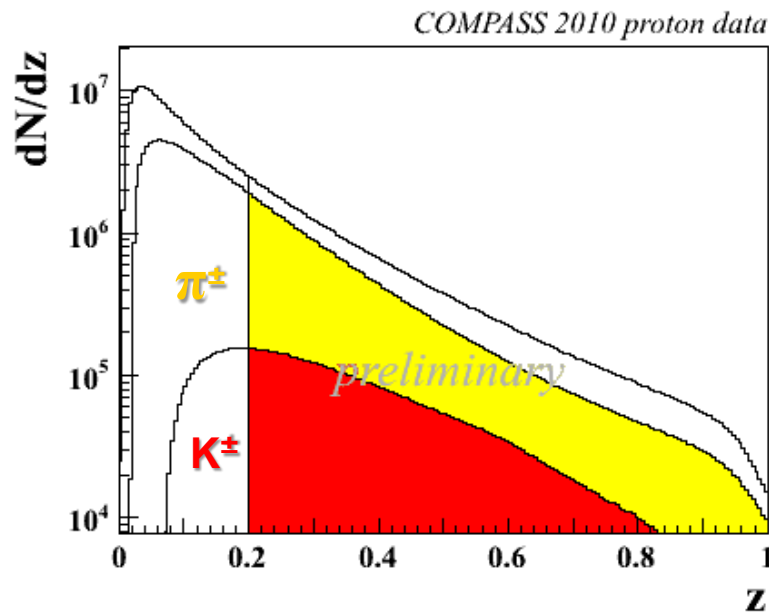
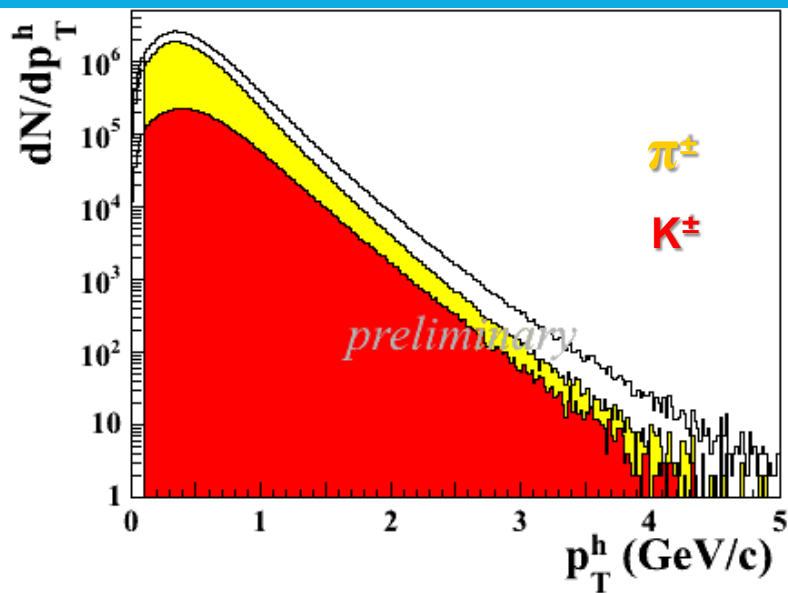
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results

Collins asymmetry



Collins asymmetry

data taken with transversely polarised targets

deuteron (${}^6\text{LiD}$) target, 160 GeV μ beam

2002, 2003, 2004

proton (NH_3) target, 160 GeV μ beam

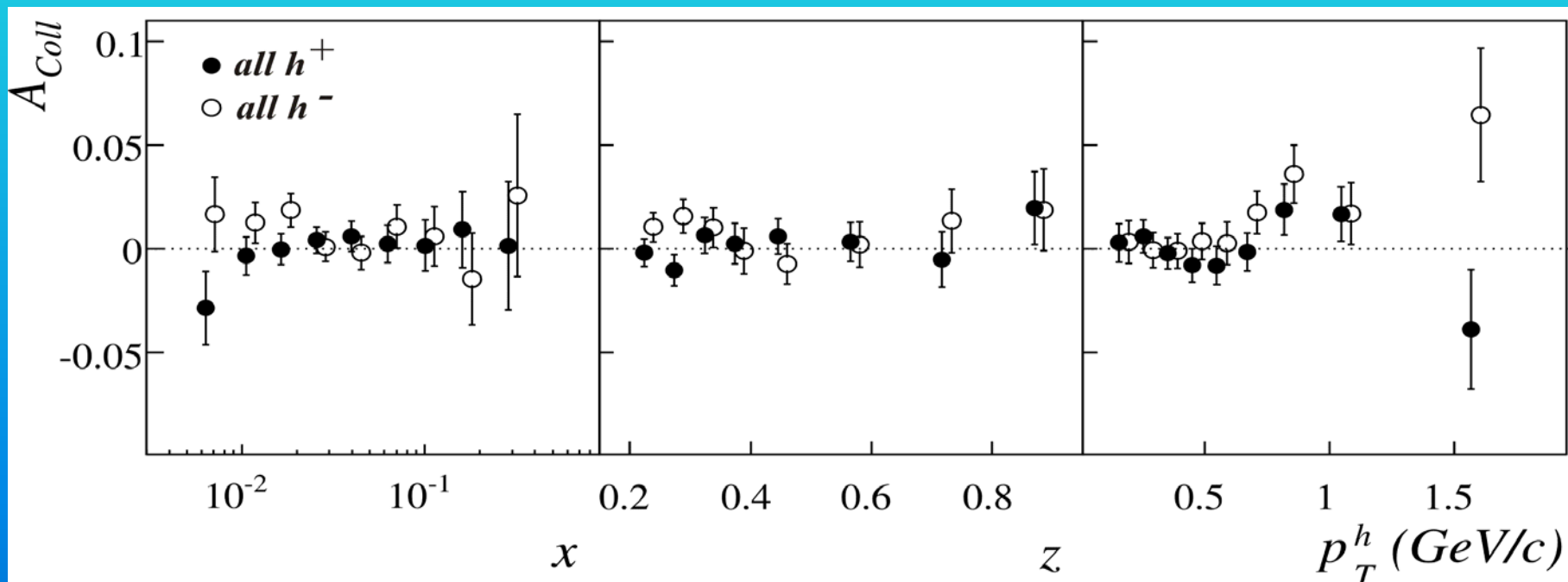
2007, 2010



Collins asymmetry on deuteron

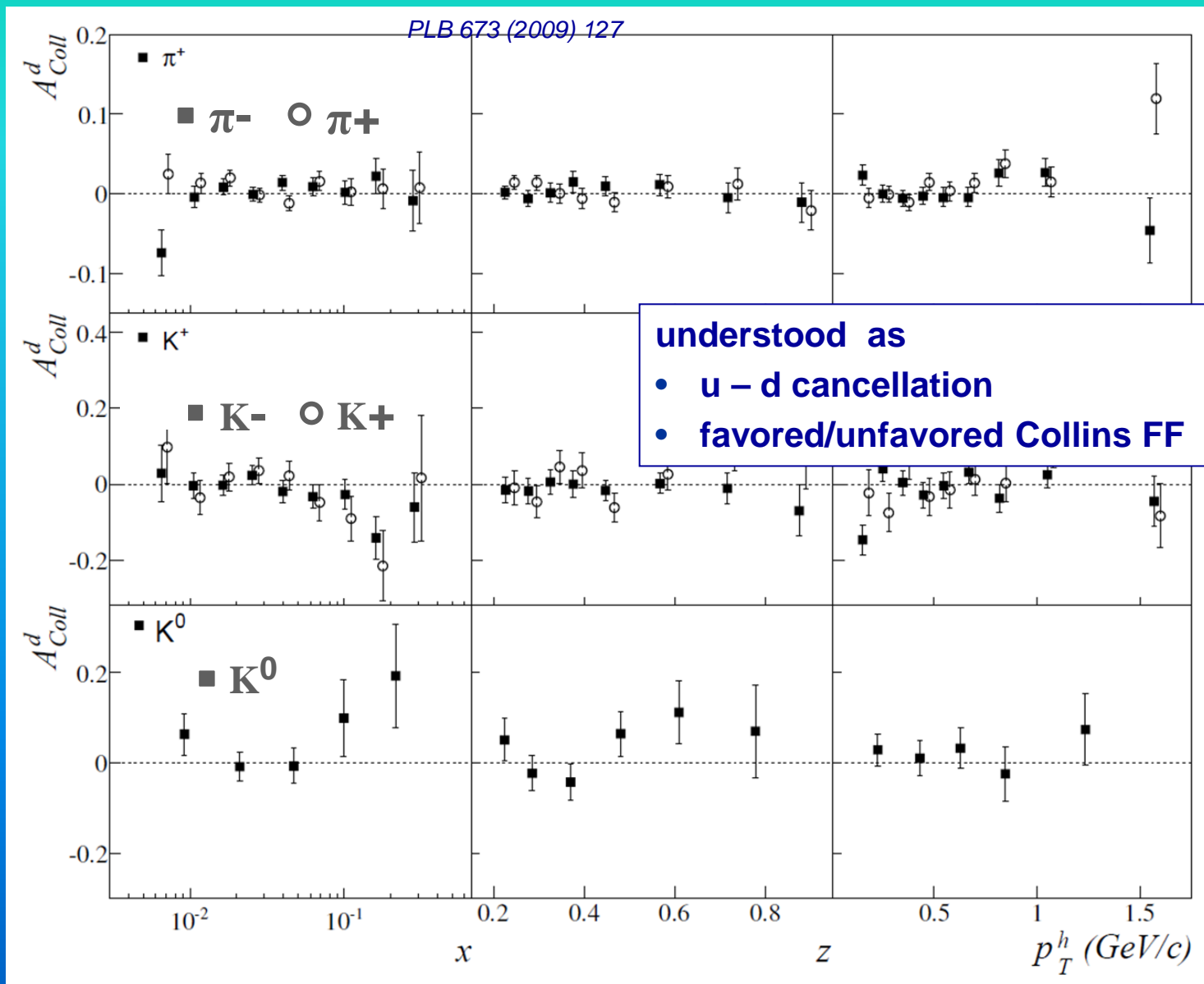
final results 2002-2004 data

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



Collins asymmetry on deuteron

final results 2003-2004 data





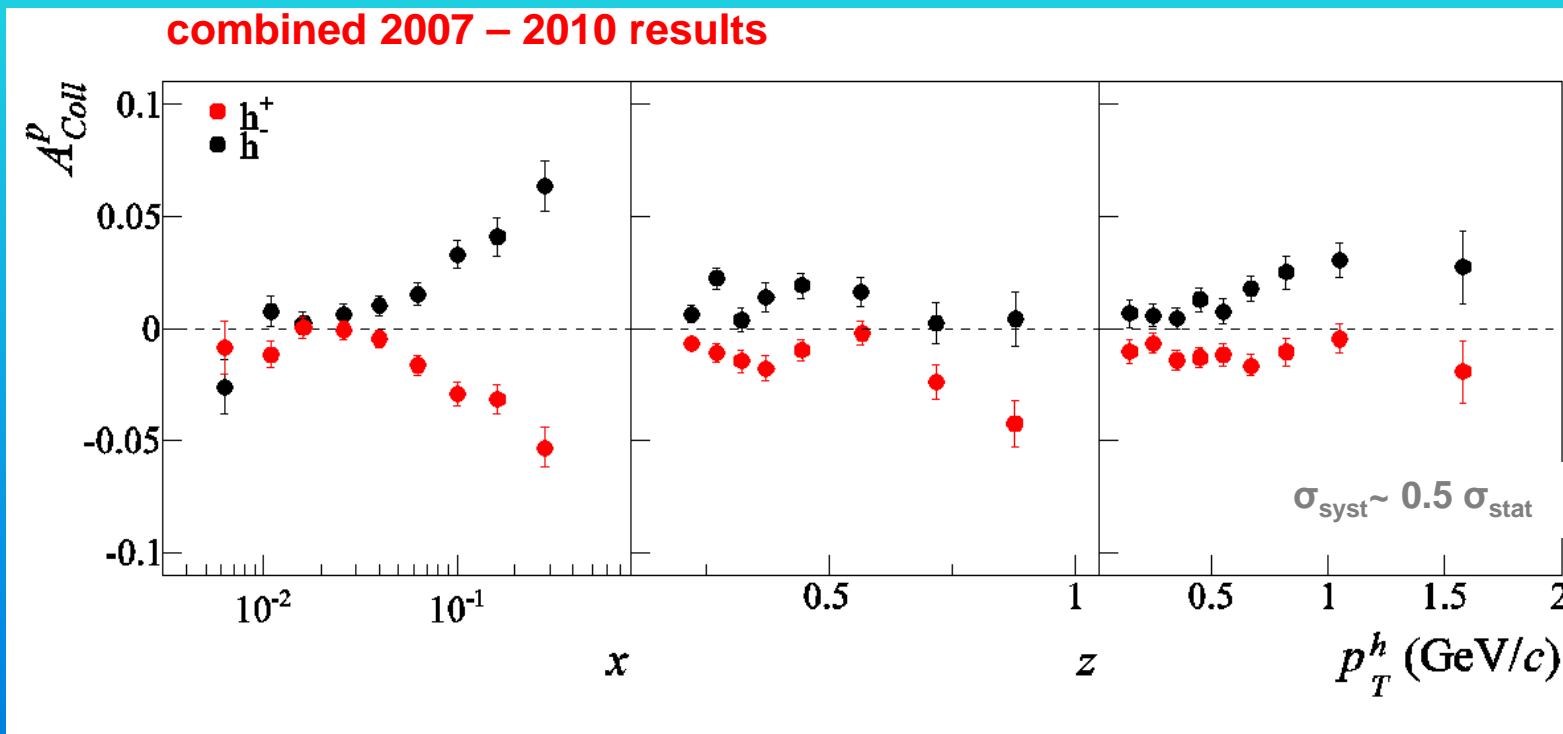
Collins asymmetry on proton



Collins asymmetry on proton

charged hadrons - published 2007 & 2010 data results

PLB 692 (2010) 240 PLB 717 (2012) 376



- precise measurements
- clear signal at $x > 0.3$, with opposite sign for h^+ and h^-

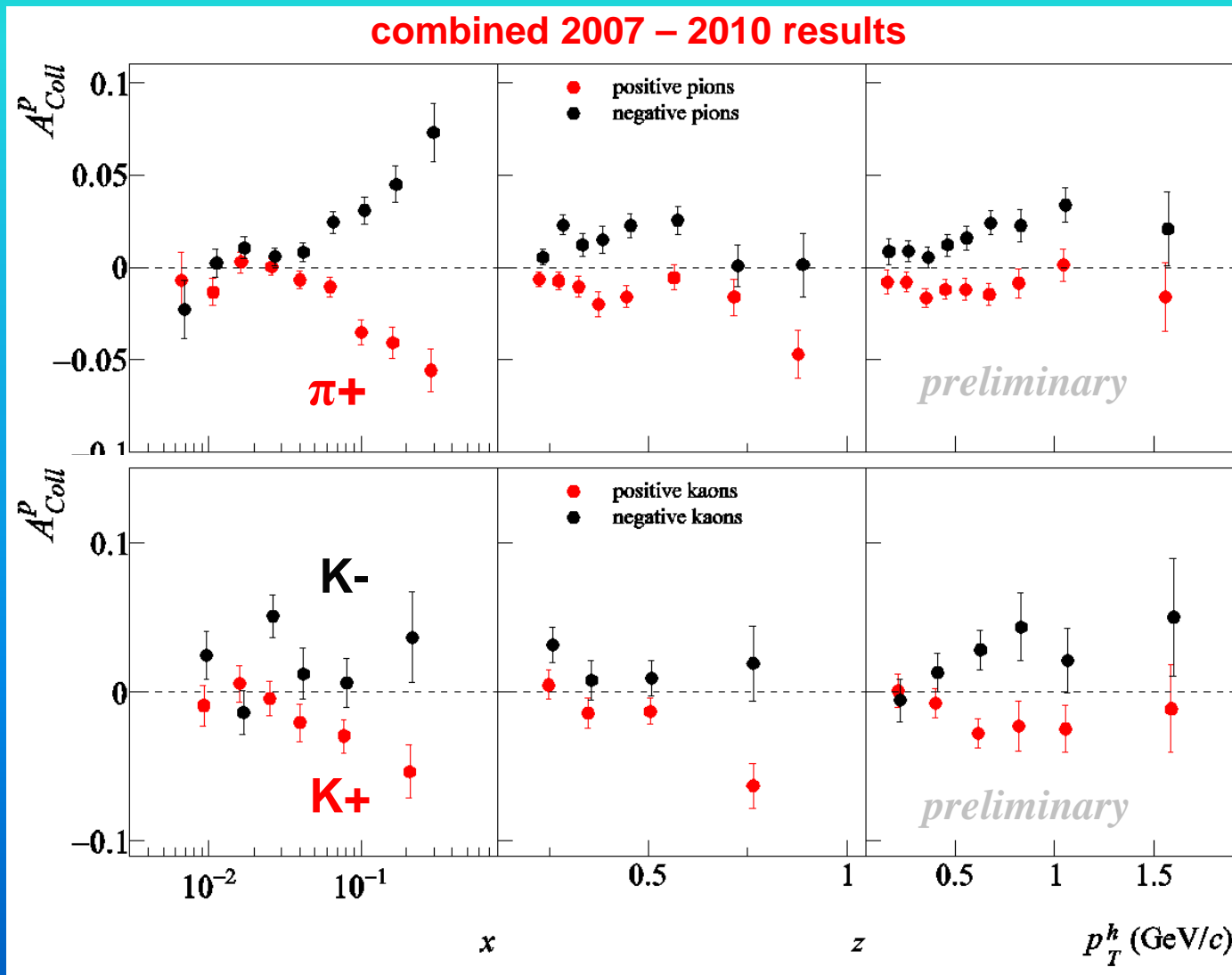


Collins asymmetry on proton

charged pions and kaons

results from 2007 (SPIN2010) and 2010 (SPIN2012) data

Palace Hotel, Como - 10/14
Structure of Nucleons and Nuclei



~ h+ / h-

compatible with π^+ / π^-

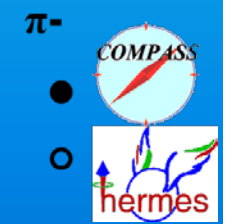
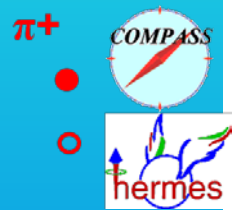
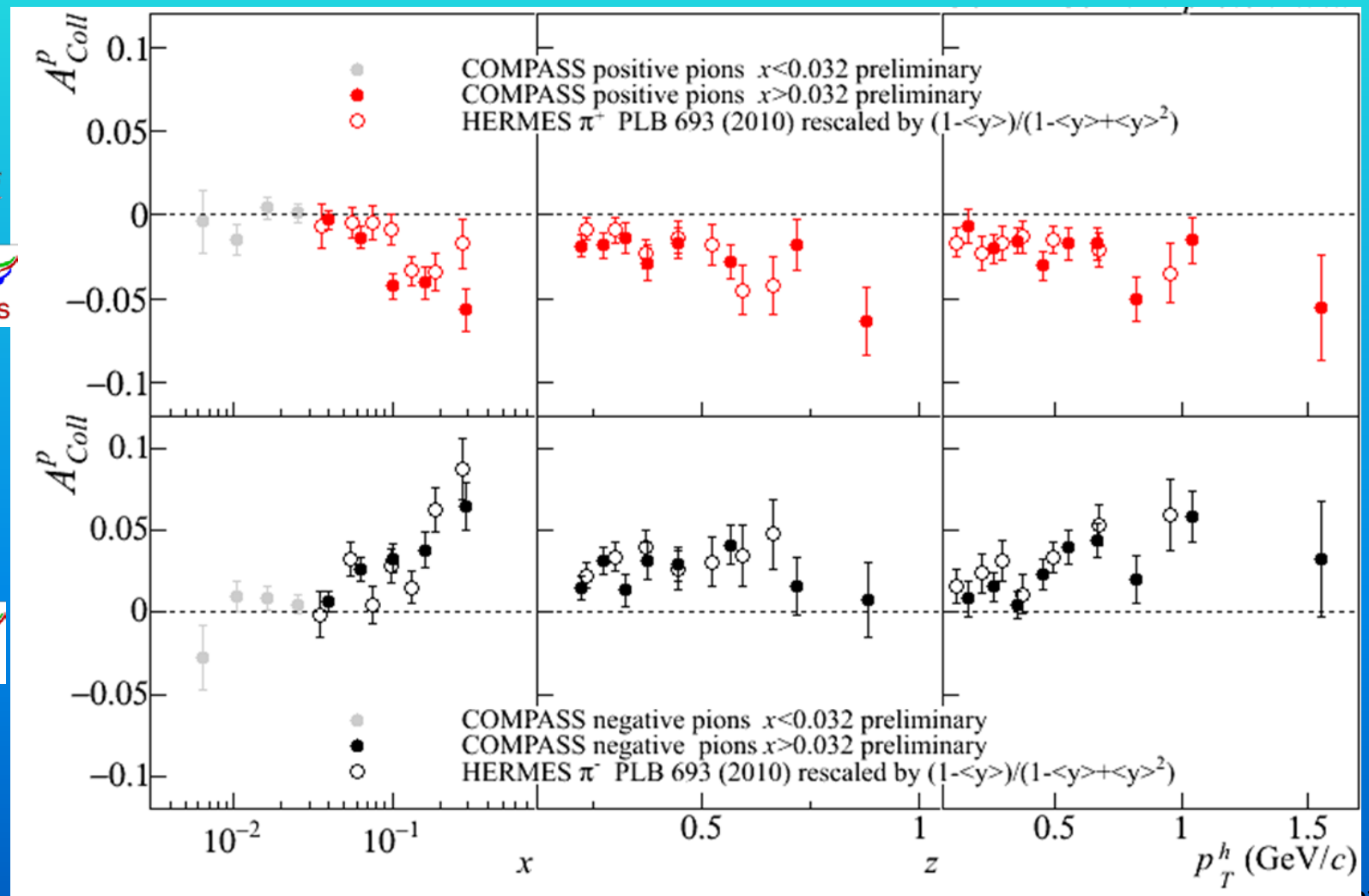


Collins asymmetry on proton

$x > 0.032$ region

charged pions (and kaons), 2010 data

comparison with HERMES results

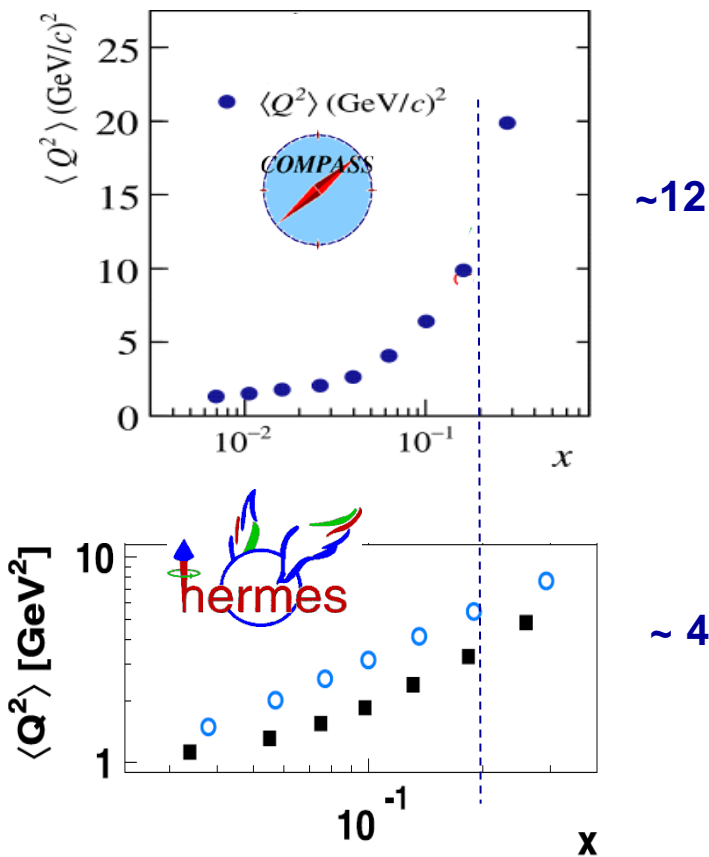




Collins asymmetry on proton

$x > 0.032$ region

same strength:
a very important, not obvious result!



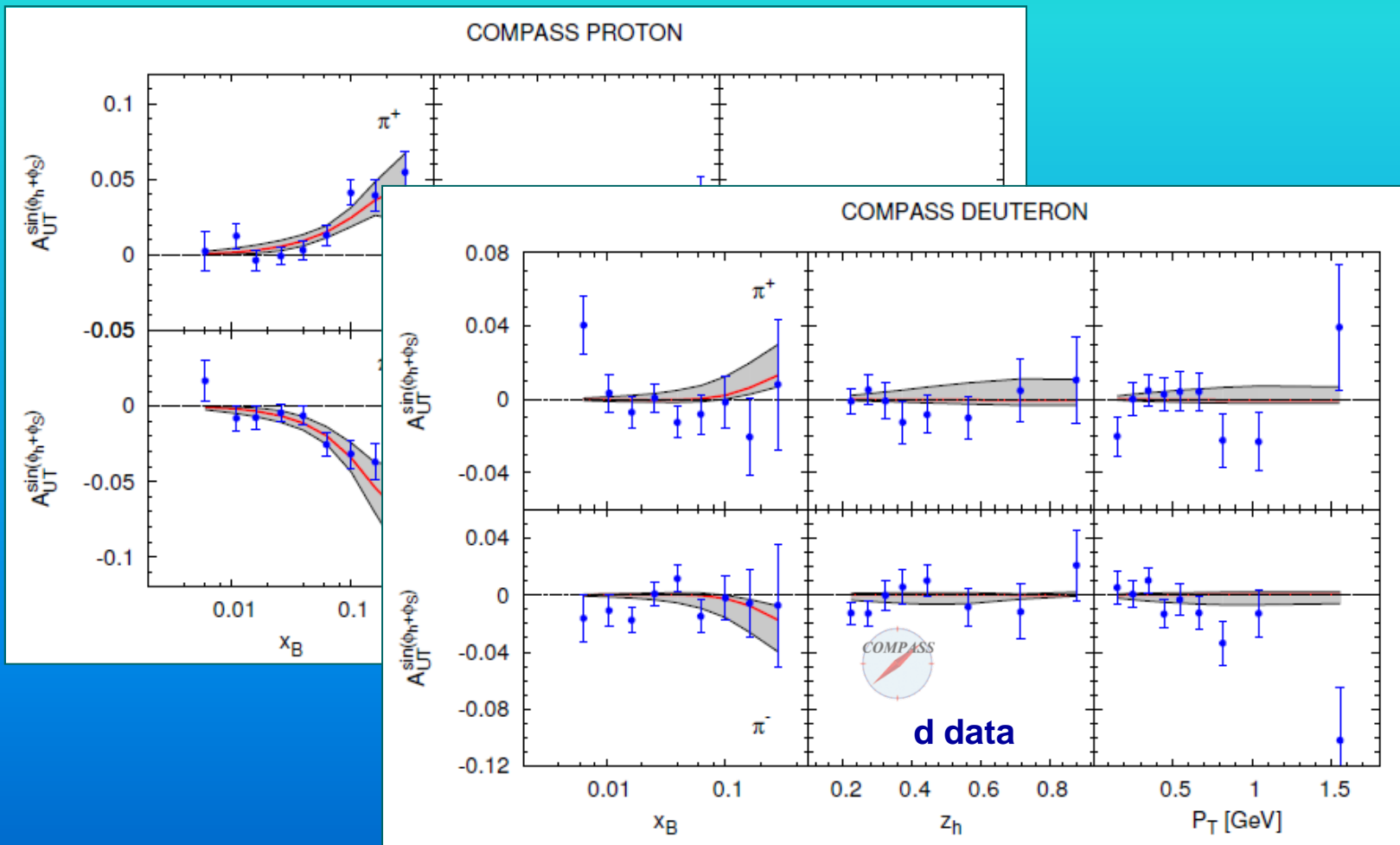
no strong Q^2 dependence



Collins asymmetry on proton

M. Anselmino et al., arXiv:1303.3822

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

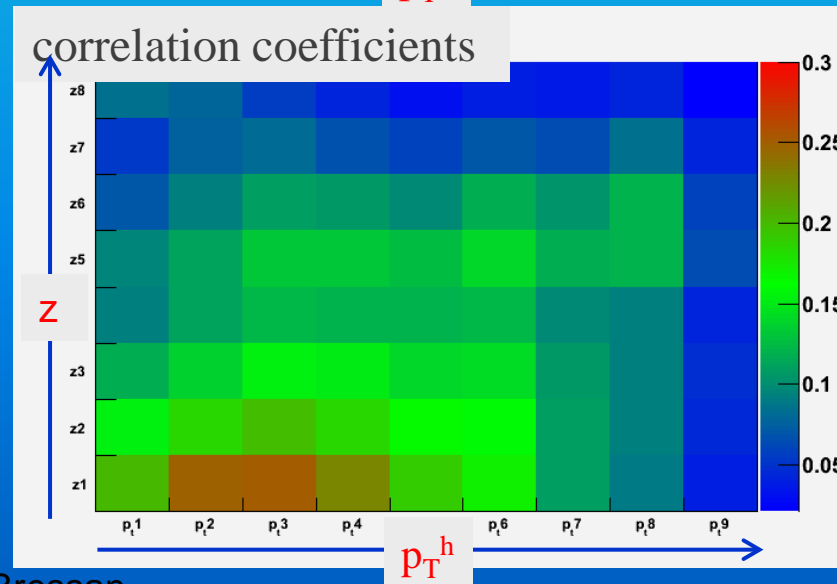
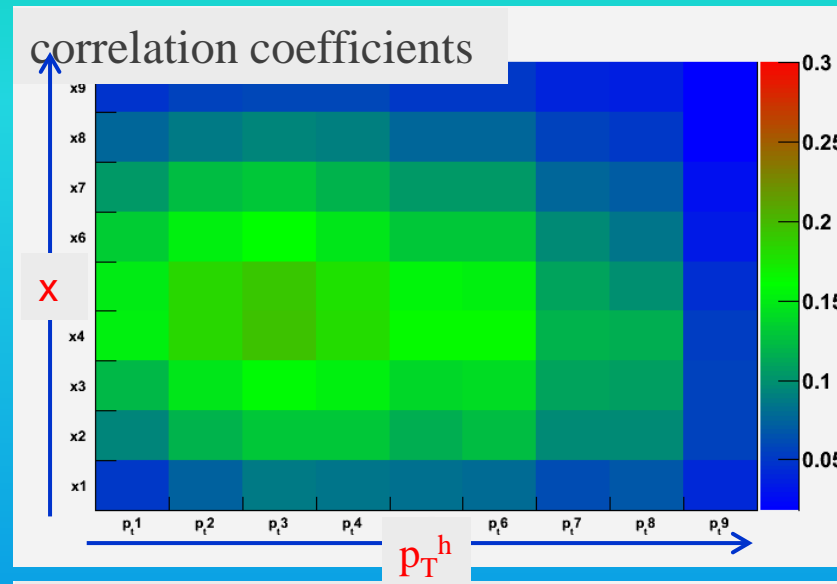
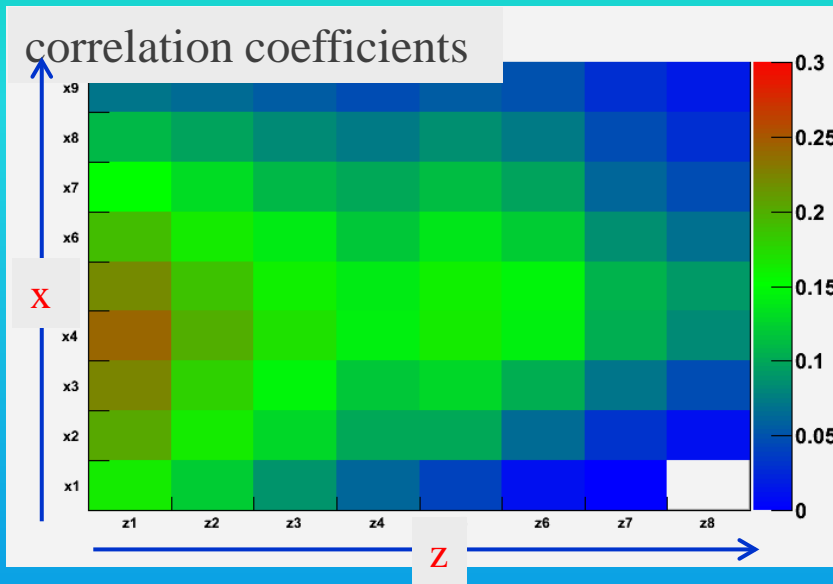




statistical correlations 2010 data

Collins (Sivers, ...) asymmetries measured vs x , z , p_T^h

Palace Hotel, Como - 10/14
Structure of Nucleons and Nuclei



charged pions

new

also available for

charged hadrons (HEPDATA)

charged kaons

new

for all data selection

have to be taken into account



results

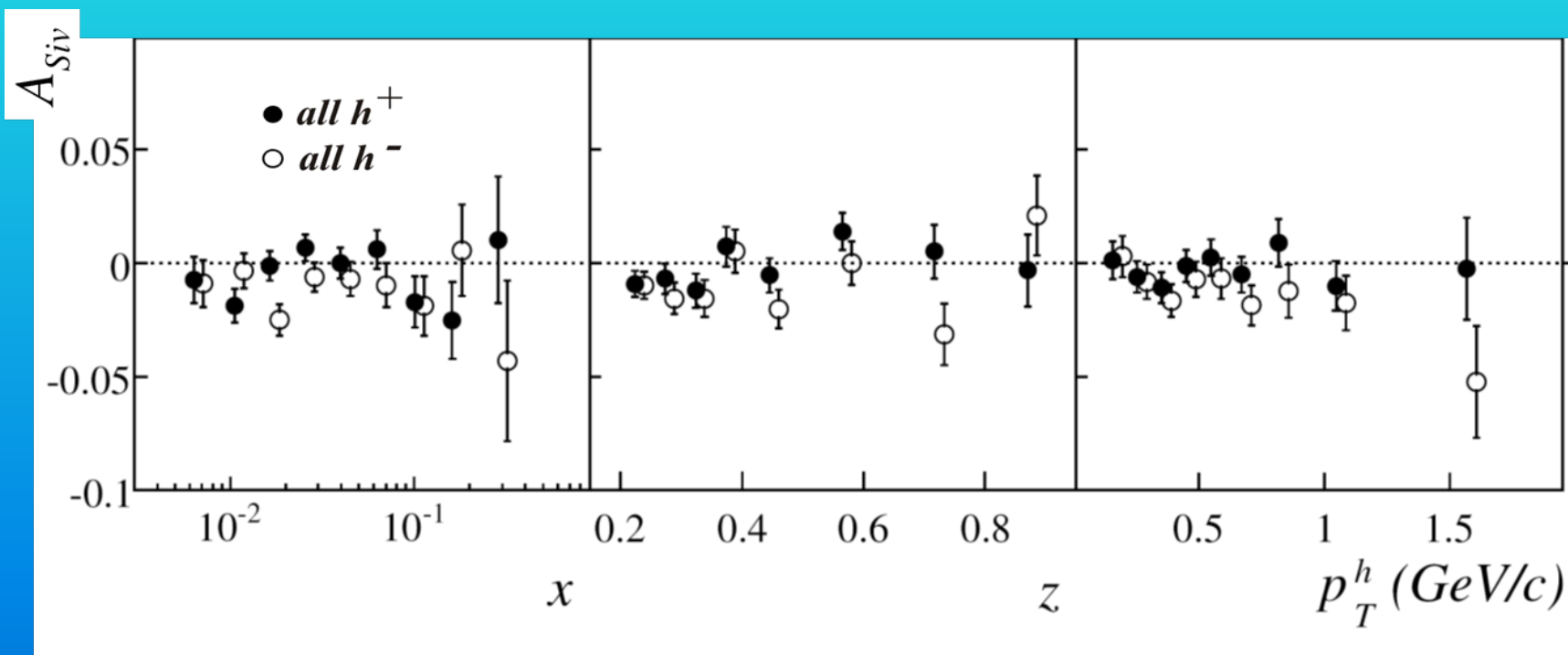
Sivers asymmetry



Sivers asymmetry on deuteron

final results 2002-2004 data

PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127

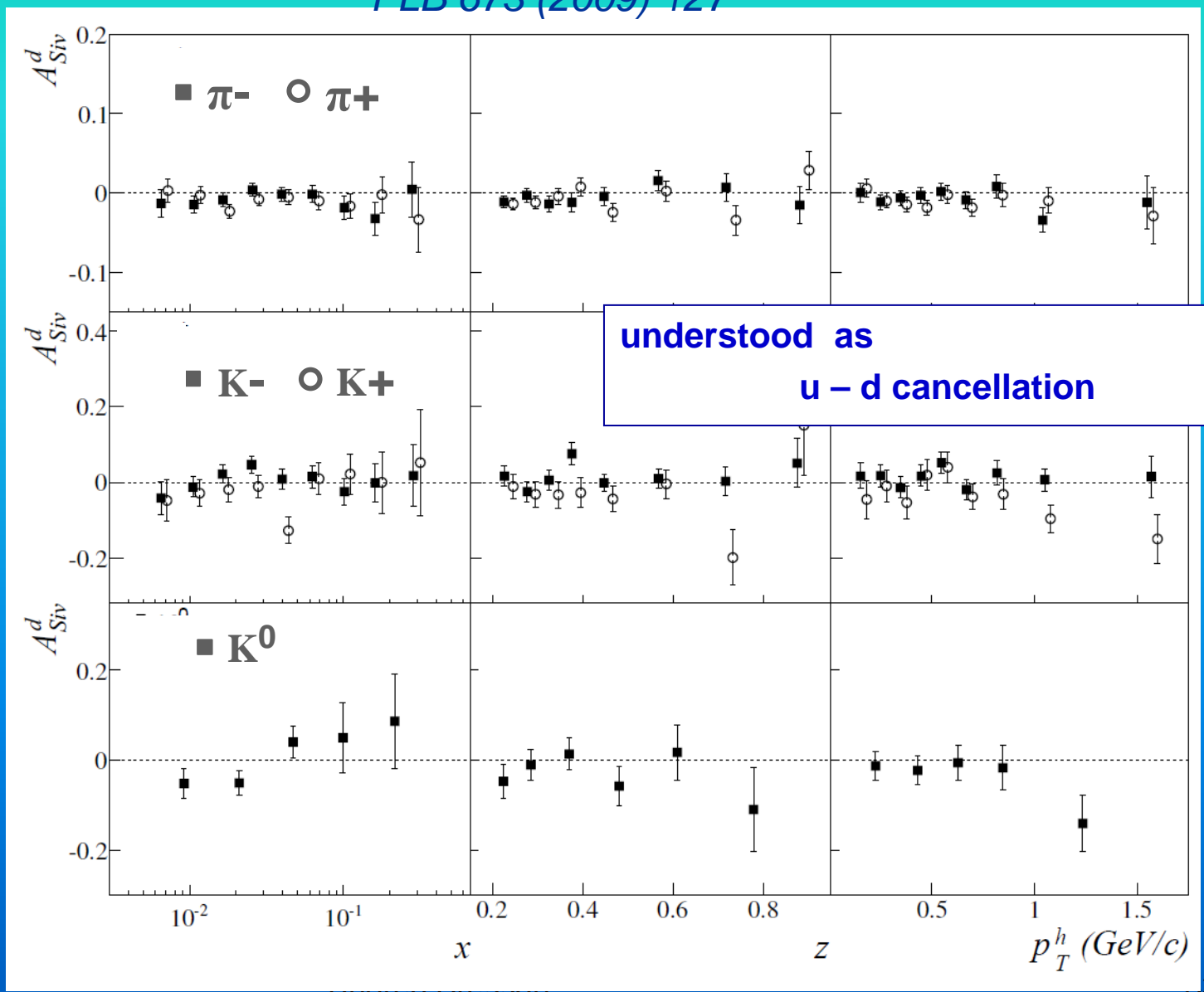




Sivers asymmetry on deuteron

final results 2003-2004 data

PLB 673 (2009) 127

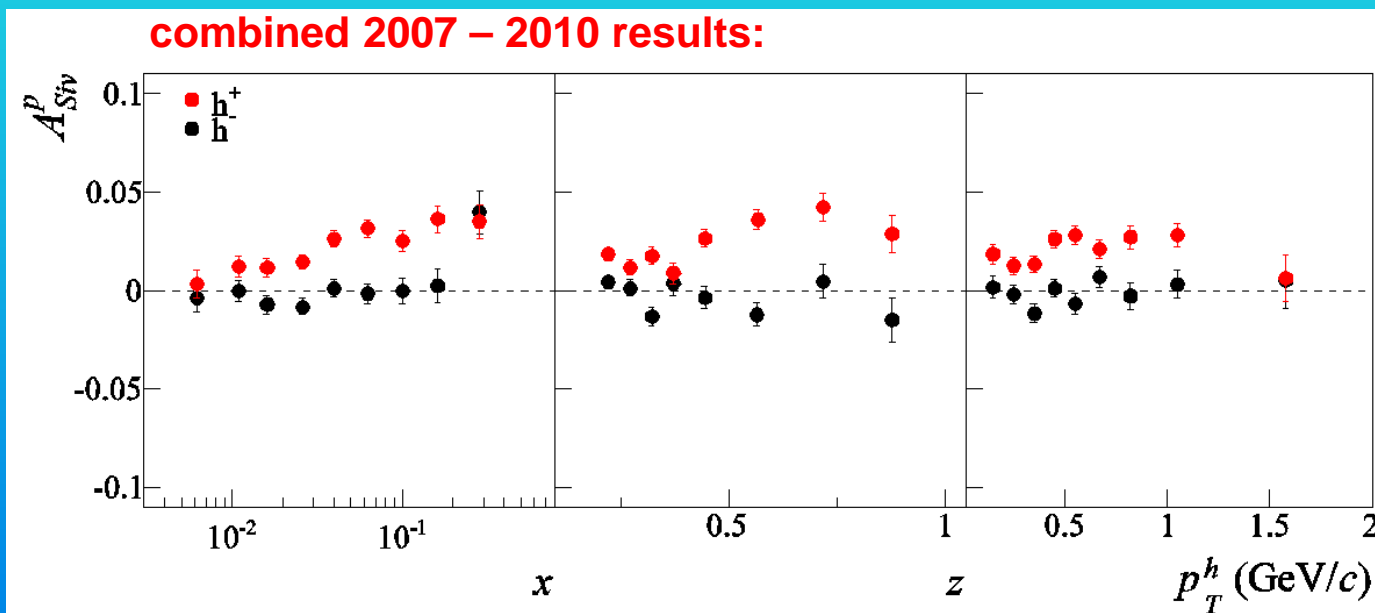




Sivers asymmetry on proton

charged hadrons - published 2007 & 2010 data results

PLB 692 (2010) 240 PLB 717 (2012)
383



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

**in the overlap x range, agreement with HERMES, but
clear indication that the strength decreases**



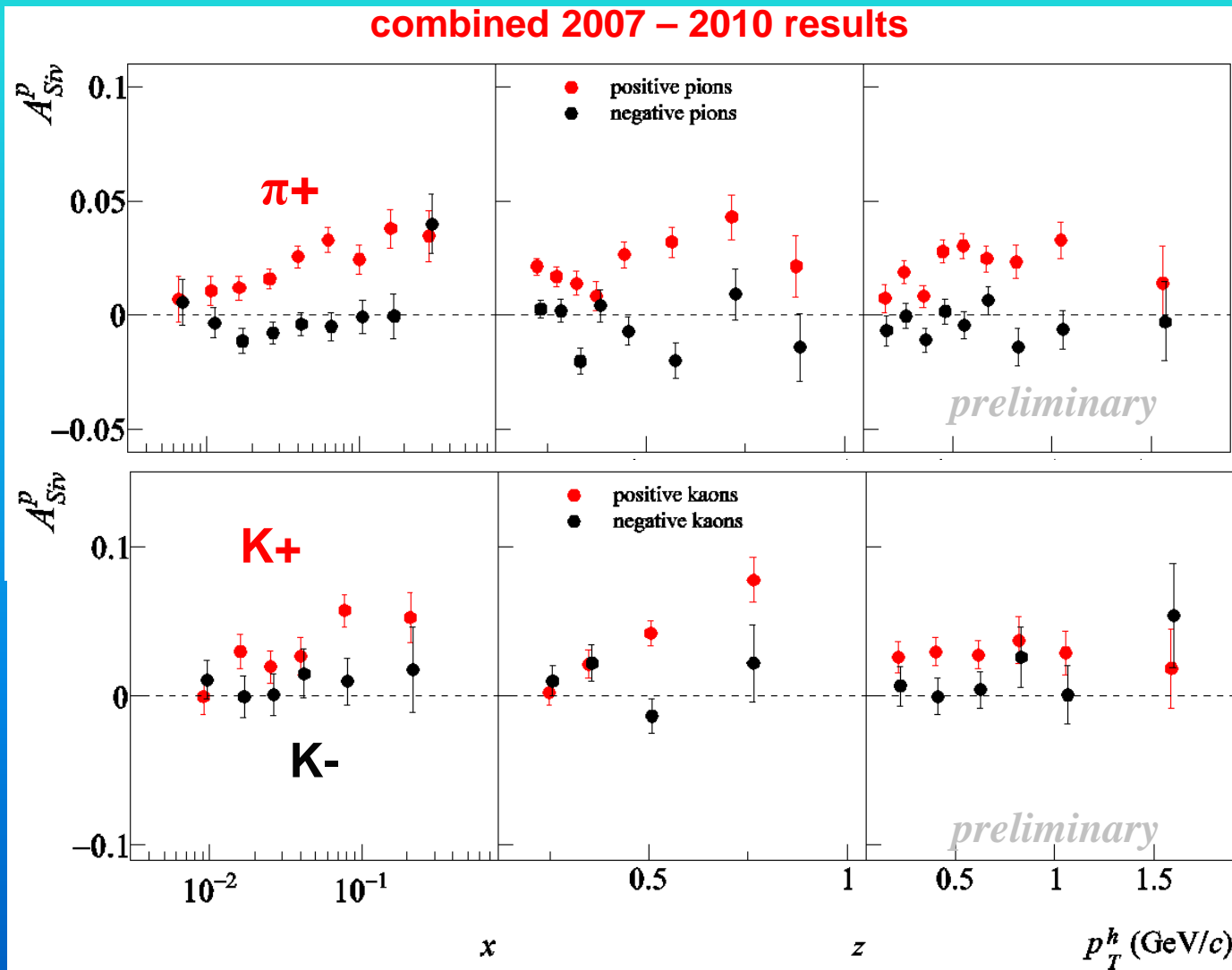
Sivers asymmetry on proton

charged pions and kaons

results from 2007 (SPIN2010) and 2010 (SPIN2012) data

$\sim h^+ / h^-$

larger than
for π^+



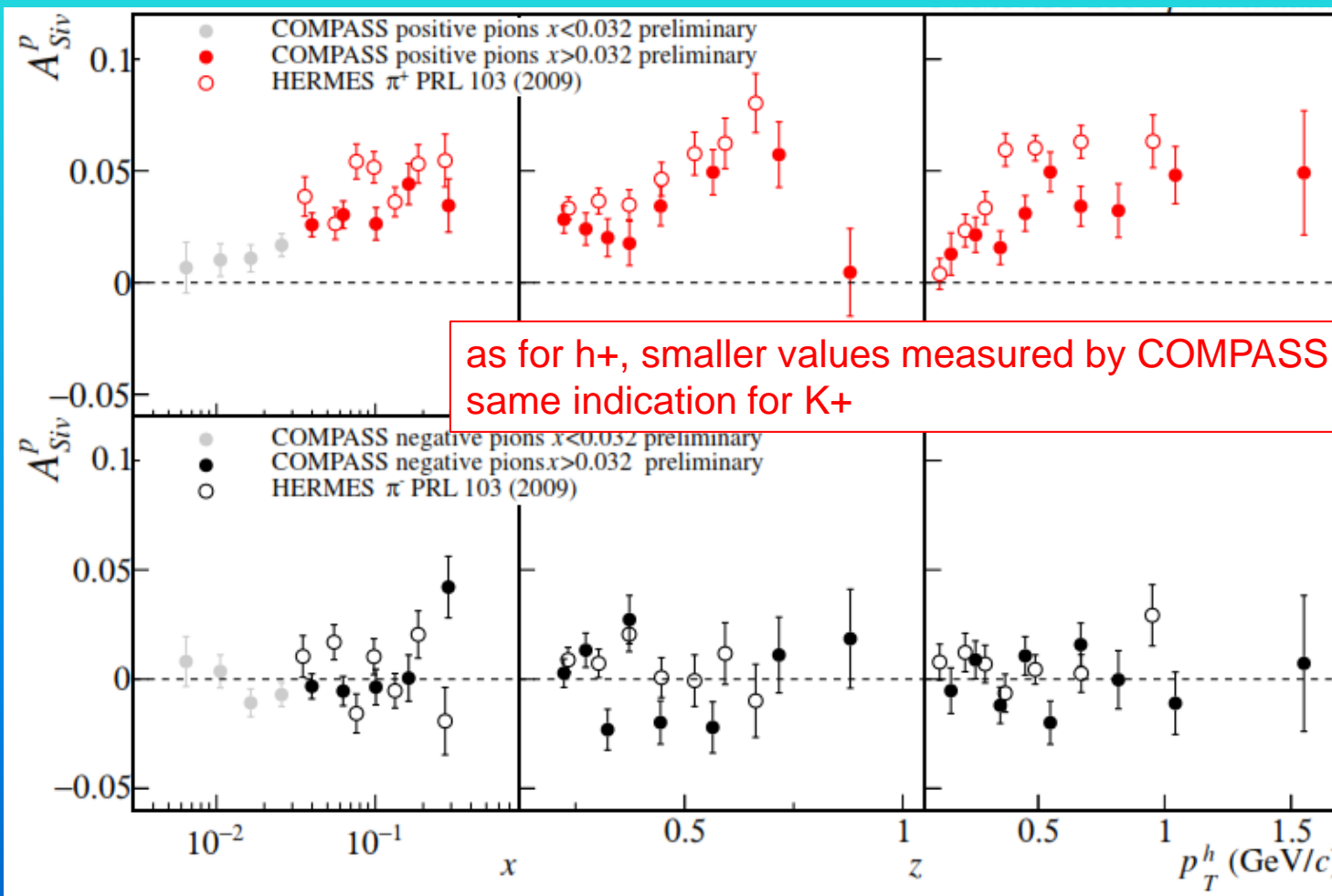


Sivers asymmetry on proton

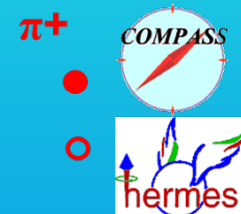
$x > 0.032$

charged pions (and kaons), 2010 data

comparison with HERMES results



as for h^+ , smaller values measured by COMPASS; same indication for K^+



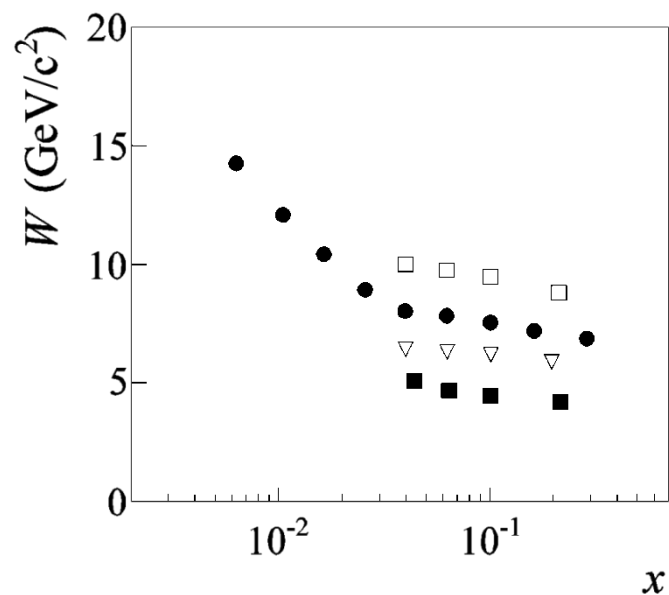
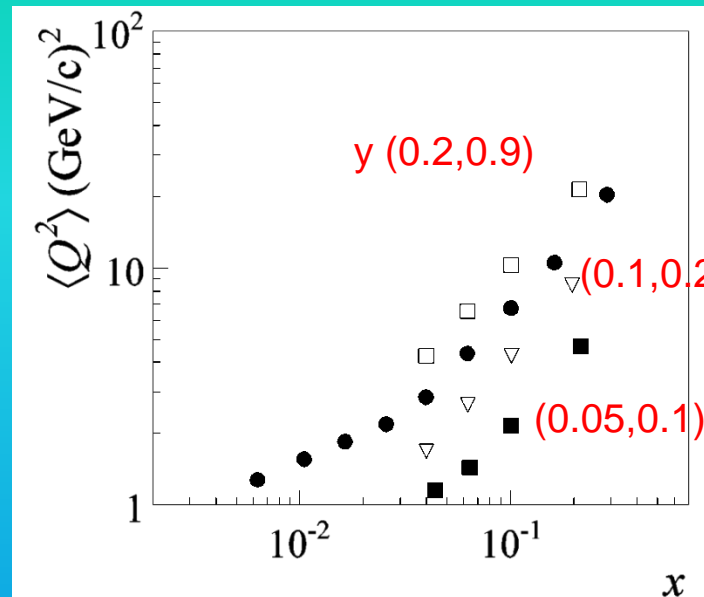
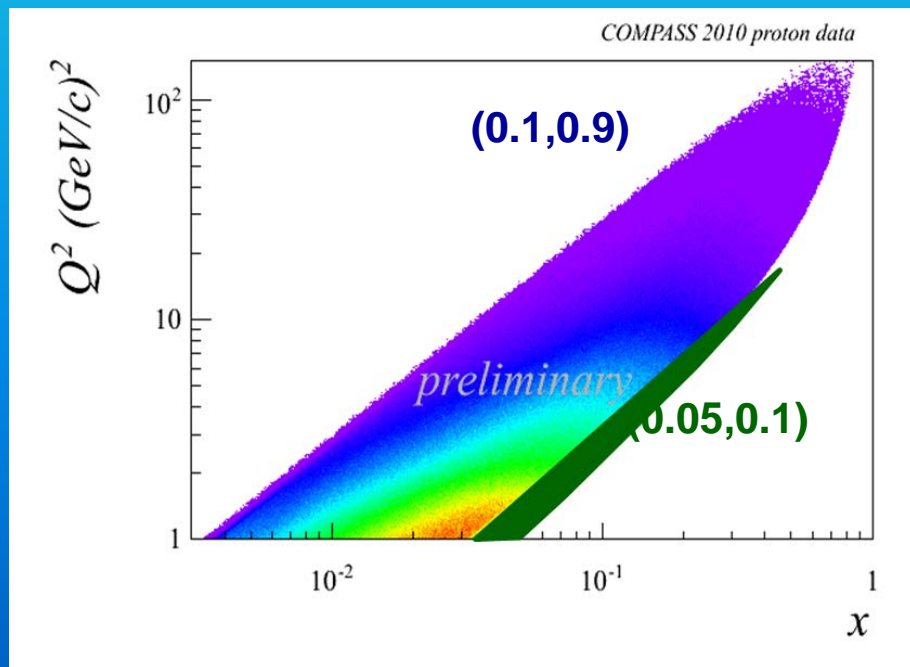


more on Sivers asymmetries

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

- low $z \rightarrow (0.1, 0.2) (0.2, 0.3) (0.3, 1.0)$
- low $y \rightarrow (0.05, 0.1) (0.1, 0.2) (0.2, 0.9)$

for charged and identified hadrons





more on Sivers asymmetries

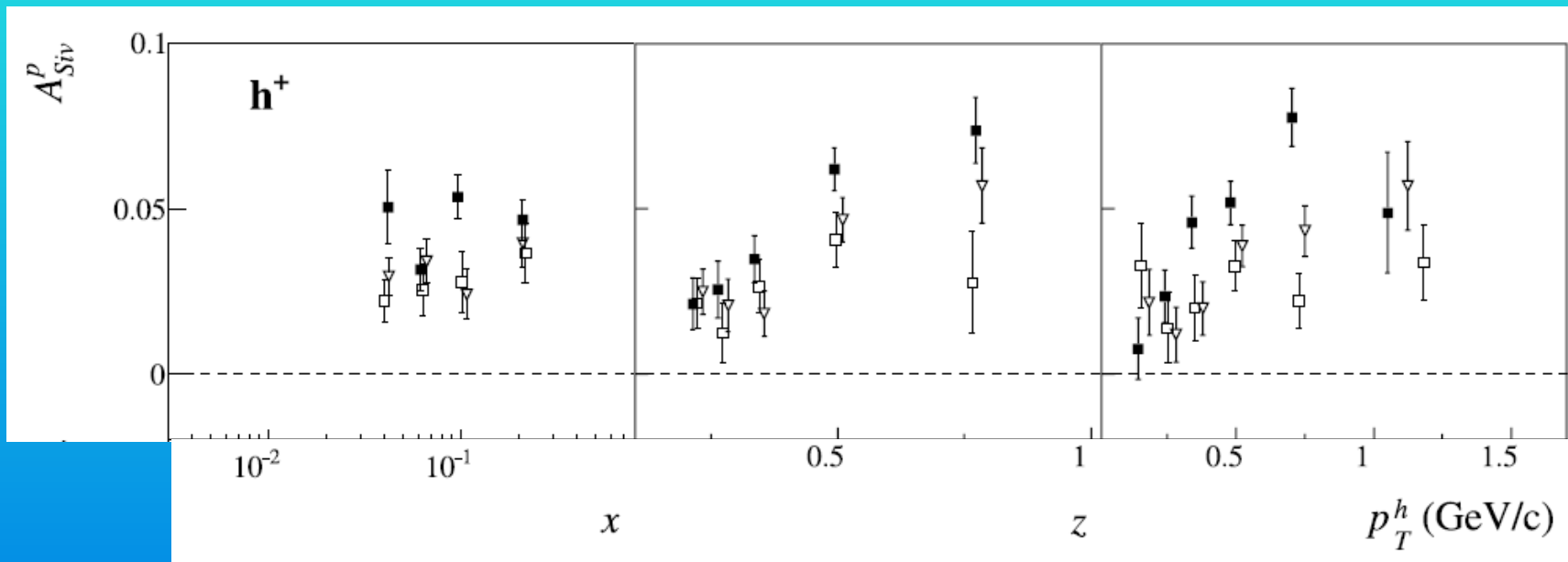
charged hadrons, **proton data**

■ $0.05 < y < 0.1$

▽ $0.1 < y < 0.2$

□ $0.2 < y < 0.9$

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complete multidimensional analysis: starting



COMPASS

has measured the Collins and Sivers asymmetries

on d and on p using a 160 GeV muon

beam

for charged and identified hadrons

clear signals on p have been measured,
with interesting kinematical

dependences

to be done soon:

multidimensional analysis (x, Q^2, z, p_t) of the p data

on a longer time scale: possible measurements with

- transversely polarised p and 100 GeV muon beam
- transversely polarised d and 160 GeV muon beam



COMPASS-II schedule

2013-14 Accelerator shutdown

2015 Drell-Yan :

Universality of TMDs

2016–2017 DVCS and DVMP:

Study GPDs,
“nucleon tomography”
Unpolarized SIDIS:
FF, strangeness PDF,
TMDs



Thank You

