Measurement of TMD observables at COMPASS

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on behalf of the COMPASS Collaboration

QCD Evolution Workshop Jefferson Lab, May 2012

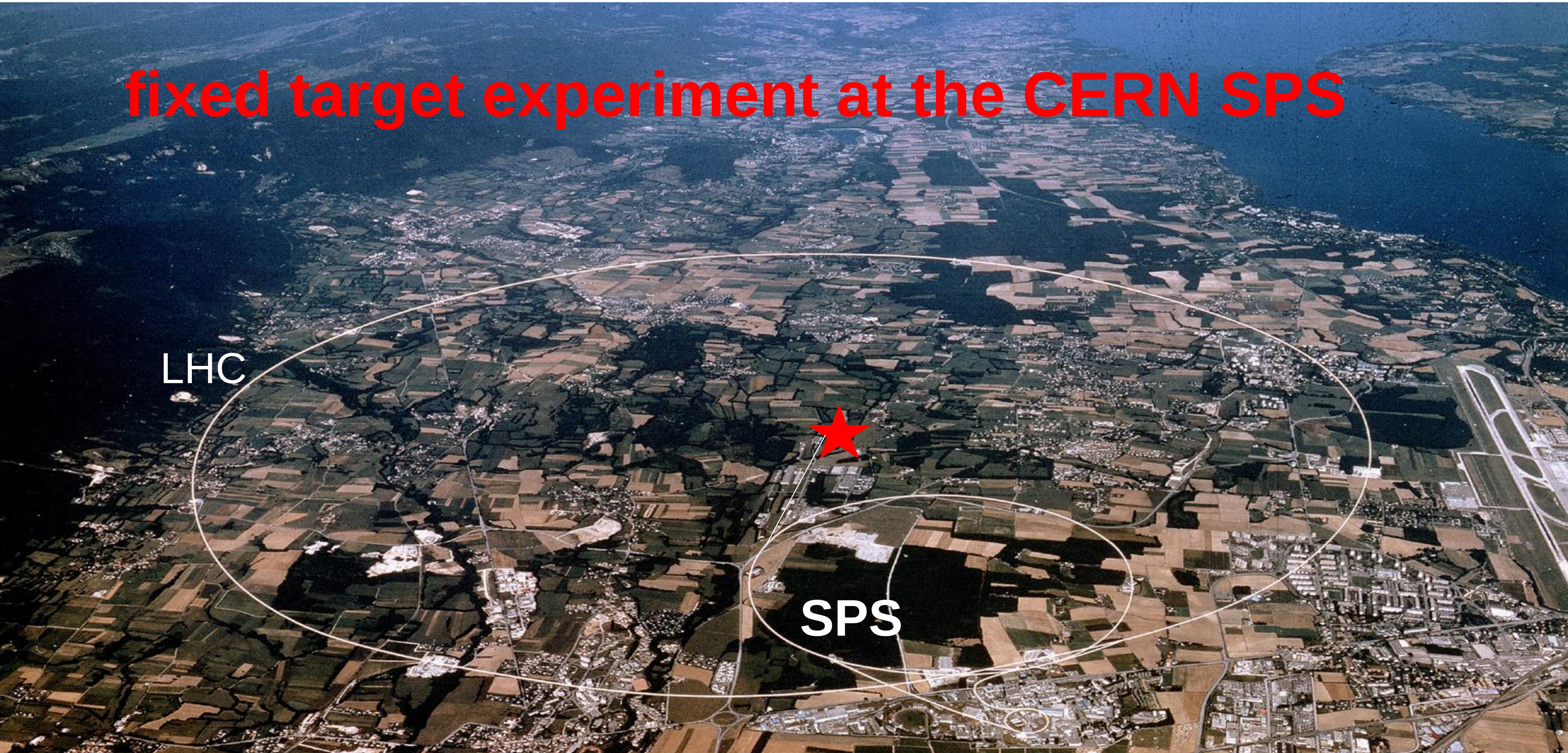
OUTLINE

- **the COMPASS experiment**

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

- **conclusions and outlook**

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy



fixed target experiment at the CERN SPS

COMPASS spectrometer

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

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

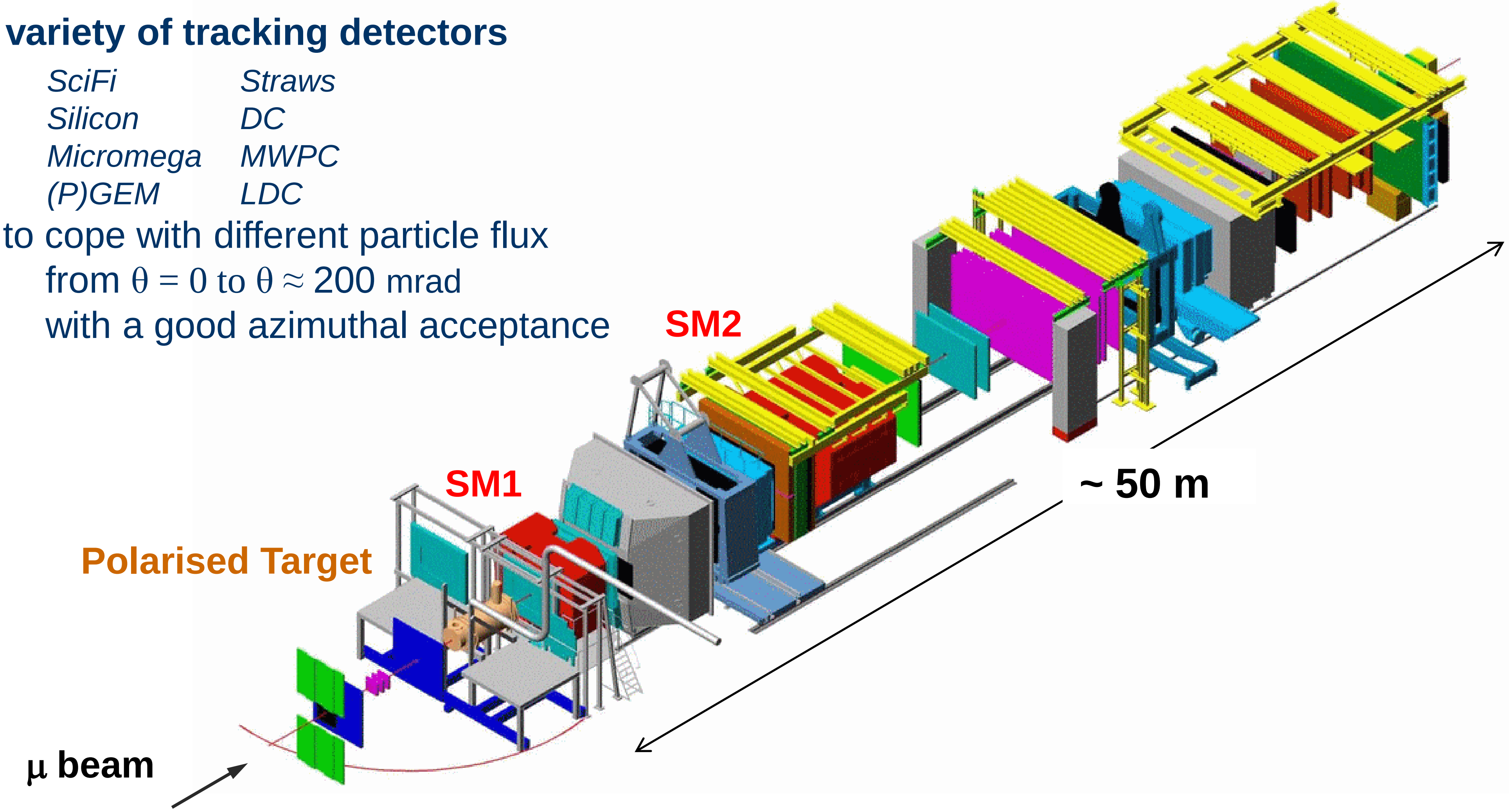
variety of tracking detectors

SciFi
Silicon
Micromega
(P)GEM
Straws
DC
MWPC
LDC

to cope with different particle flux

from $\theta = 0$ to $\theta \approx 200$ mrad

with a good azimuthal acceptance



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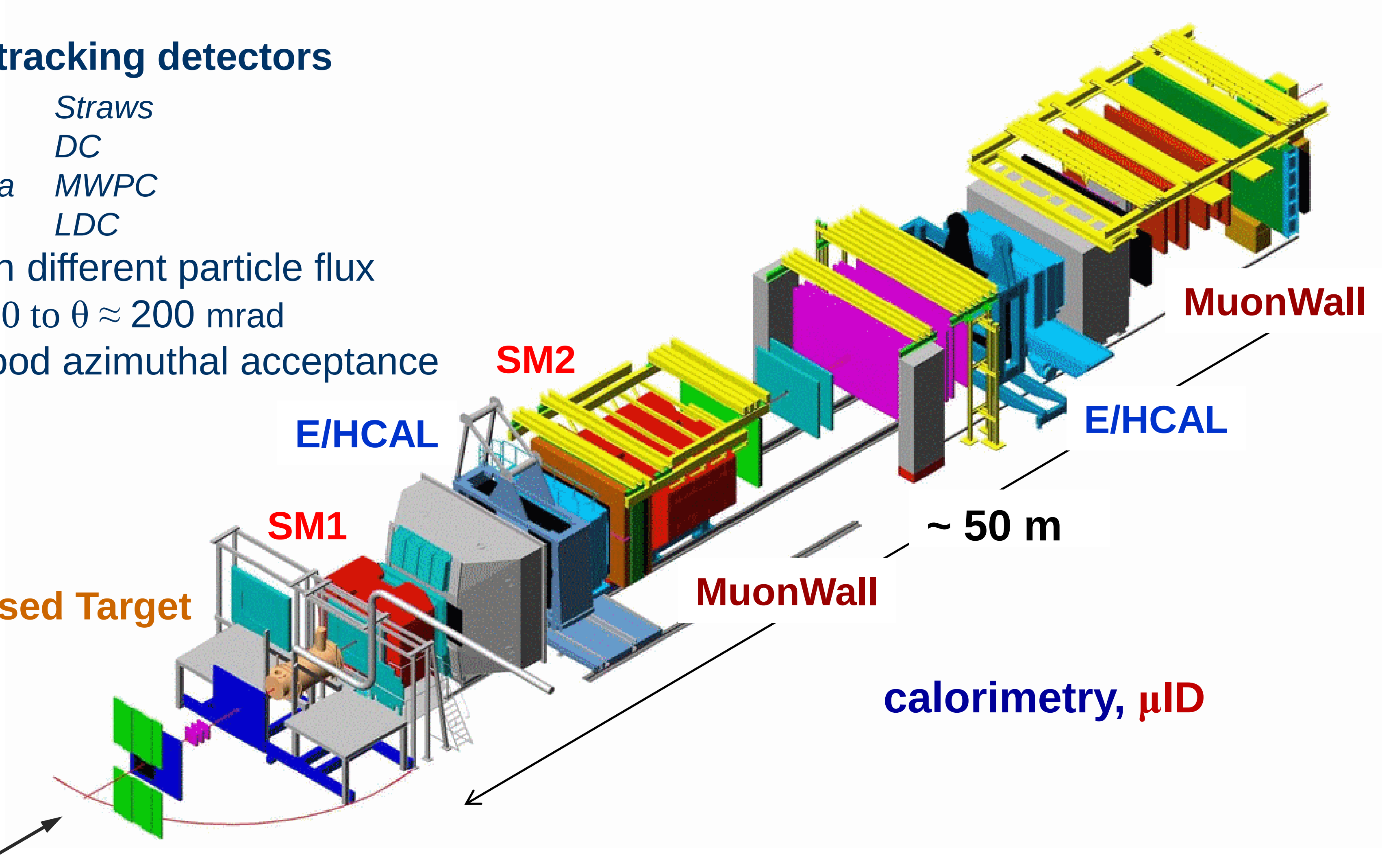
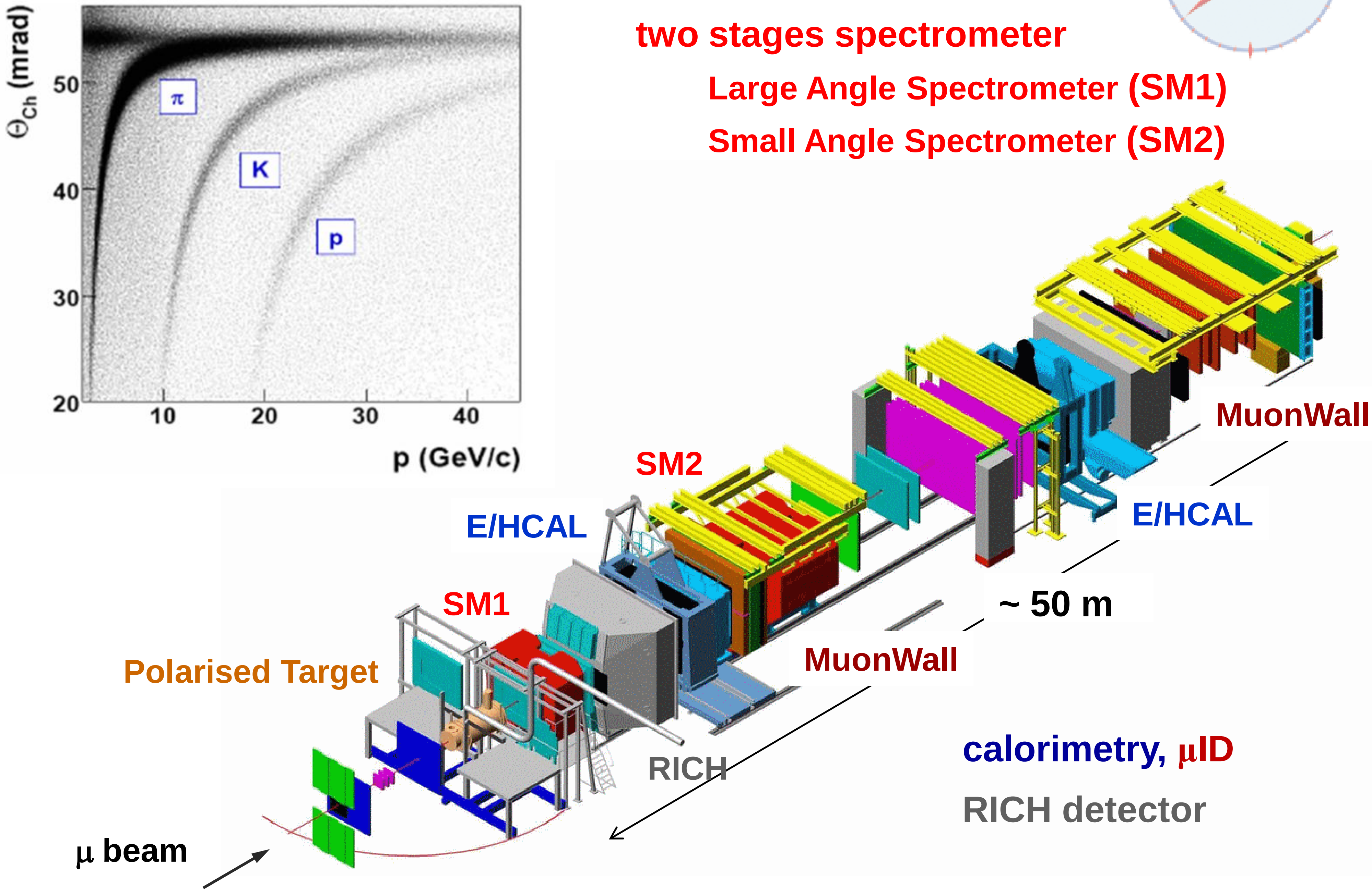


COMPASS spectrometer

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)



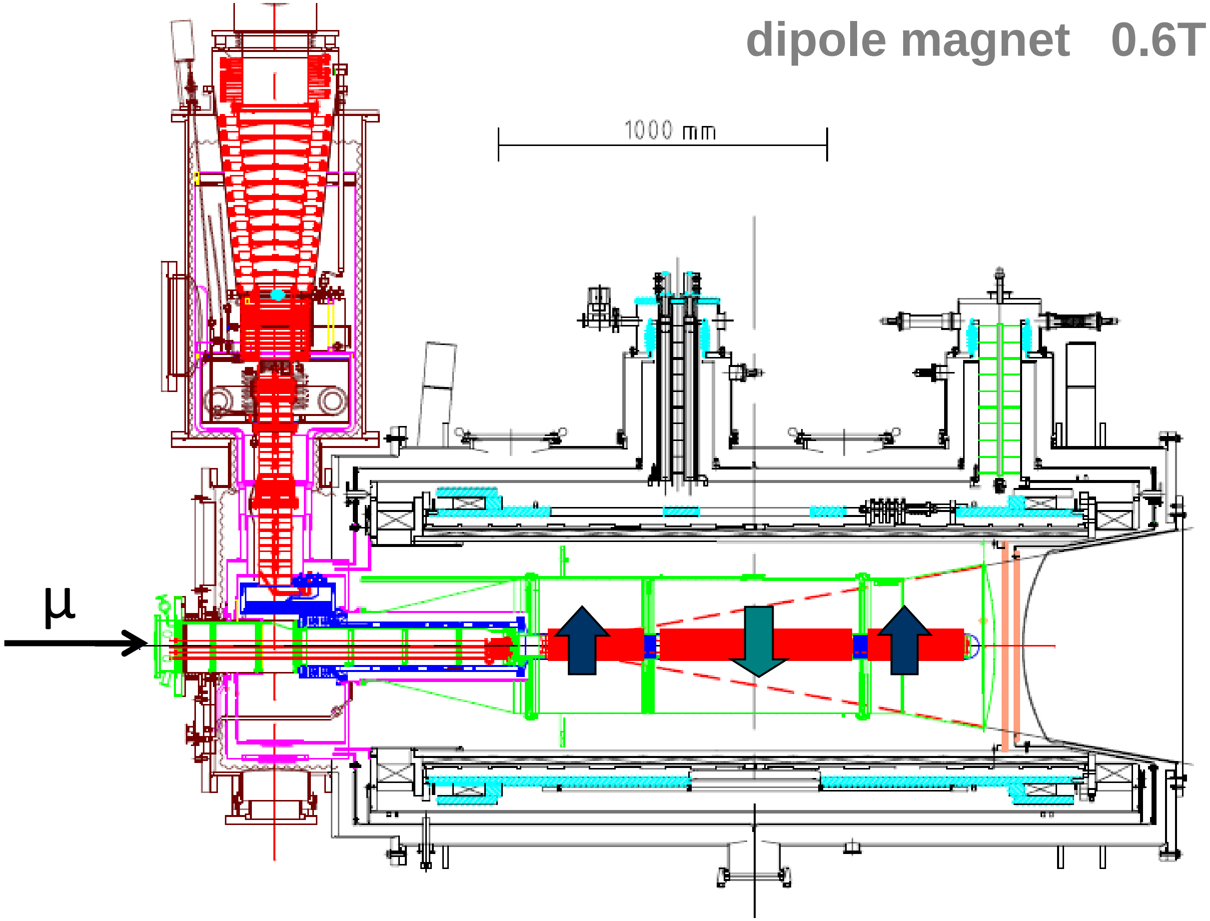
calorimetry, μID

RICH detector

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%

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

COMPASS data taking

2002 **2003** **2004**	**SIDIS with L & T**	**polarised deuteron target**	**160 GeV μ**	**ΔG**
2005		*CERN shutdown*		
2006	**SIDIS with L**	**polarised deuteron target**	**160 GeV μ**	

2007	**SIDIS with L & T**	**polarised proton target**	**160 GeV μ**
2008 / 2009		**hadron spectroscopy**	
2010	**SIDIS with T**	**polarised proton target**	**160 GeV μ**
2011	**SIDIS with L**	**polarised proton target**	**190 GeV μ**

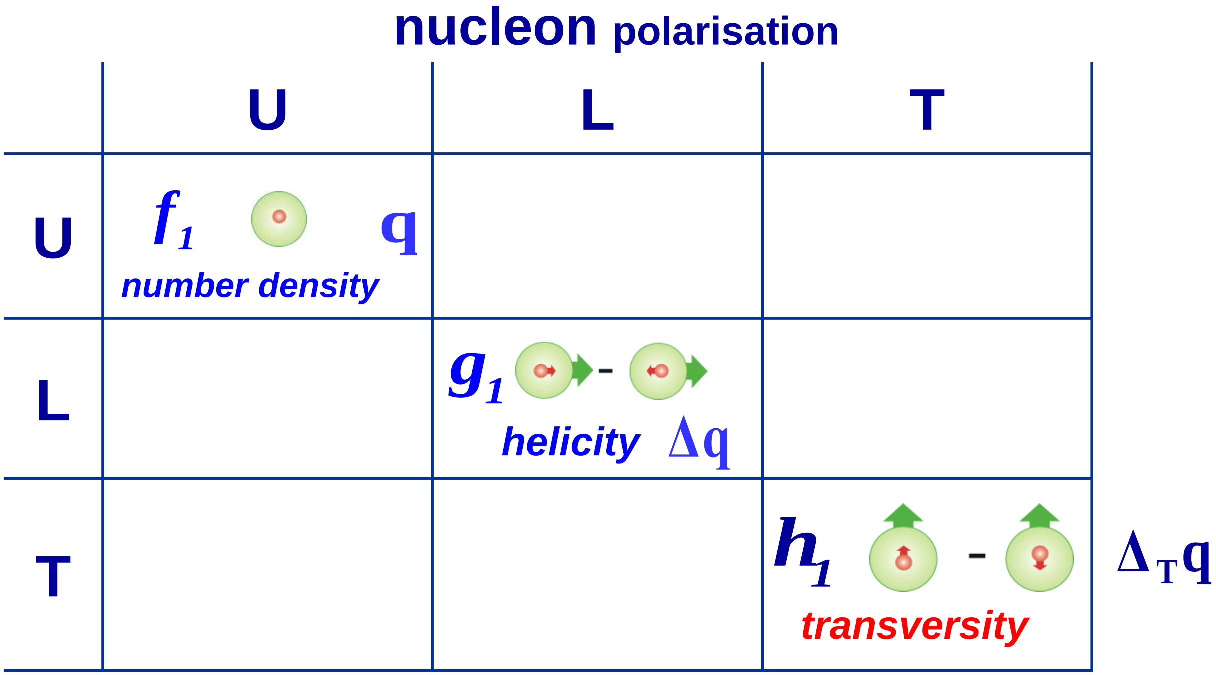
2012 ***Primakoff / DVCS test***

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 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 - $\Delta_T q$ *transversity*

chiral odd

can be measured in SIDIS off transversely polarised nucleons

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

The Structure of the Nucleon

taking into account the quark intrinsic transverse momentum k_T ,

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

Sivers function

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

sensitive to orbital angular momentum

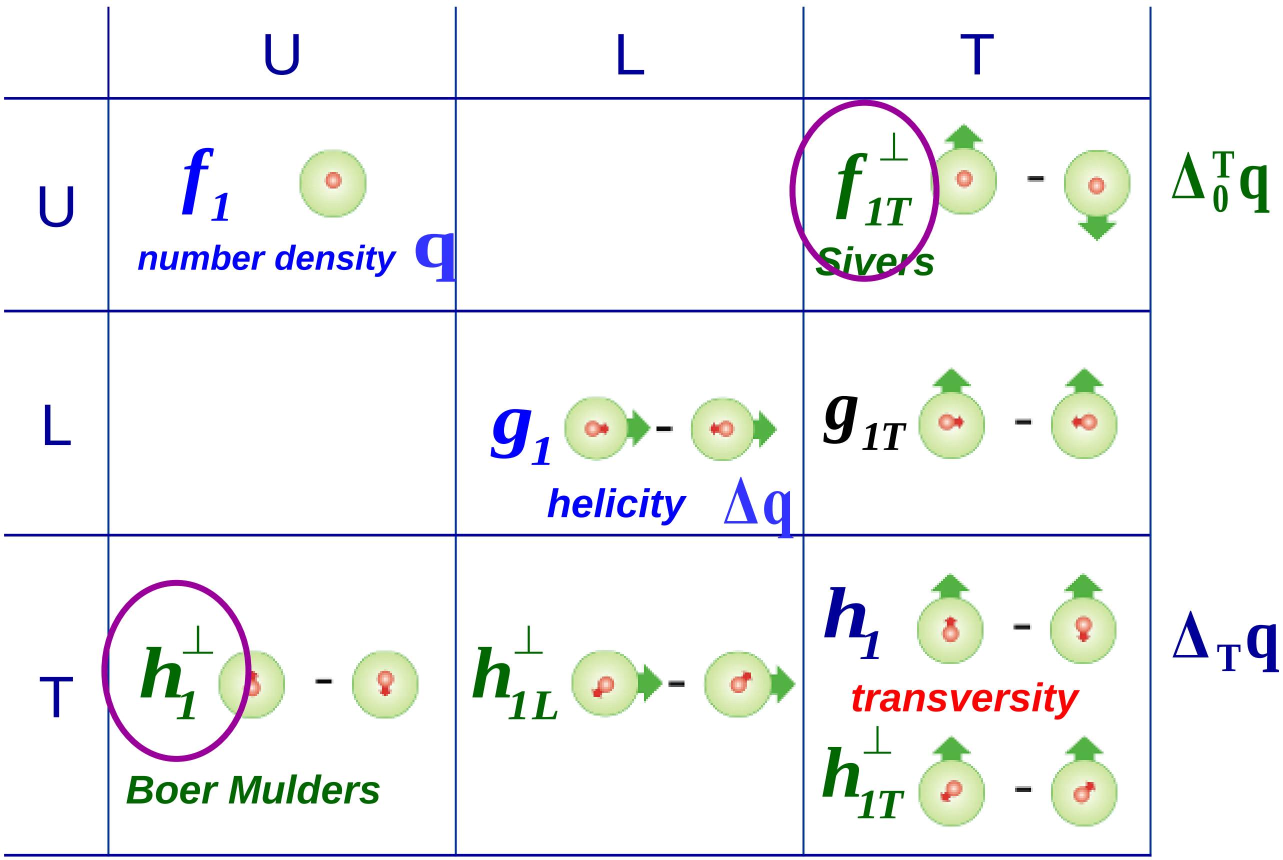
Boer-Mulders function

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

T-odd

nucleon polarisation

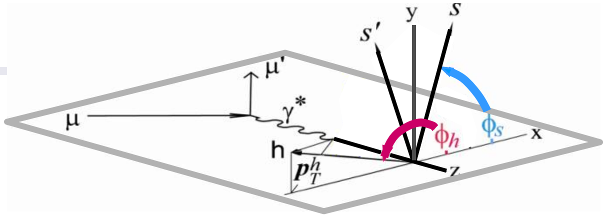
quark polarisation



	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 gives access to all of them

SIDIS cross-section



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

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

$h_1^\perp H_1^\perp$

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

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

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

$f_{1T}^\perp D_1$

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

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

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

$h_1\,H_1^\perp$

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

$g_{1T}D_1$

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

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

18 structure functions
14 azimuthal modulations
all measured in COMPASS

A Bacchetta et al., 2006

SIDIS cross-section - unpolarised targets

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

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

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

twist3

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

Boer-Mulders DF x Collins FF

+ Cahn effect (twist 4, 1/Q²)

Boer-Mulders DF

Cahn effect

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

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

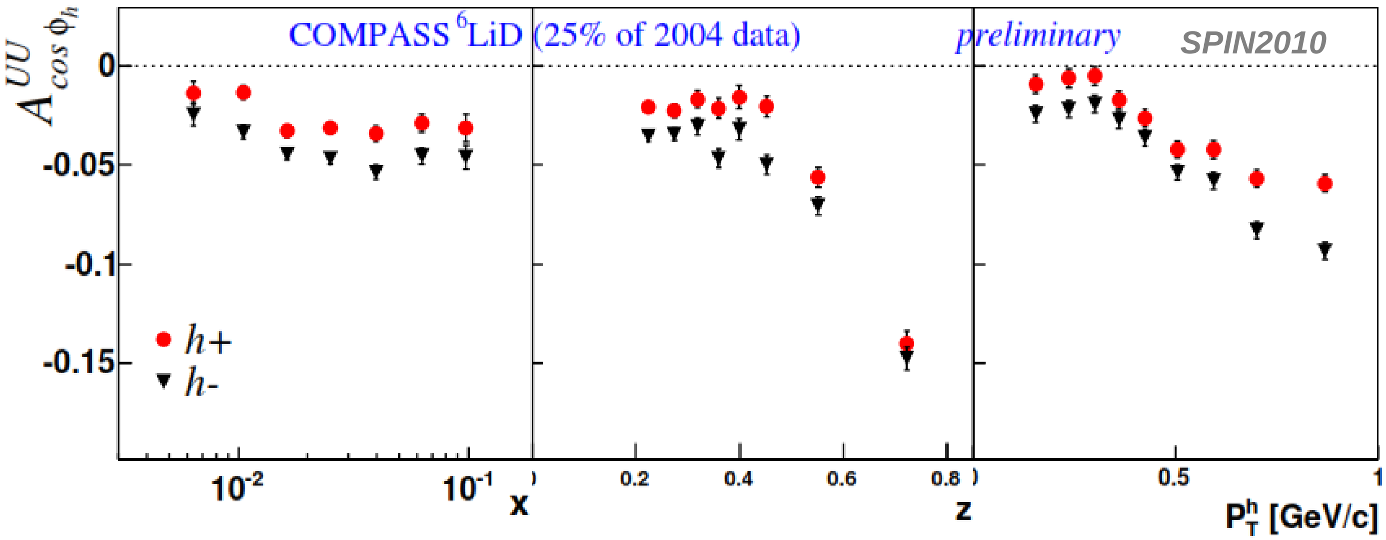
→ $\langle k_T^2\rangle$

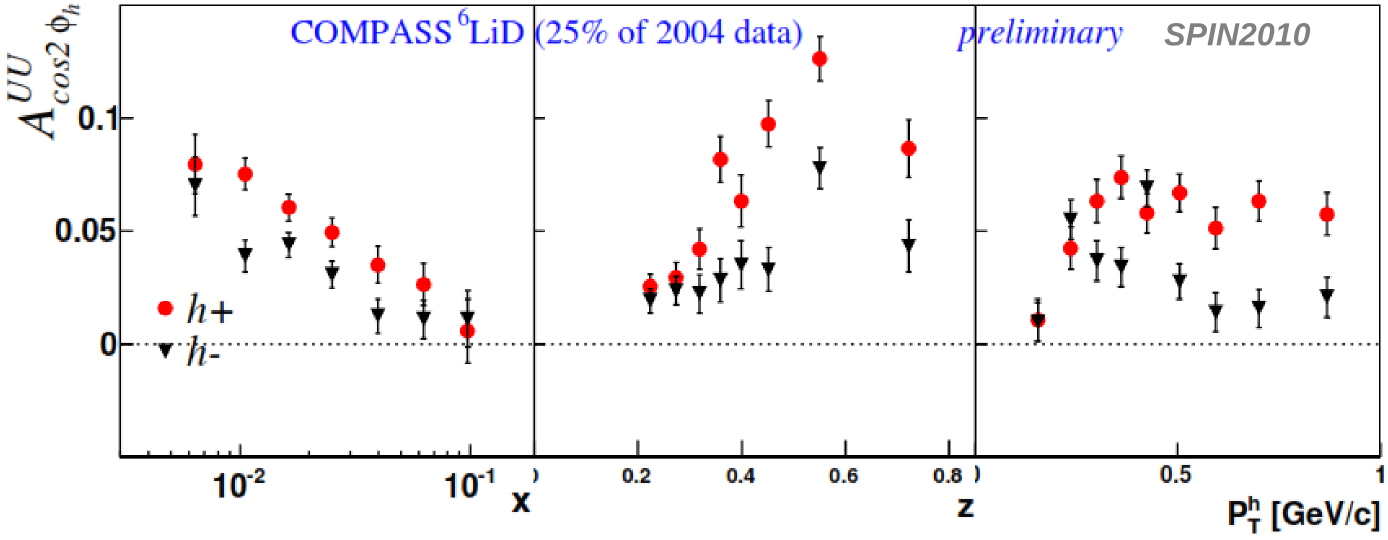
$\cos\phi$ and $\cos2\phi$ modulations ^{6}LiD

first results for

h^+ and h^- separately from COMPASS
presented at Transversity2008

$W > 5GeV/c^2$
$Q^2 > 1GeV^2$
$0.003 < x < 0.13$
$0.2 < y < 0.9$
$0.2 < z < 0.85$
$0.1 < P_T^h < 1.0GeV/c$
$\theta_{\gamma^*}^{lab} < 0.06rad$





$\cos\phi$

- large signals over all the x range

$\cos2\phi$

- large signals at small x

➢ **different for h^+ and h^-**

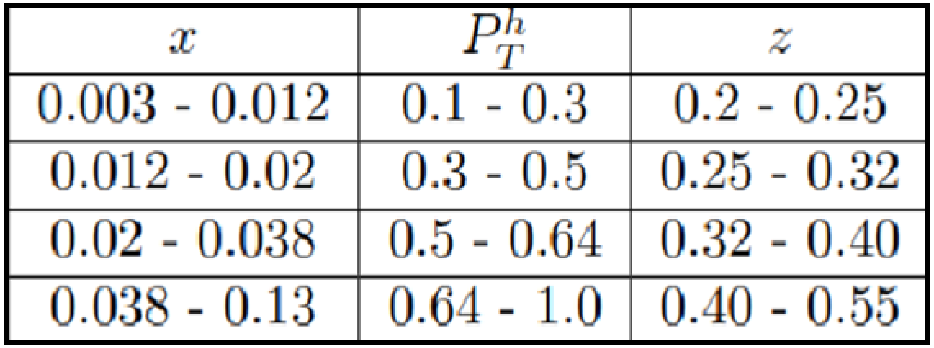
➢ **strong dependence on x, z, $P_T{}^h$**

difficult to describe

$\cos\phi$ and $\cos 2\phi$ modulations ^{6}LiD

multidimensional analysis

***new**: QNP2012*

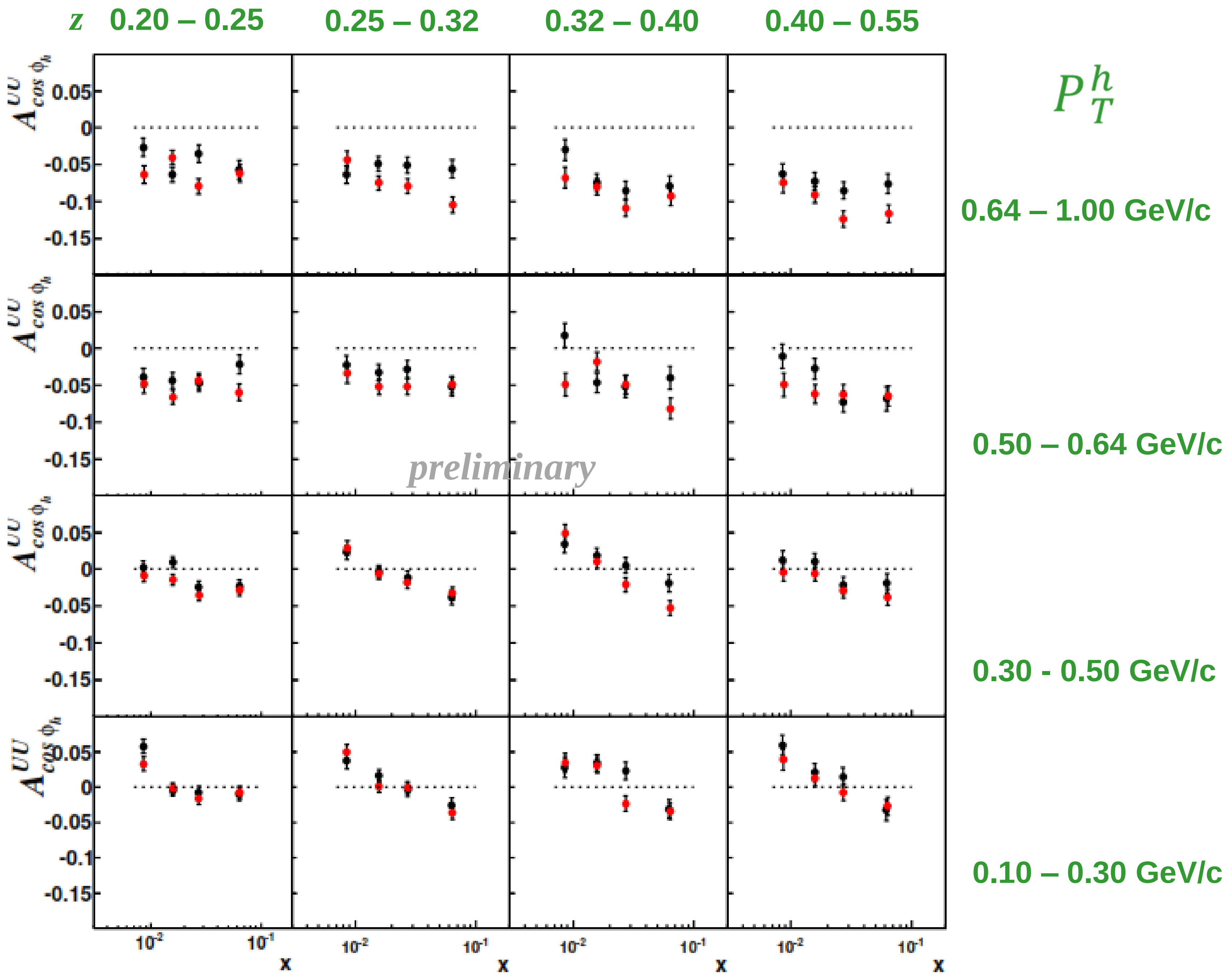


x	P_T^h	z
0.003 - 0.012	0.1 - 0.3	0.2 - 0.25
0.012 - 0.02	0.3 - 0.5	0.25 - 0.32
0.02 - 0.038	0.5 - 0.64	0.32 - 0.40
0.038 - 0.13	0.64 - 1.0	0.40 - 0.55

- **different for h^+ and h^-**
- **strong dependence on x, z, P_T^h**

cosϕ modulation

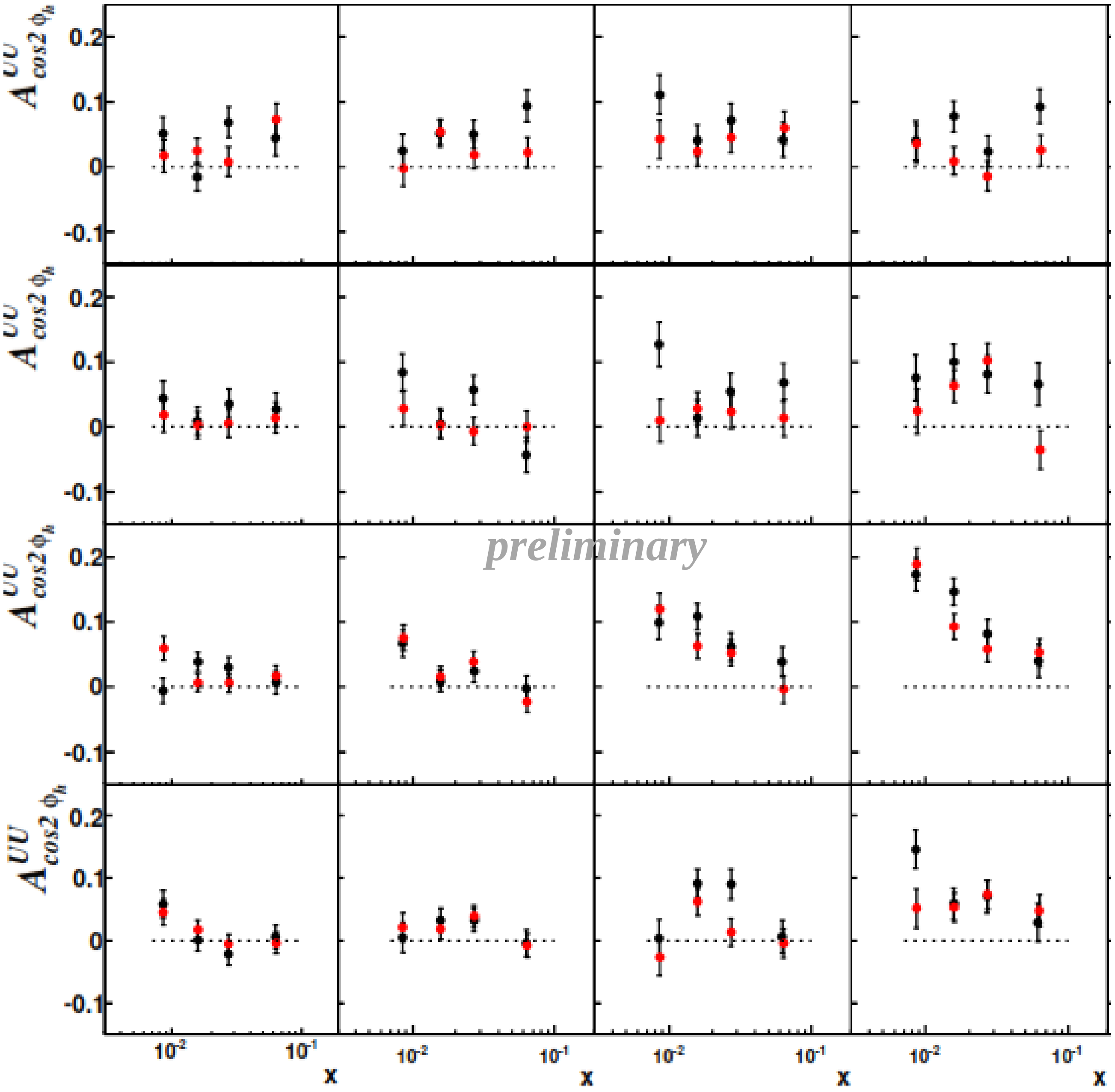
QNP2012



cos2ϕ modulation

QNP2012

z 0.20 – 0.25 0.25 – 0.32 0.32 – 0.40 0.40 – 0.55



P_T^h

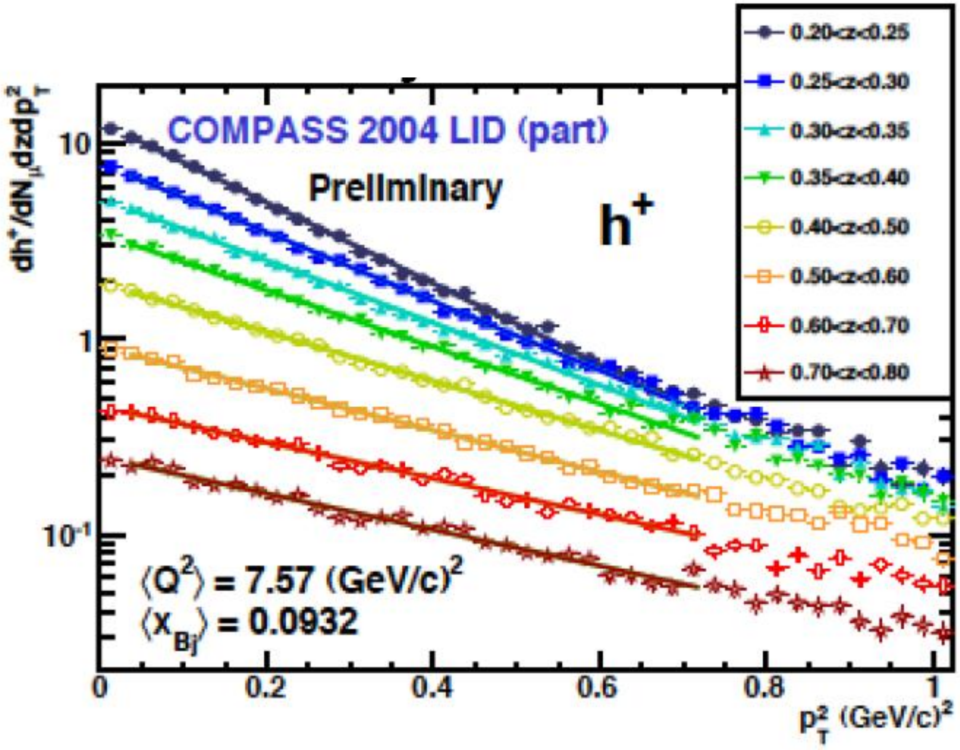
0.64 – 1.00 GeV/c

0.50 – 0.64 GeV/c

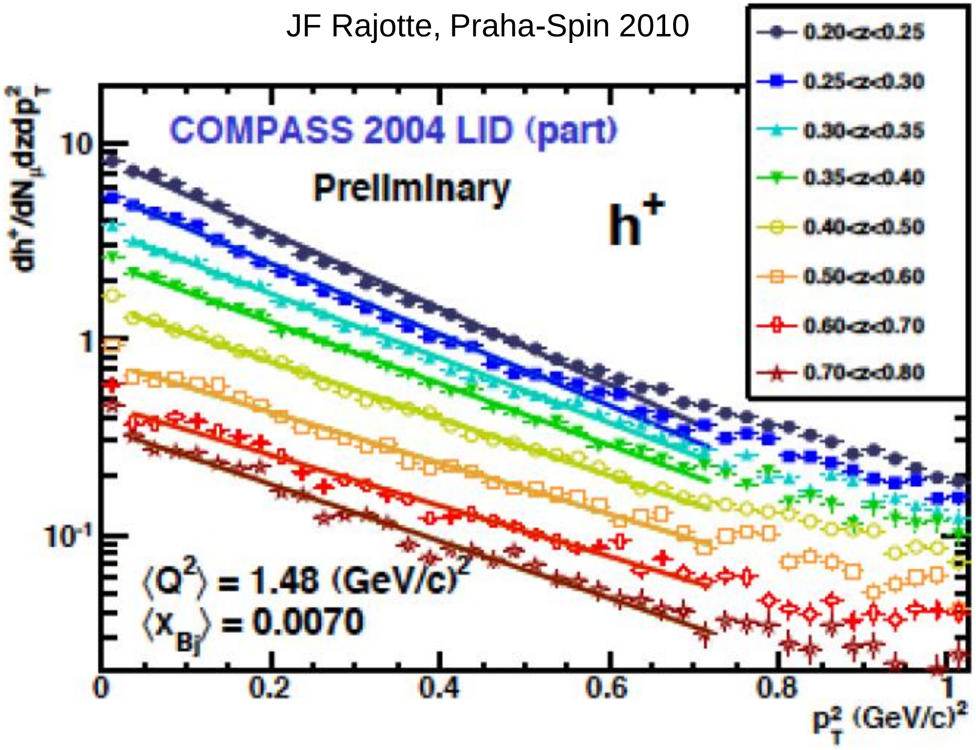
0.30 - 0.50 GeV/c

0.10 – 0.30 GeV/c

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

SIDIS cross-section

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

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

$h_1^\perp H_1^\perp$

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

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

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

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

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

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

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

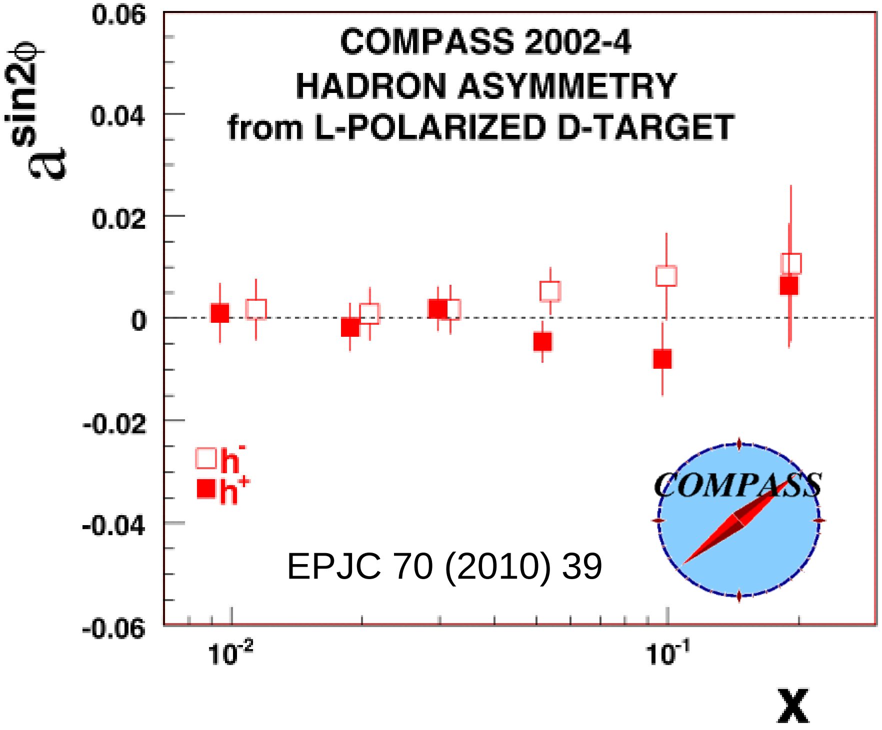
all the longitudinal
spin azimuthal asymmetries
have been measured
on d (2004)**:**
all compatible with zero

longitudinally polarised target

$$F_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

published results from 2002-2004 **deuteron** data

"worm gear" PDF
⊗ Collins FF



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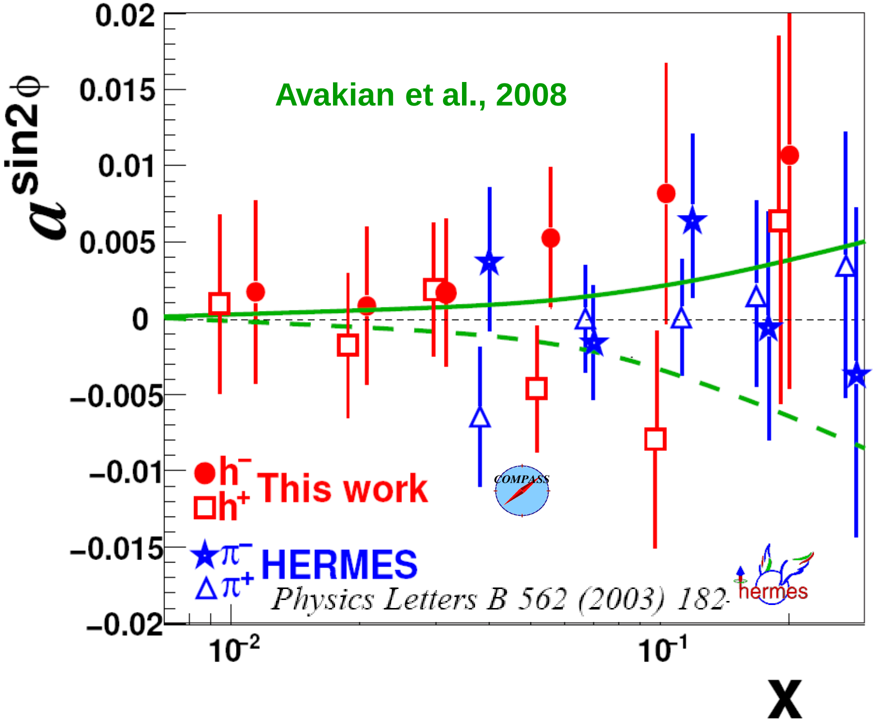

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**small, compatible with zero
within the statistical errors**

COMPASS sign convention

SIDIS cross-section

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

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

$$h_1^\perp H_1^\perp$$

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

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

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

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

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

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

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

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

next: results from
2006 d data
2007, 2011 p data

SIDIS cross-section

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

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

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

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

Collins

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

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

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

$h_1\,H_1^{\perp}$

Sivers

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

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

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

SIDIS cross-section

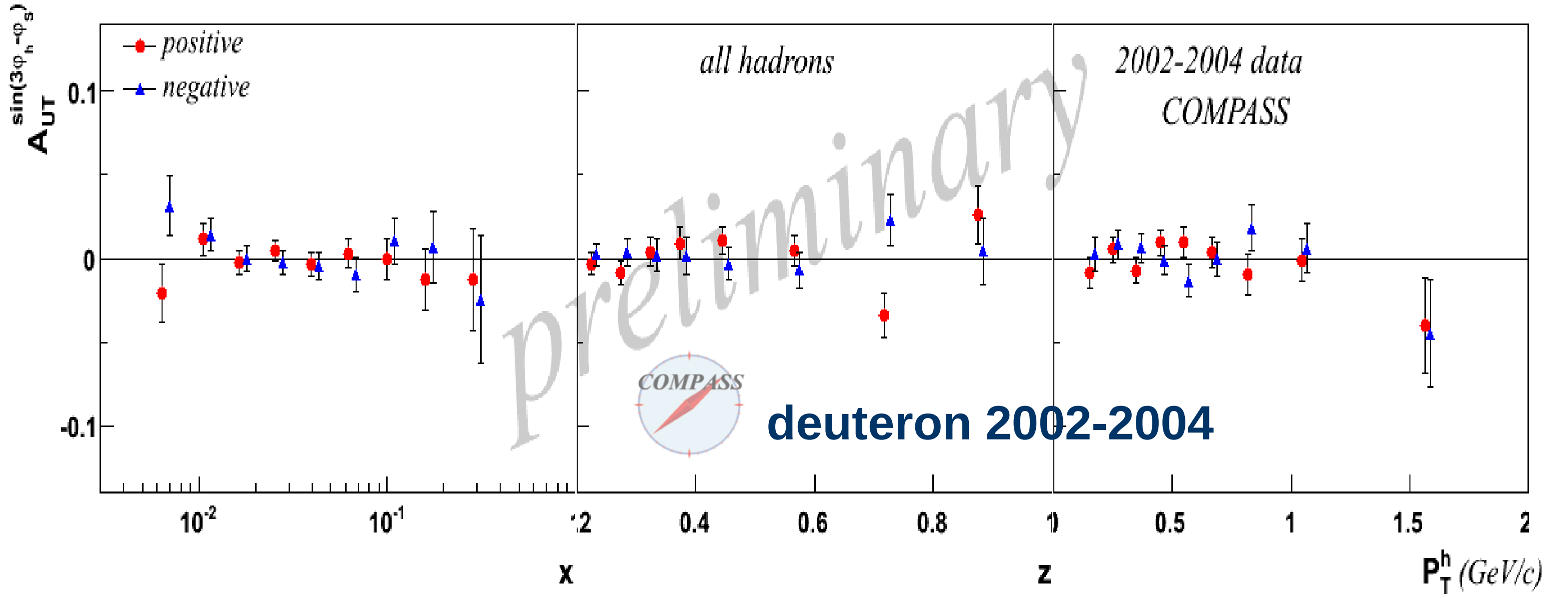
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos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

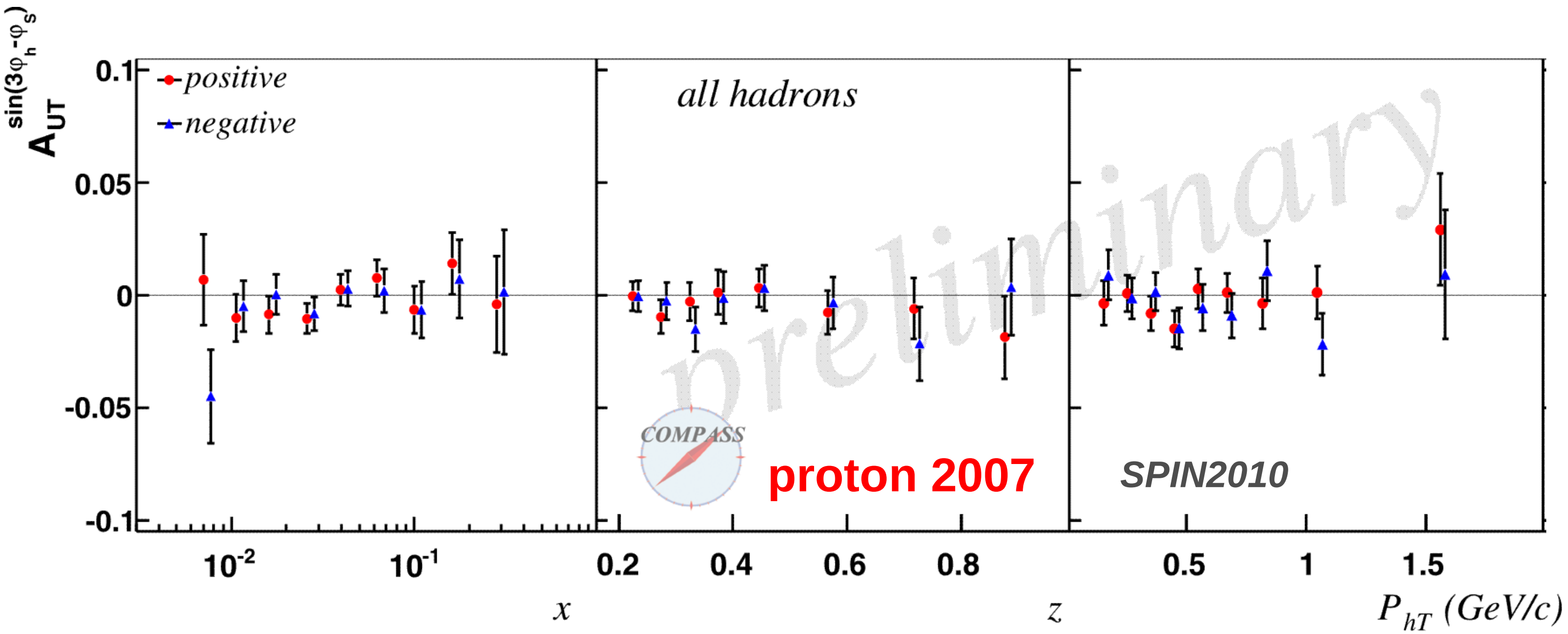
all the other 6 transverse spin azimuthal asymmetries have been measured on d (2002-2004) and p (2007) : all compatible with zero

transversely polarised target

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

“pretzelosity” PDF
⊗ Collins FF





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

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

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

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

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

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

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

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

$$g_{1T}D_1$$

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

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

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

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

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

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

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

Collins

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

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

Sivers

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

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

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

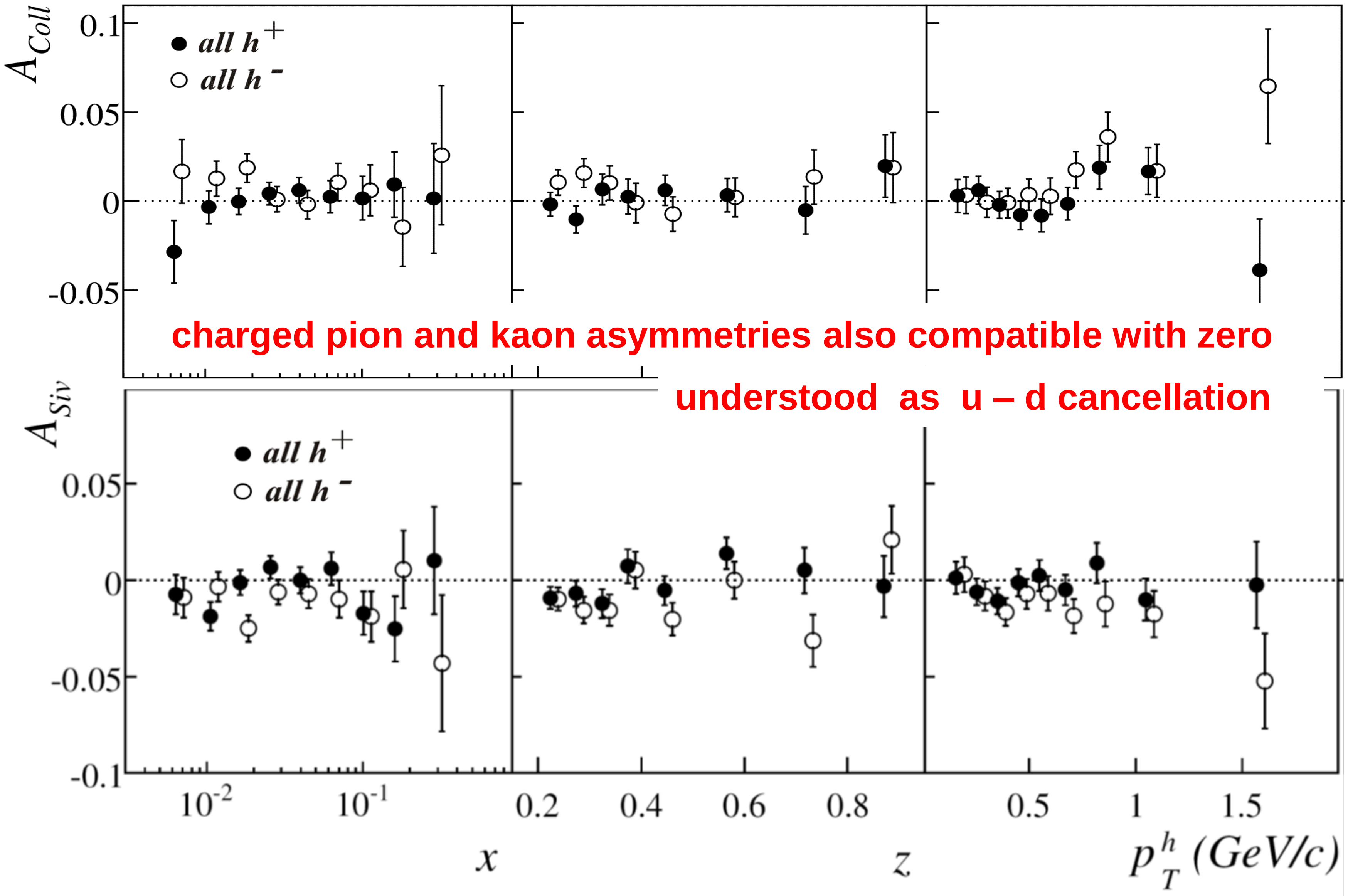
$$A_{Coll} \approx \frac{\sum_q e_q^2\,\Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2\,q \otimes D_q^h}$$

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

Collins and Sivers asymmetries on deuteron

first results in 2005 *compatible with zero*

final results on deuteron 2002-2004 data *NPB 765 (2007) 31, PLB 673 (2009) 127*



charged pion and kaon asymmetries also compatible with zero

understood as u – d cancellation

Collins and Sivers asymmetries on proton

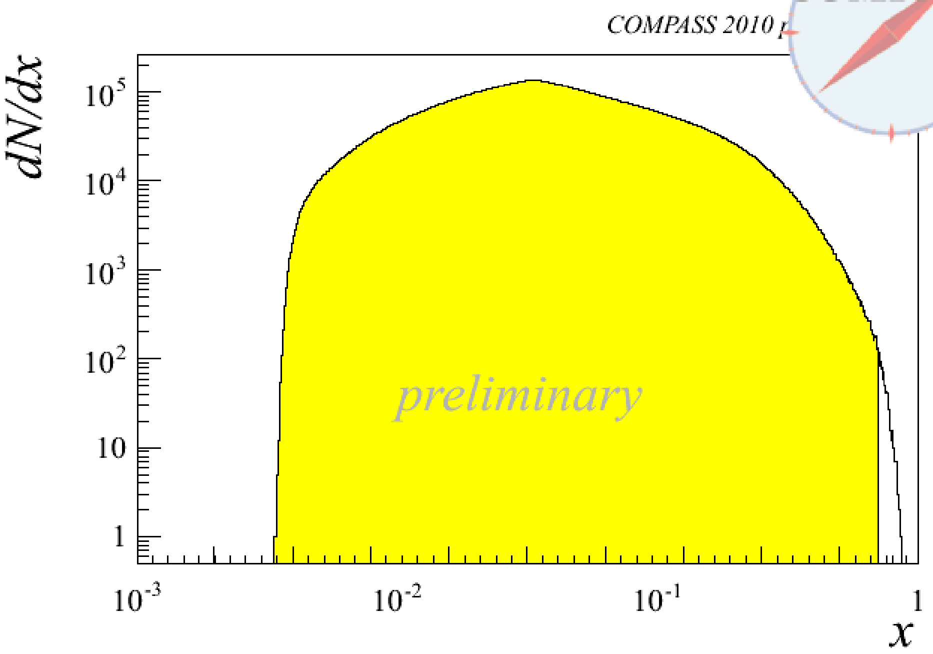
2007 data: final results published

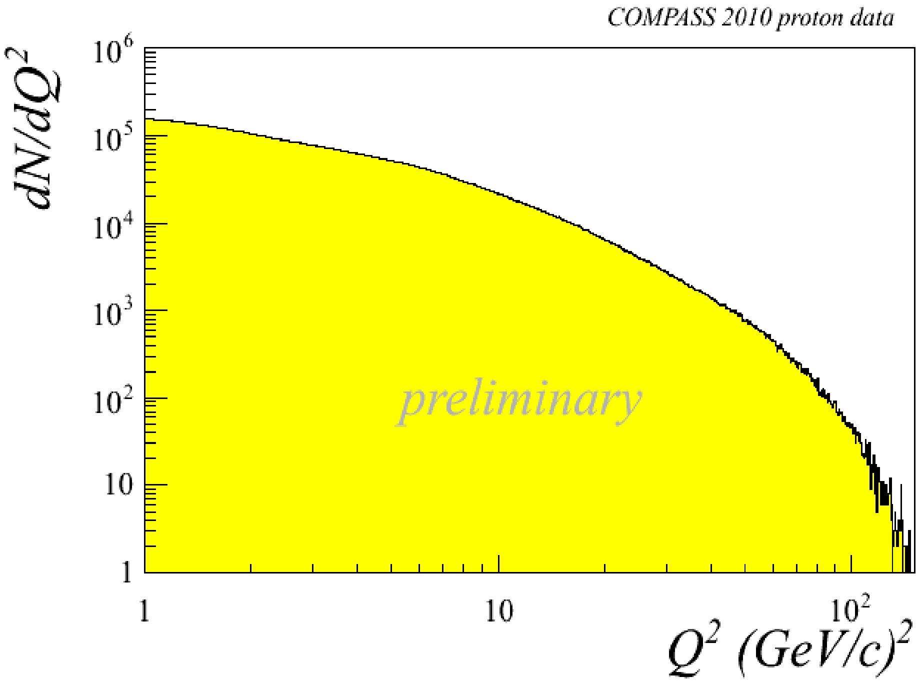
2010 data: results shown at Transversity2011

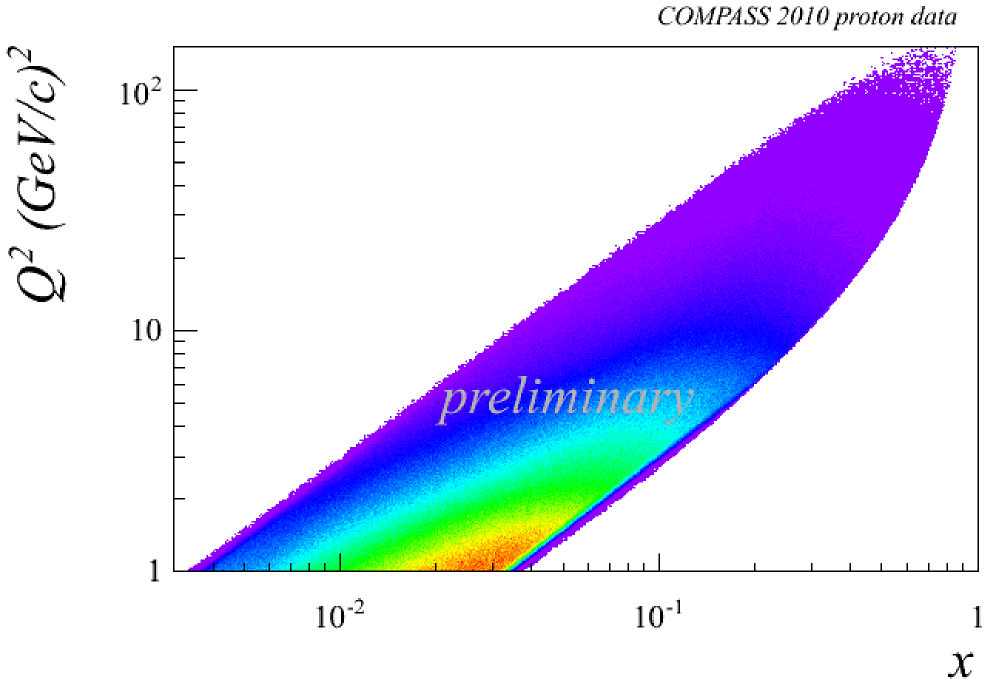
2 papers with all the Collins and Sivers results from 2010 data
and the correlation
between Collins and Sivers asymmetries
and asymmetries measured vs x, z, P_T^h
being sent for publication

SIDIS event selection

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

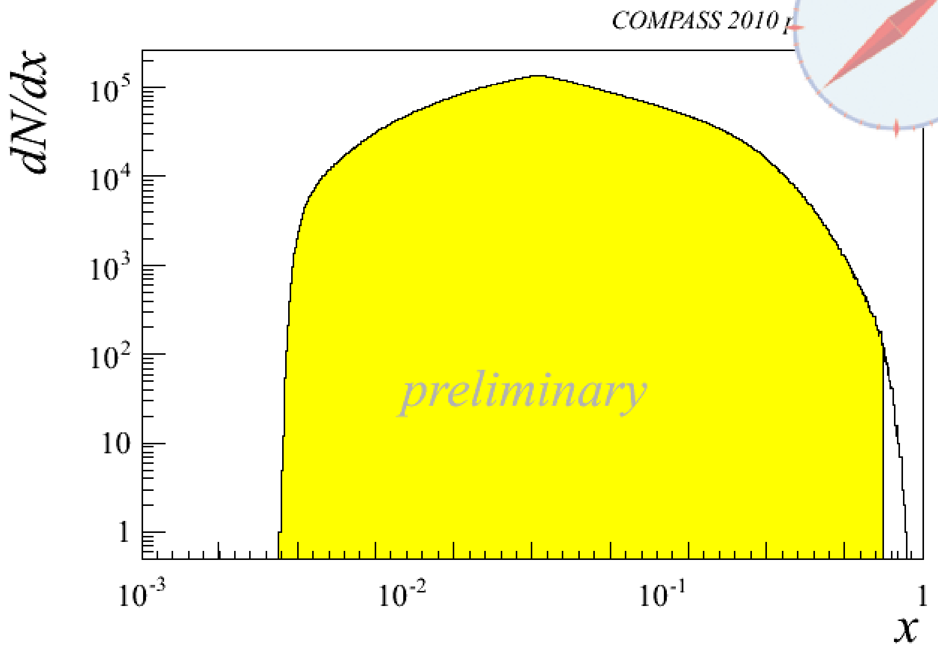


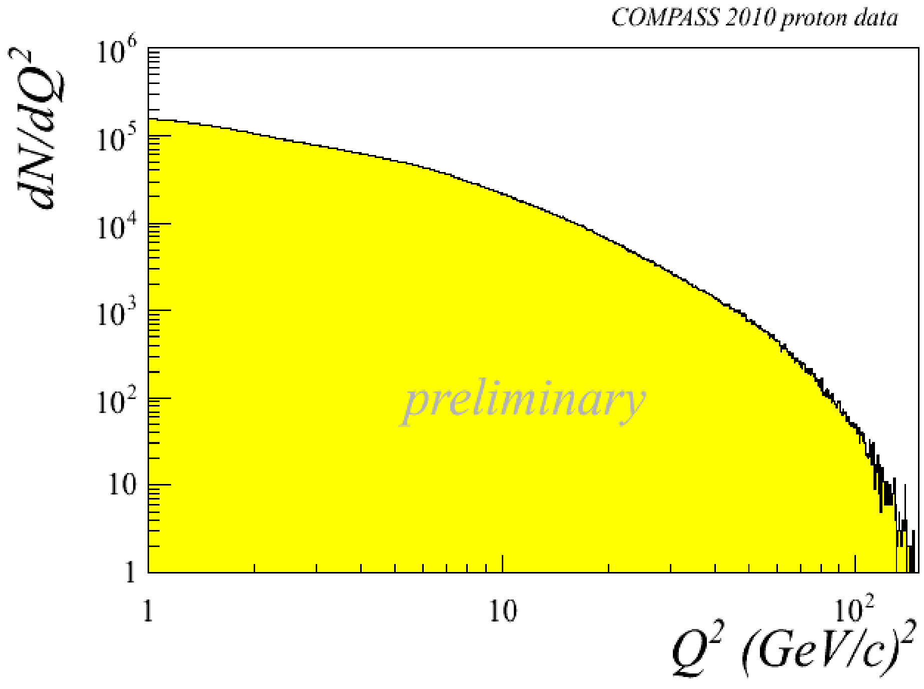


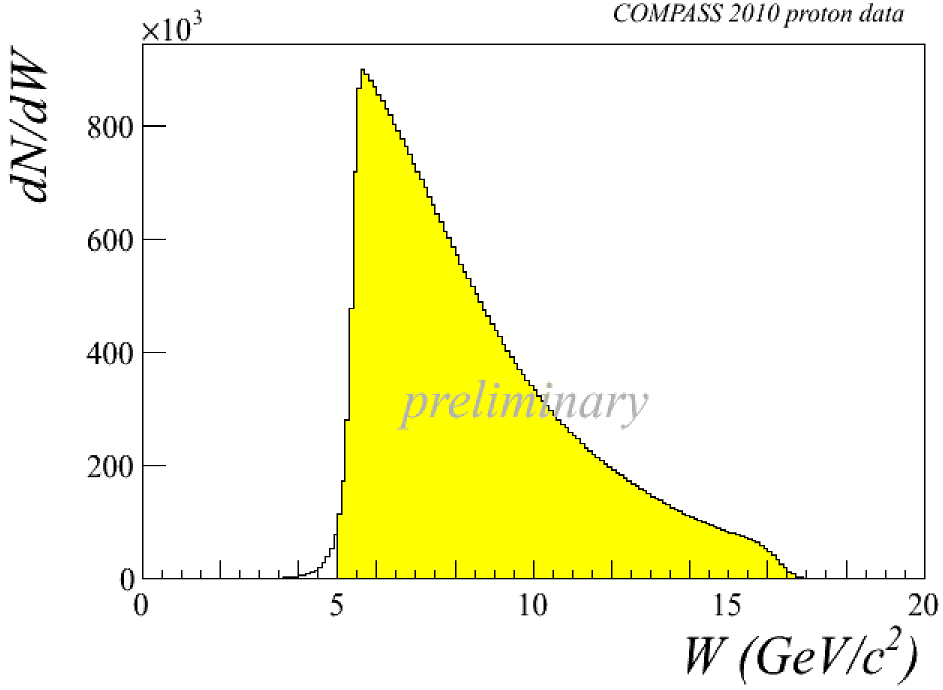


SIDIS event selection

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



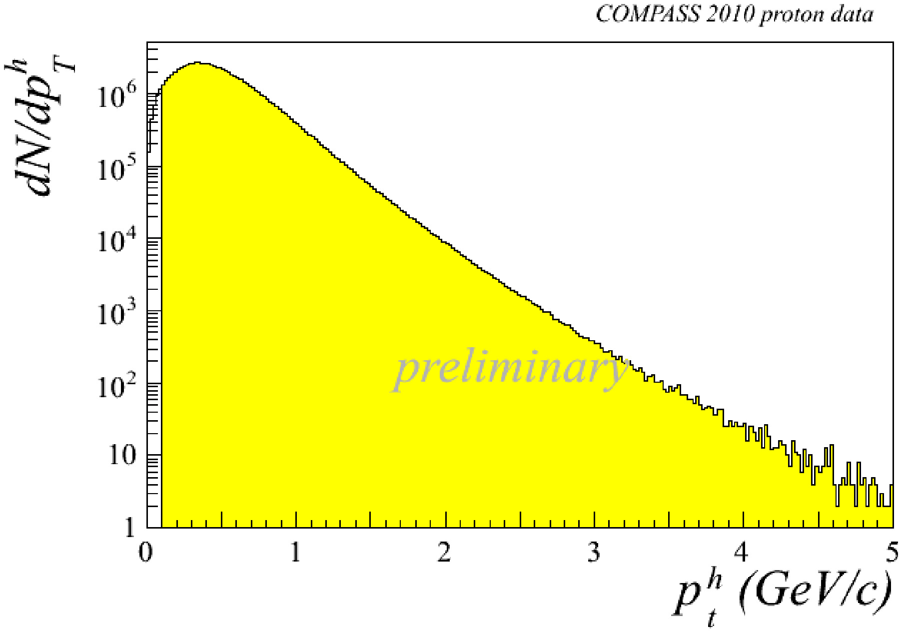


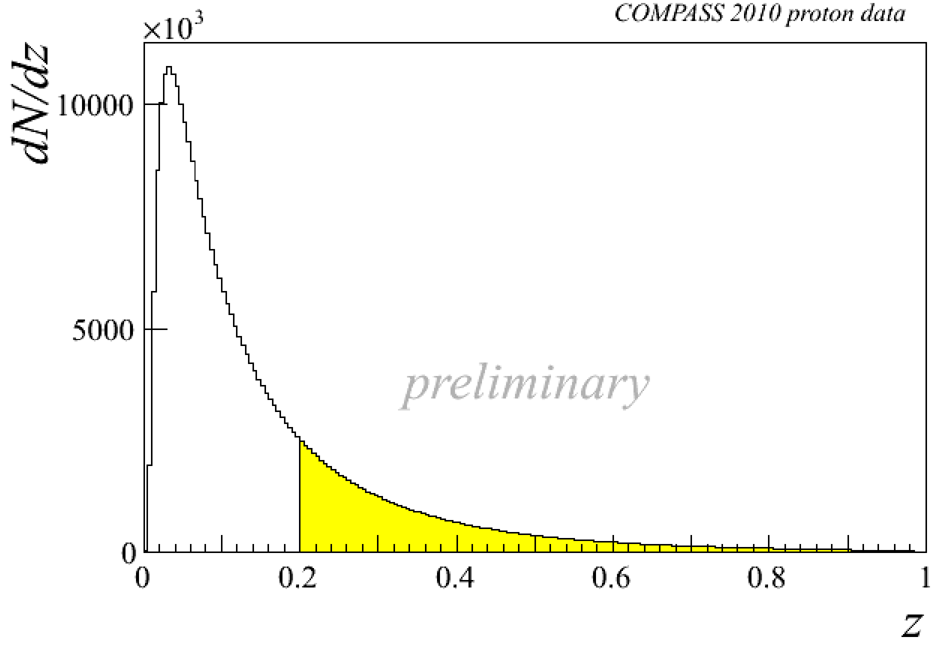


SIDIS event selection

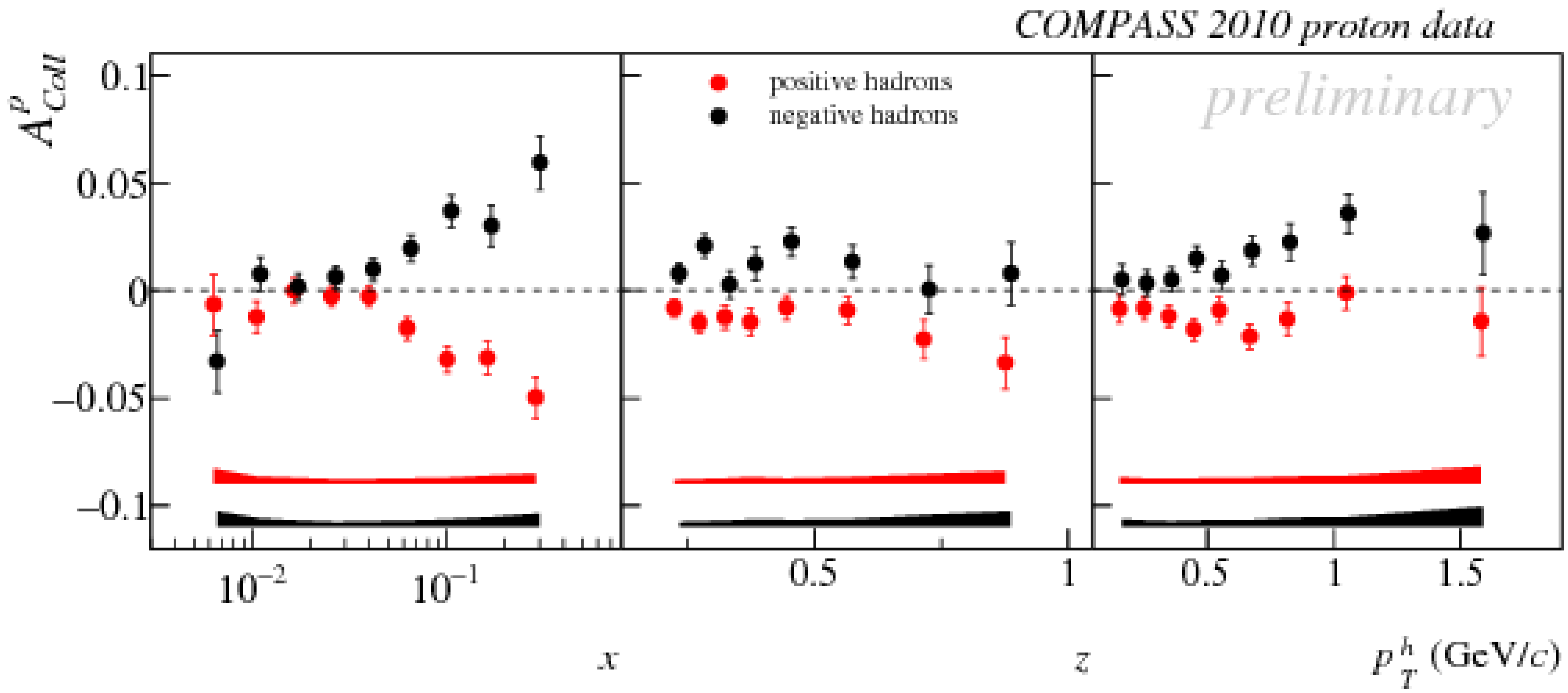
DIS cuts: $Q^2 > 1$ (GeV/c)^2
$0.1 < y < 0.9$
$W > 5$ GeV/c^2

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





Collins asymmetry   2010 data



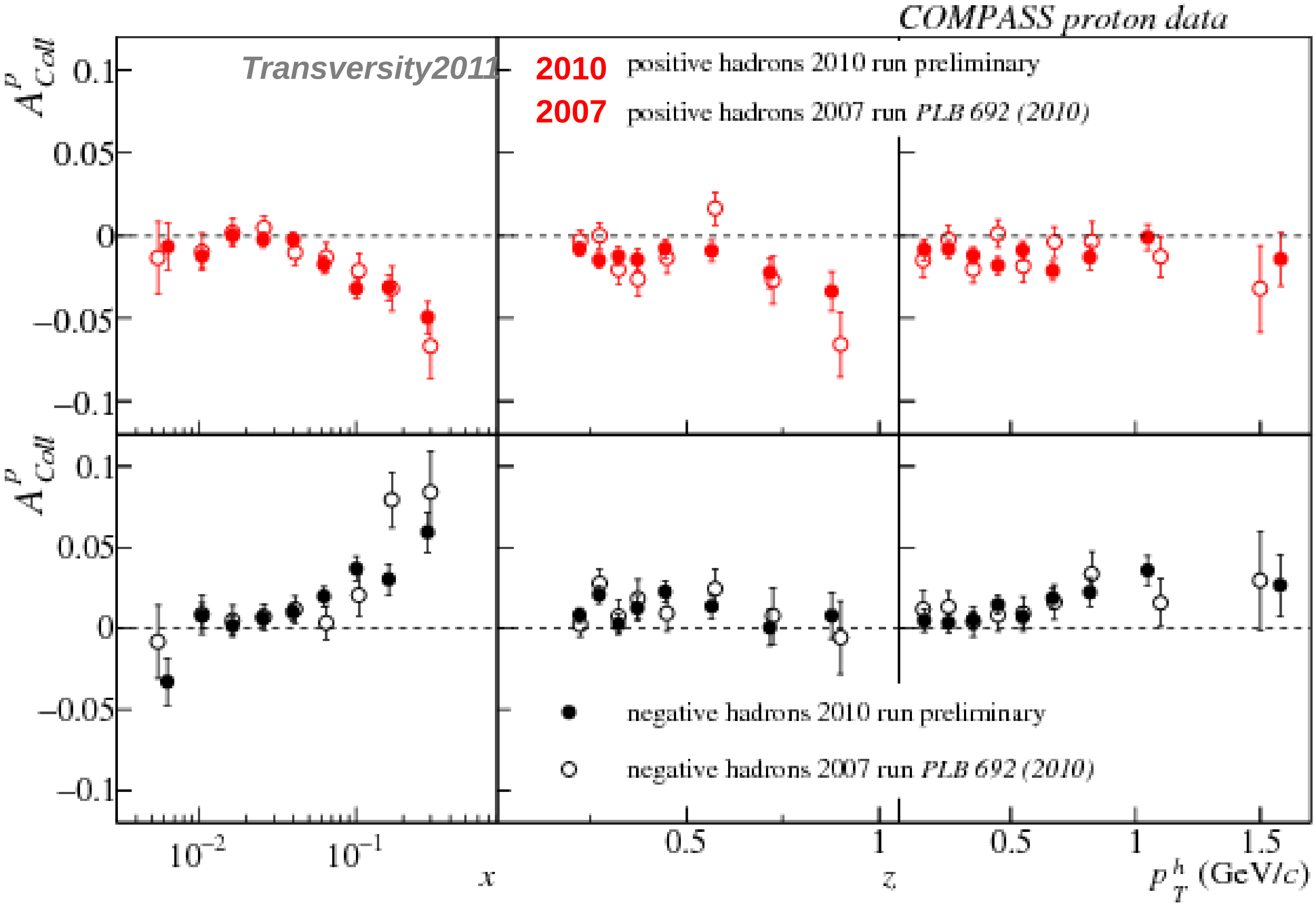
h-

h+

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

nice confirmation of the 2007 results,
with   better statistics

Collins asymmetry 2010 vs 2007 data

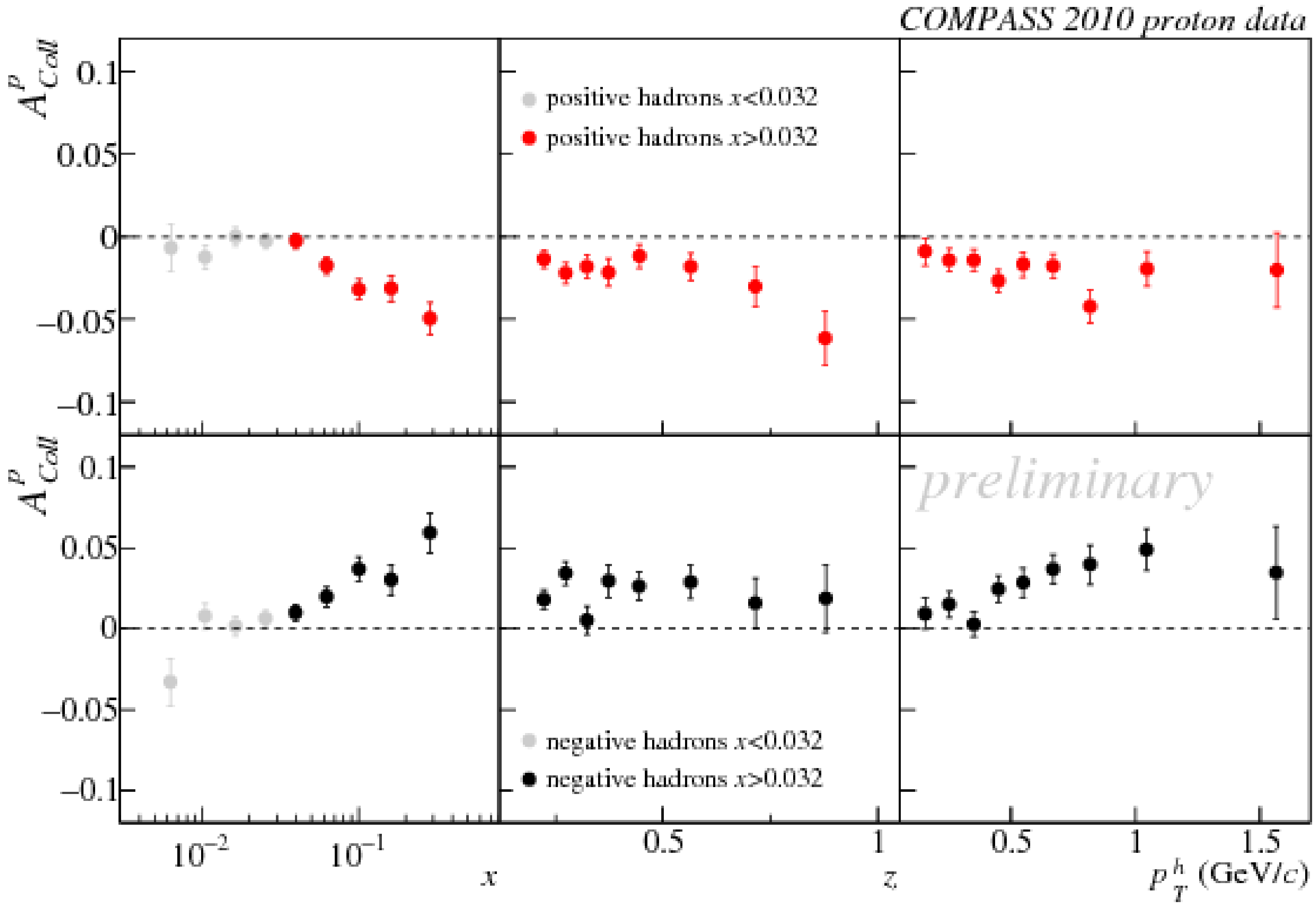


h+

h-

Collins asymmetry   2010 data

x > 0.032 region

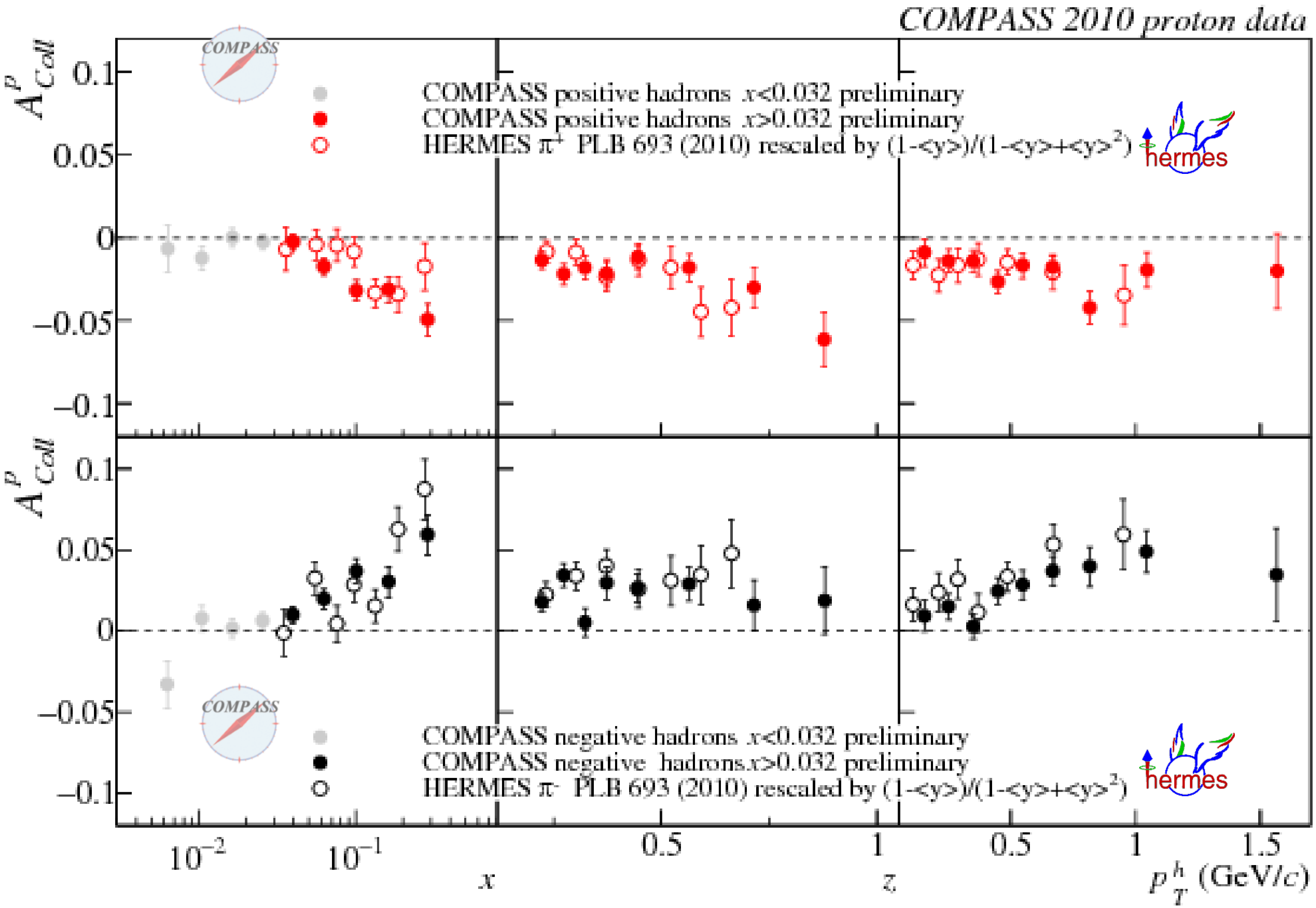


h+

h-

Collins asymmetry 2010 data

x > 0.032 region - comparison with HERMES results



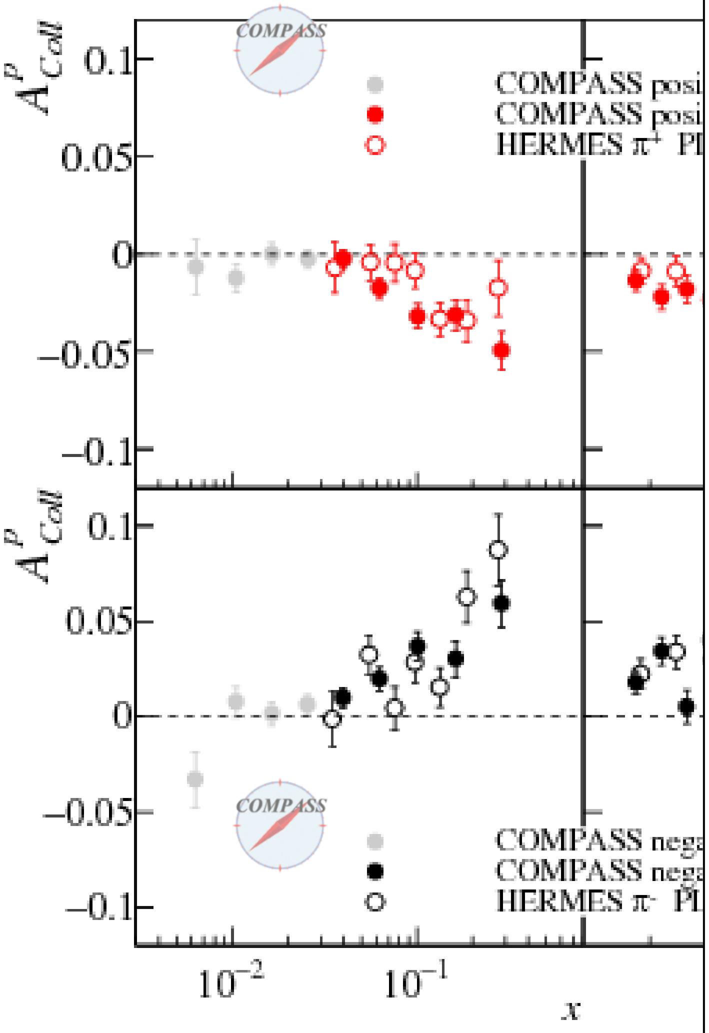
h+

h-

nice agreement

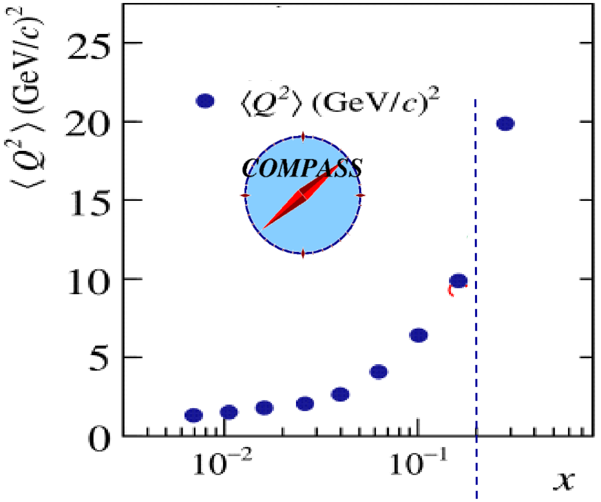
Collins asymmetry 2010 data

x > 0.032 region - comparison with HERMES results

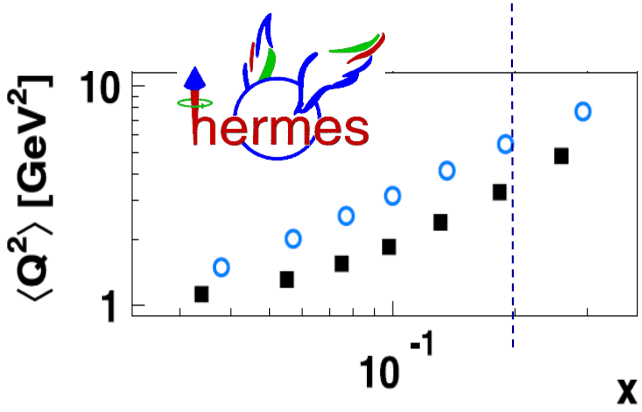


nice agreement

same strength:
a very important, not obvious result!



~12



~ 4

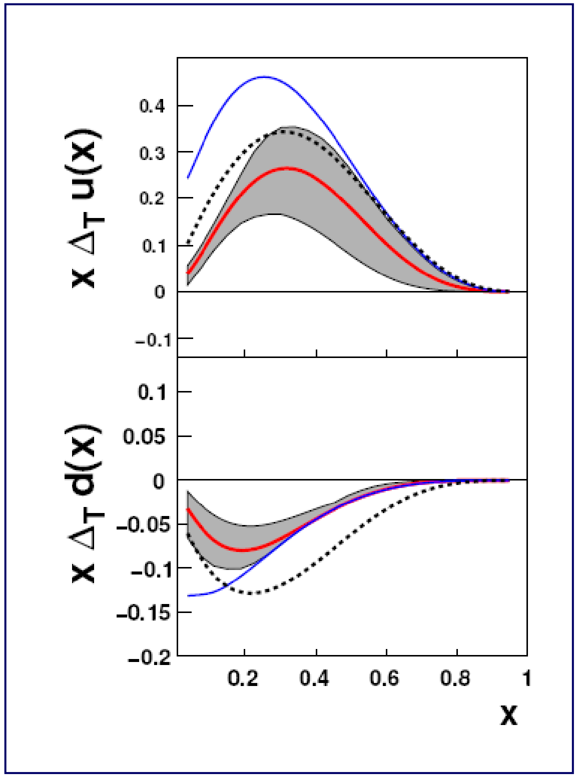
indication for not a higher twist effect,

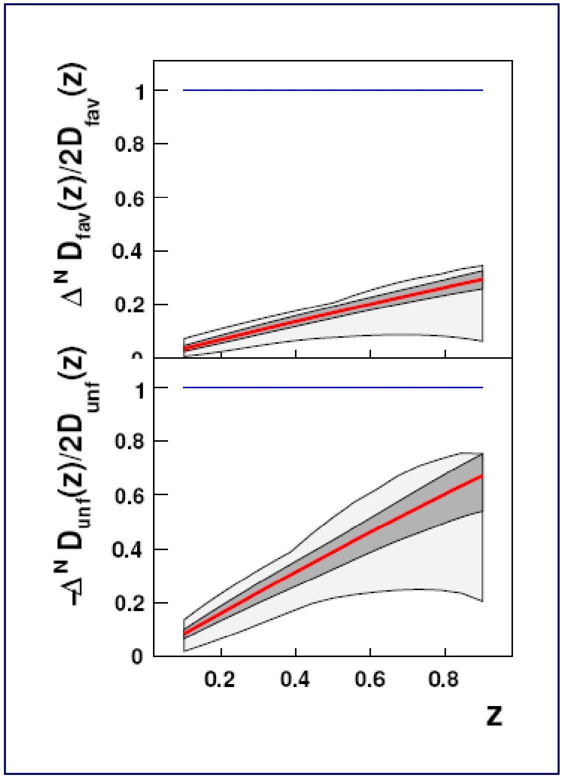
no strong Q^2 dependence of the Collins FF

Collins asymmetry

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

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

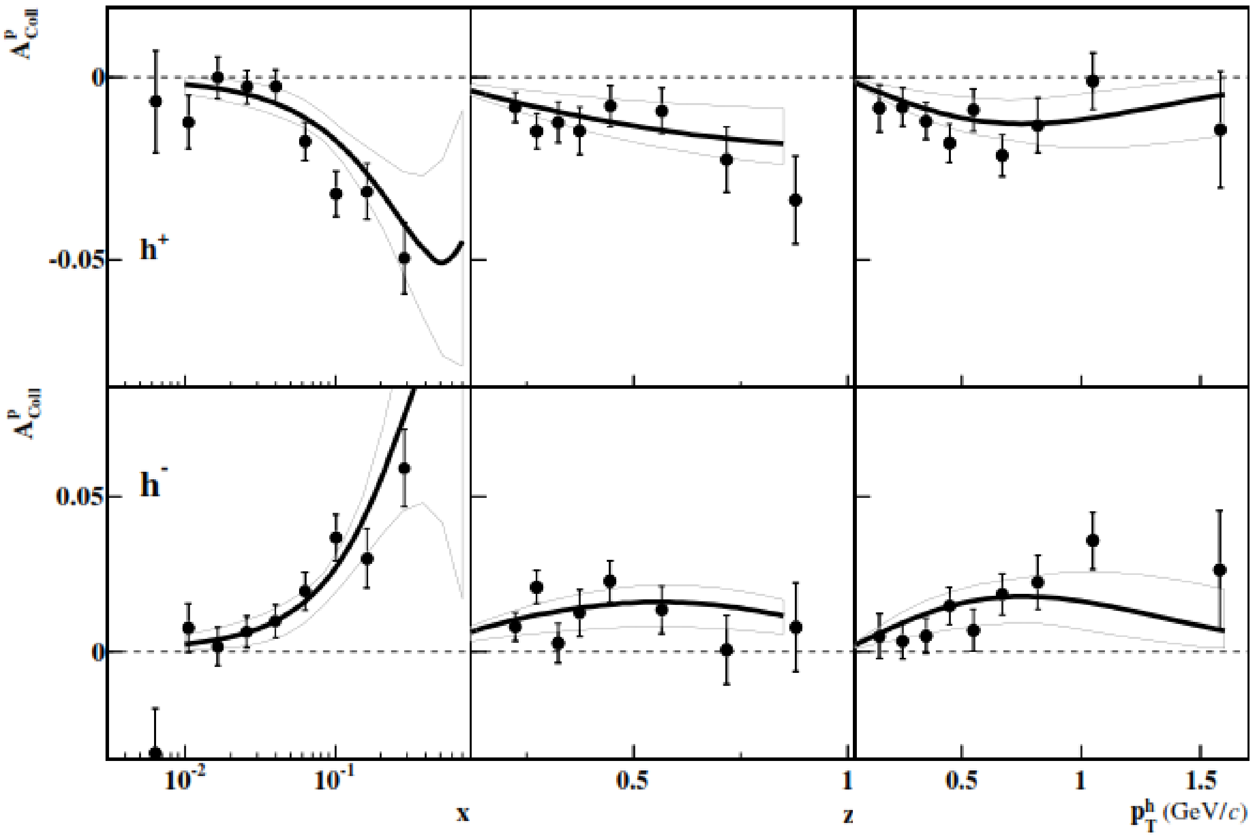




Collins asymmetry

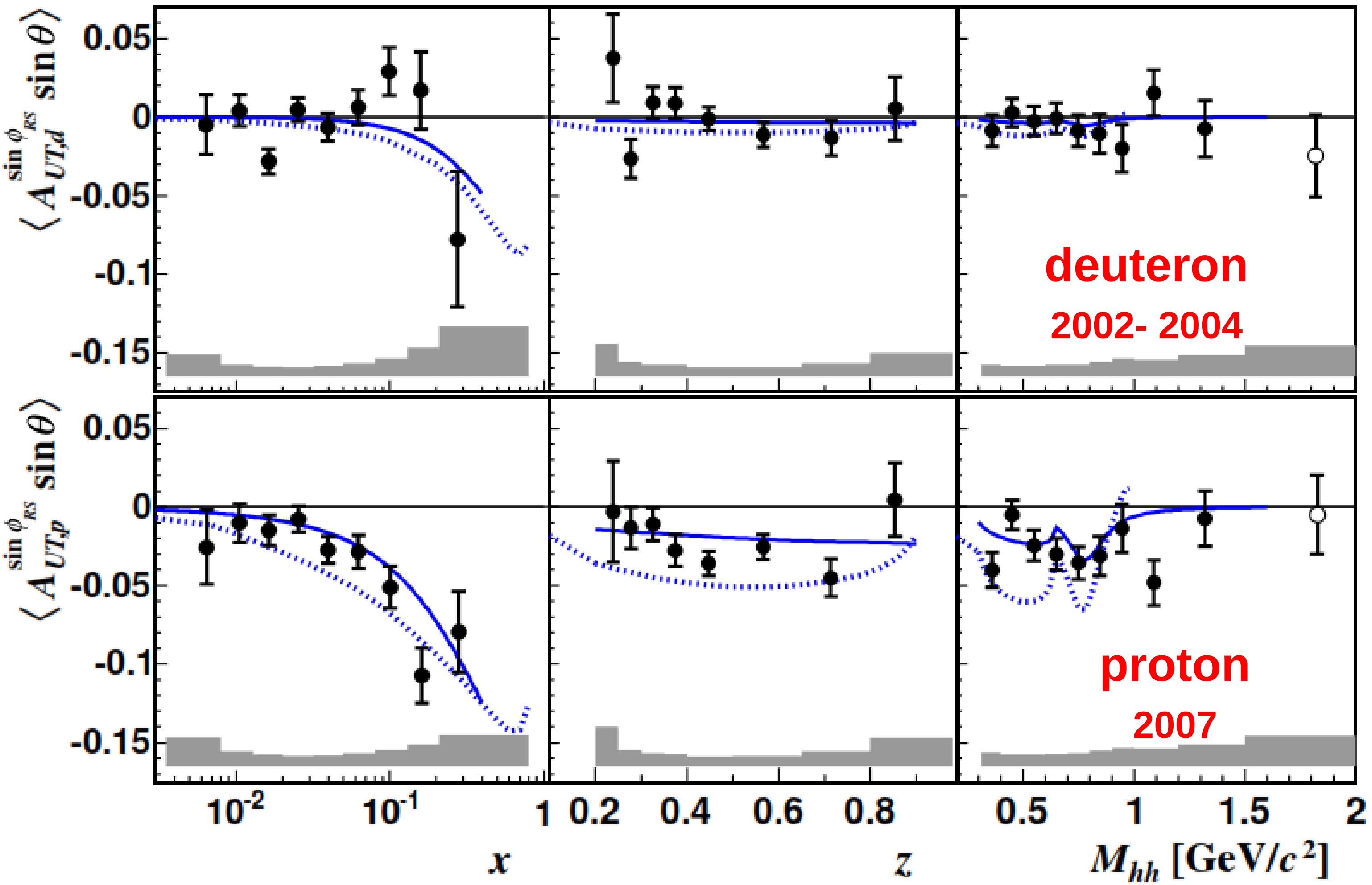
M. Anselmino et al., Nucl. Phys. Proc. Suppl. 2009

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



2010 p data

Two hadron asymmetries

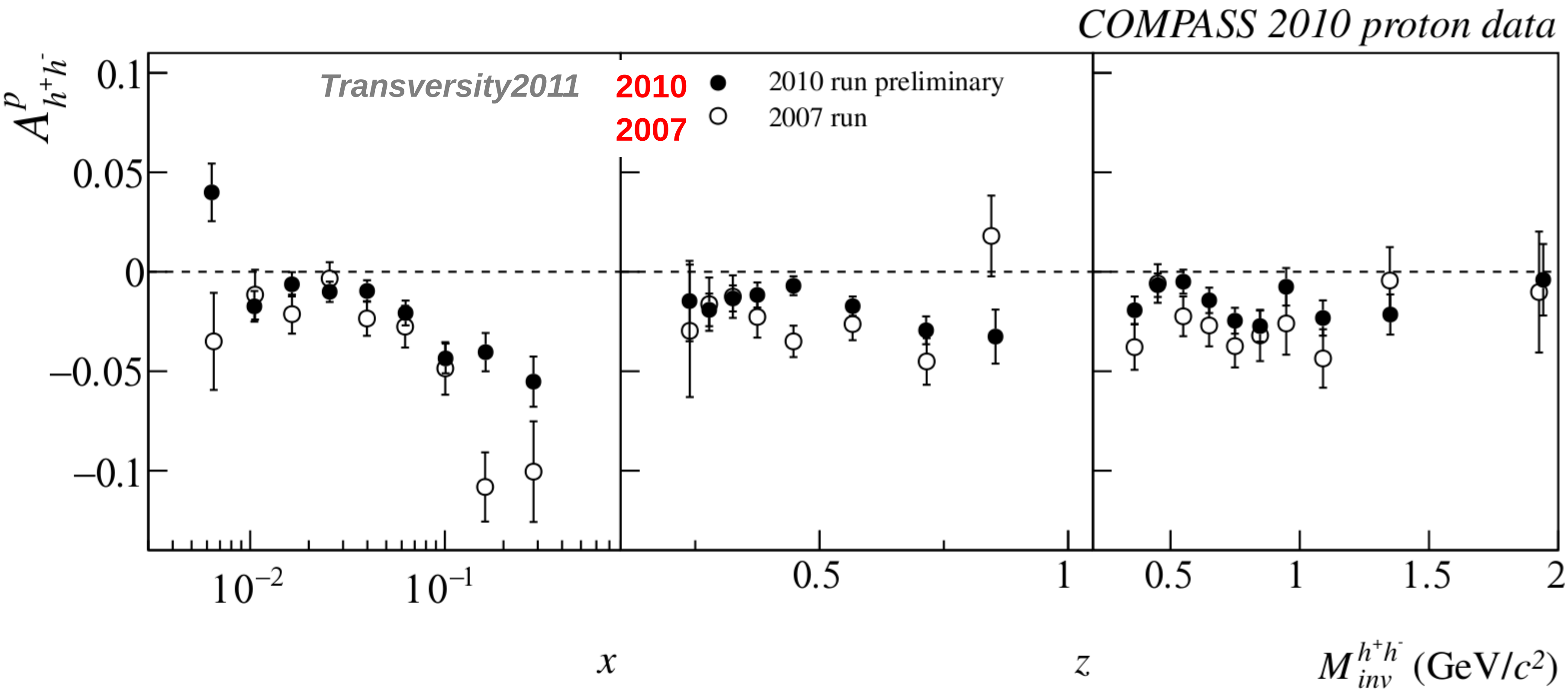


arXiv:1202.6150v1 [hep-ex] 28 Feb 2012

accepted for publication on Phys. Lett. B

Two hadron asymmetries

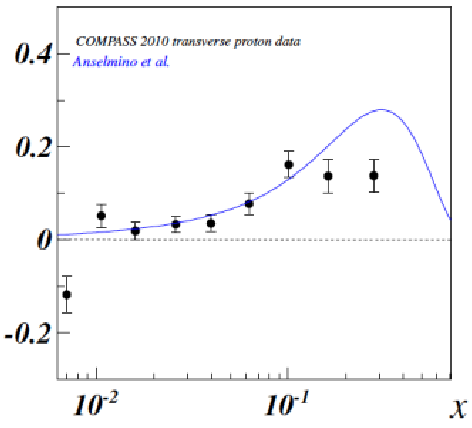
new results from 2010 run



these data and the deuteron data have been used for a first extraction of the u and d quark transversity PDF [C. Elia, PhD th., Trieste Univ.]

COMPASS 2010 proton data

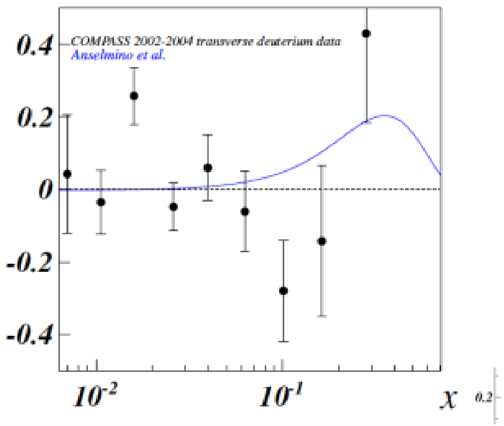
$xh_1^{u_v}(x) - \frac{1}{4}xh_1^{d_v}(x)$



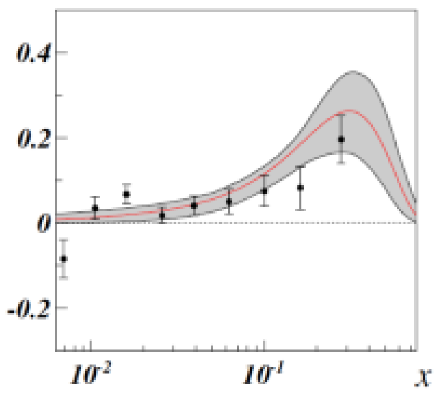
New

COMPASS 2002-2004 deuterium data

$xh_1^{u_v}(x) + xh_1^{d_v}(x)$

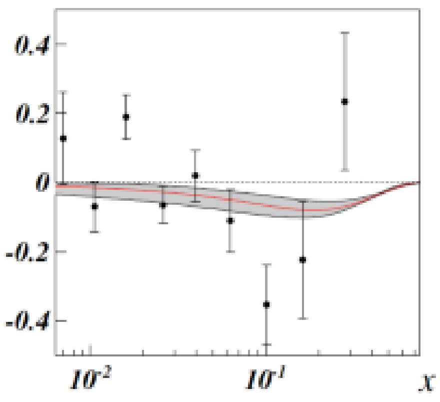


$xh_1^{u_v}(x)$



New

$xh_1^{d_v}(x)$



from C. Elia PhD thesis
using

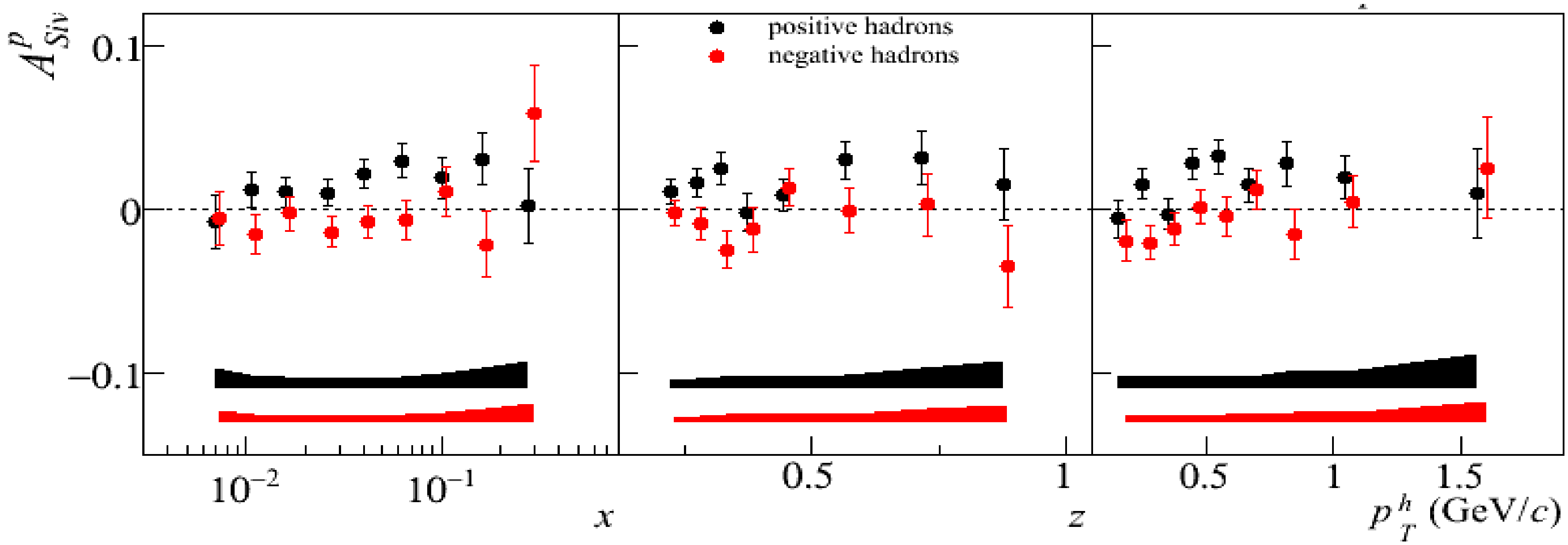
A Bacchetta, A. Courtoy, M Radici

Phys.Rev.Lett.107:012001,2011

Sivers asymmetry

final COMPASS results from 2007 proton data

PLB 692 (2010) 240



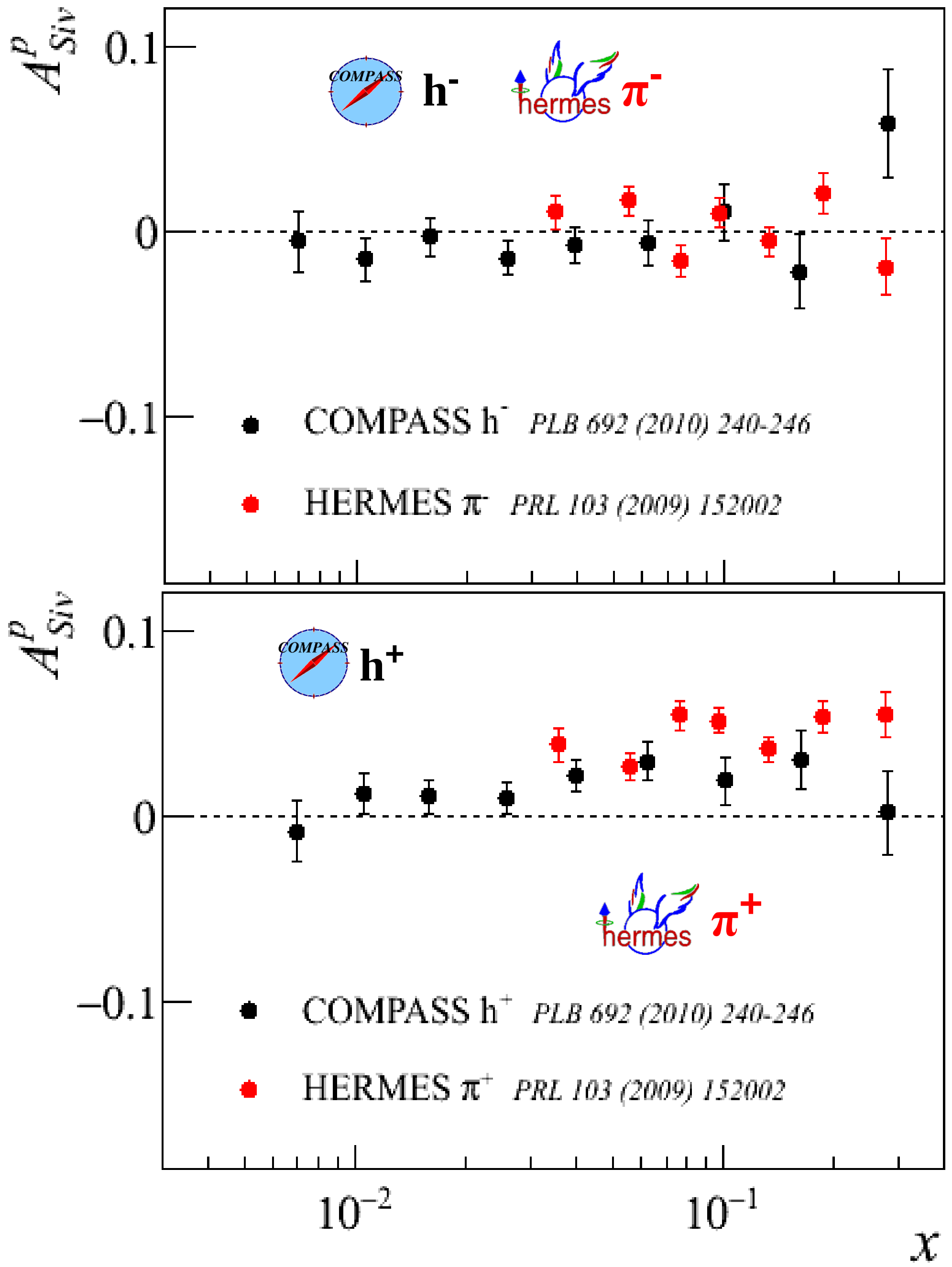
evidence for a positive signal for h⁺,
which extends to small x, in the region not measured before

systematic errors

$h^- \sim 0.5\ \sigma_{stat}$

$h^+ \sim 0.8\ \sigma_{stat}$ plus a scale (abs) uncertainty of ± 0.01

Sivers asymmetry



- good agreements

- same sign

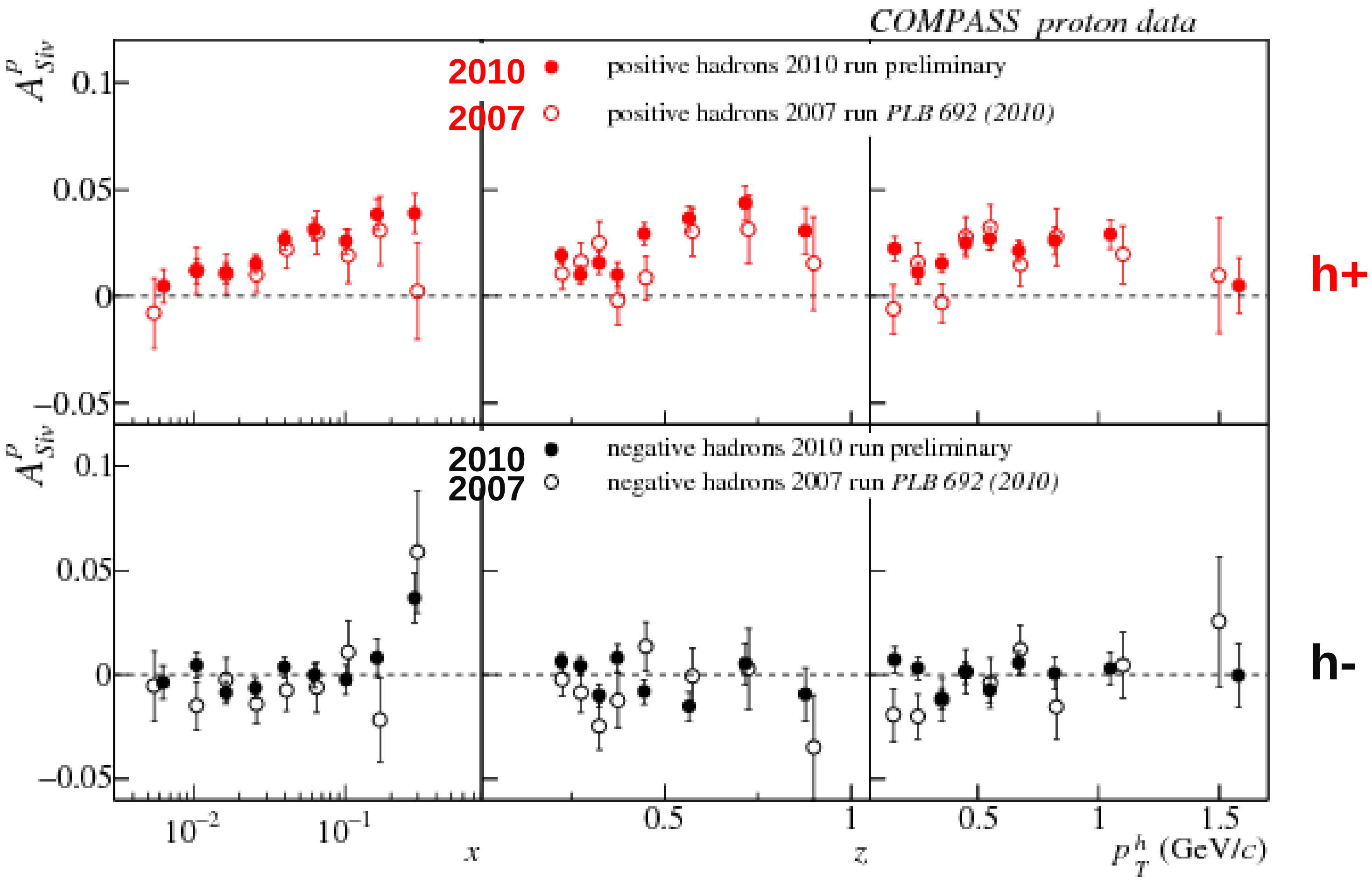
- COMPASS results in the overlap region smaller by a factor ~ 2

higher precision measurements needed soon

→ 2010 run

Anna Martin

the Sivers asymmetry 2010 vs 2007 data



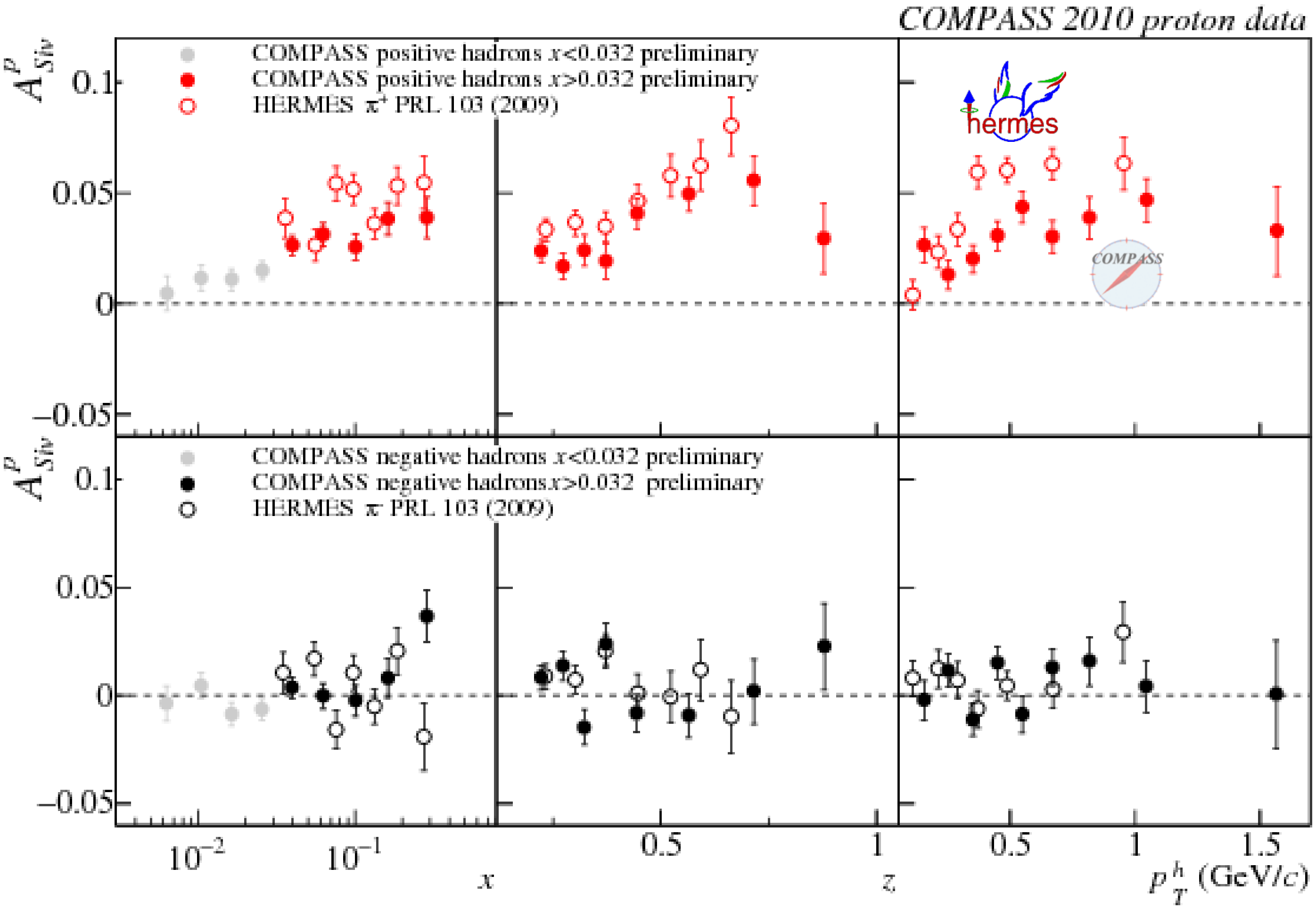
2010 systematic errors

h^- ~ 0.5 σ_{stat}

h^+ ~ 0.5 σ_{stat}

the Sivers asymmetry   2010 data

x > 0.032 region   - comparison with HERMES results



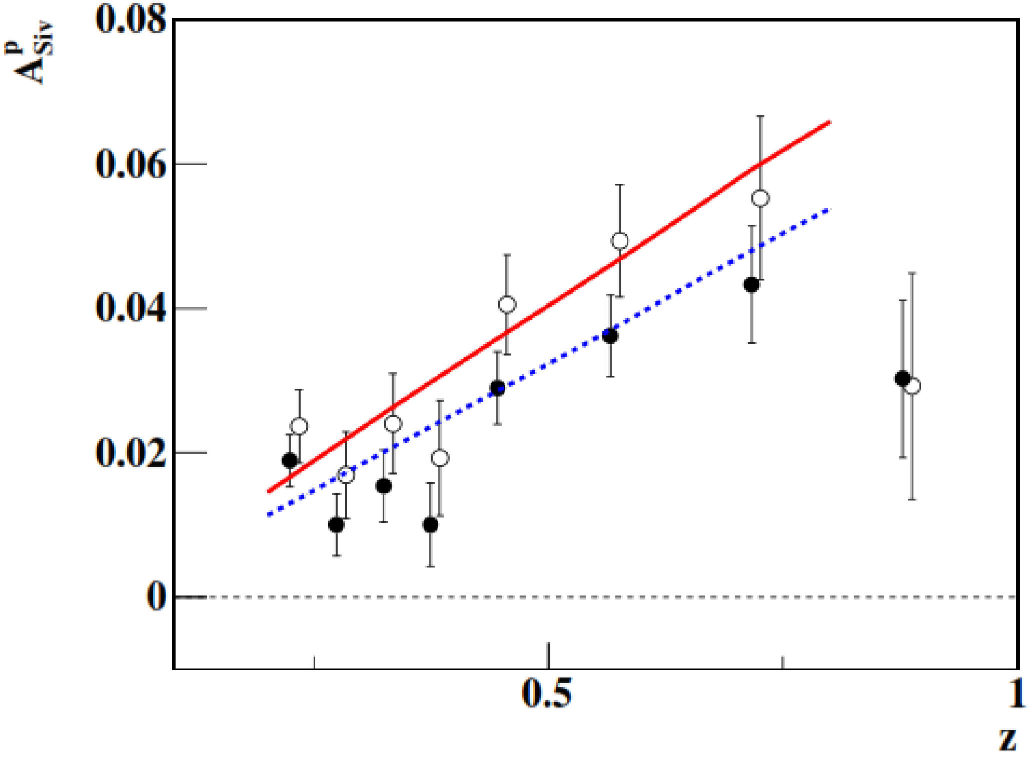
h+

h-

the Sivers asymmetry   2010 data

comparison with

S. M. Aybat, A. Prokudin and T. C. Rogers calculations arXiv:1112.4423



2010 p data

● full x range

○ $0.032 < x < 0.70$

→ M. Anselmino, M. Boglione, S. Melis arXiv:1204.1239

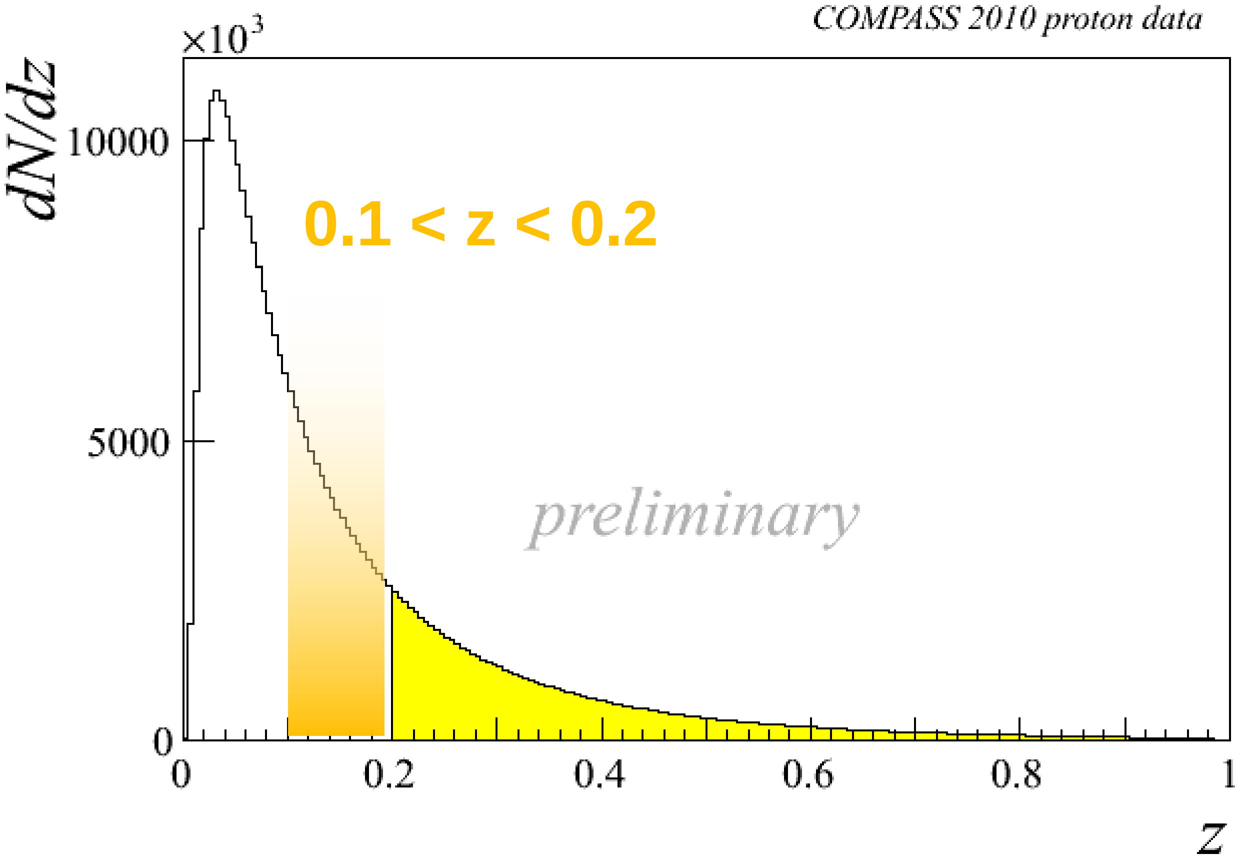
**thanks to the high beam momentum,
we have enlarged the usual COMPASS phase space
still remaining in the DIS CF regime**

- **low z**
- **low y**

Transversity2011

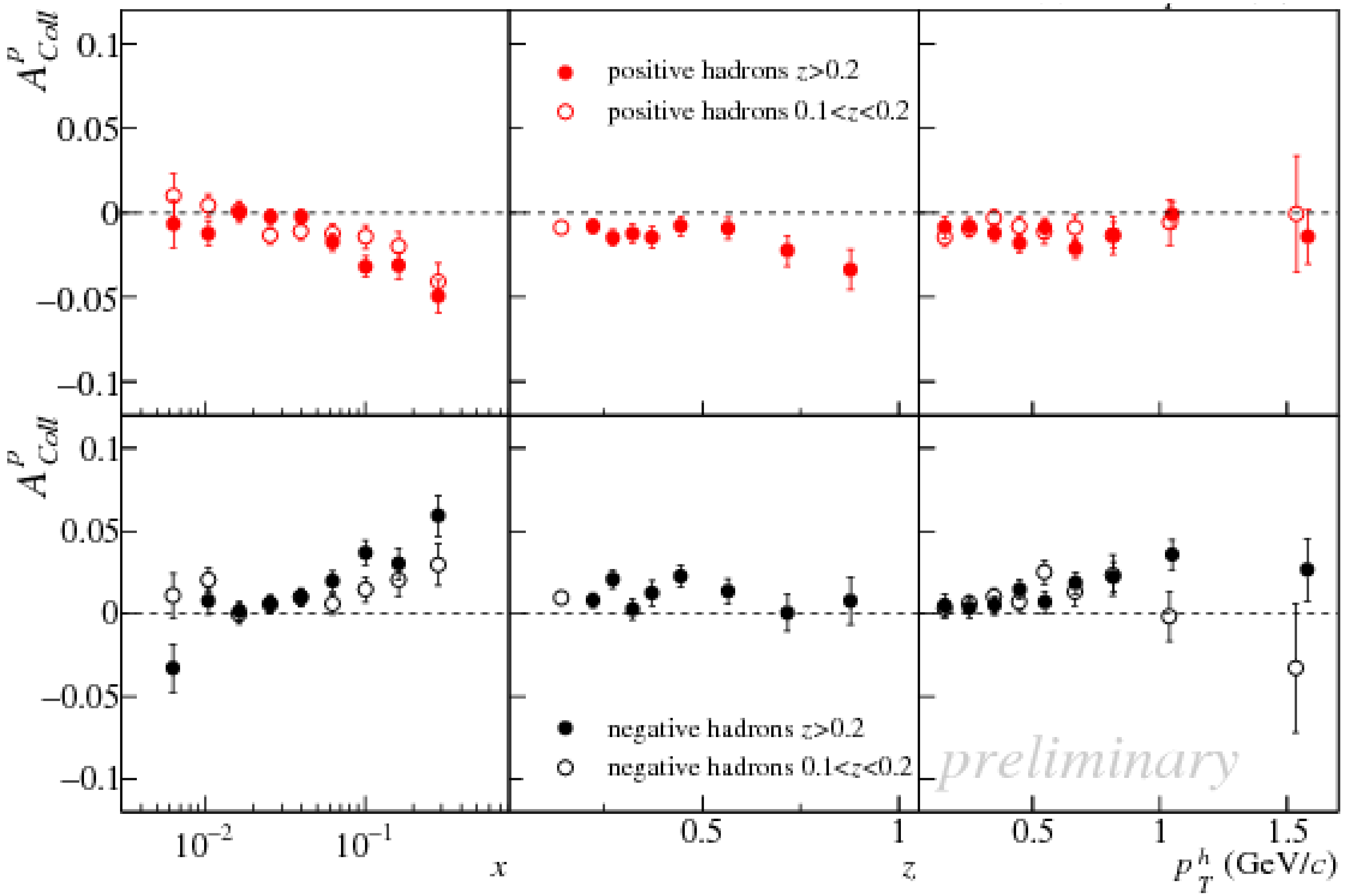
thanks to the high beam momentum, we have enlarged the usual COMPASS phase space still remaining in the DIS CF regime

- **low z**
- **low y**



0.1 < z < 0.2 - **Collins** asymmetry

COMPASS 2010 p data



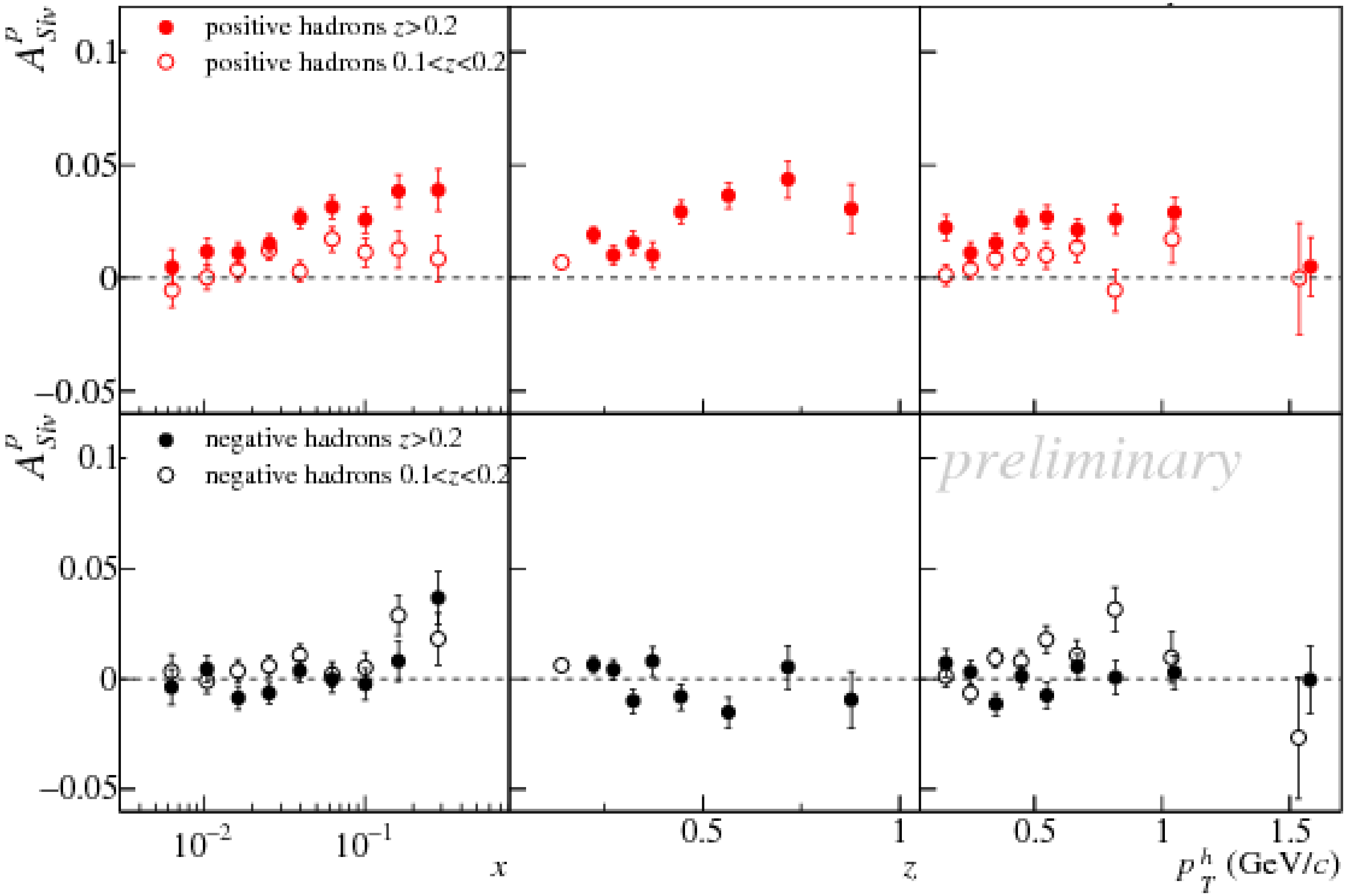
h+

h-

asymmetries somewhat smaller for 0.1<z<0.2 sample

0.1 < z < 0.2 - Sivers asymmetry

COMPASS 2010 p data

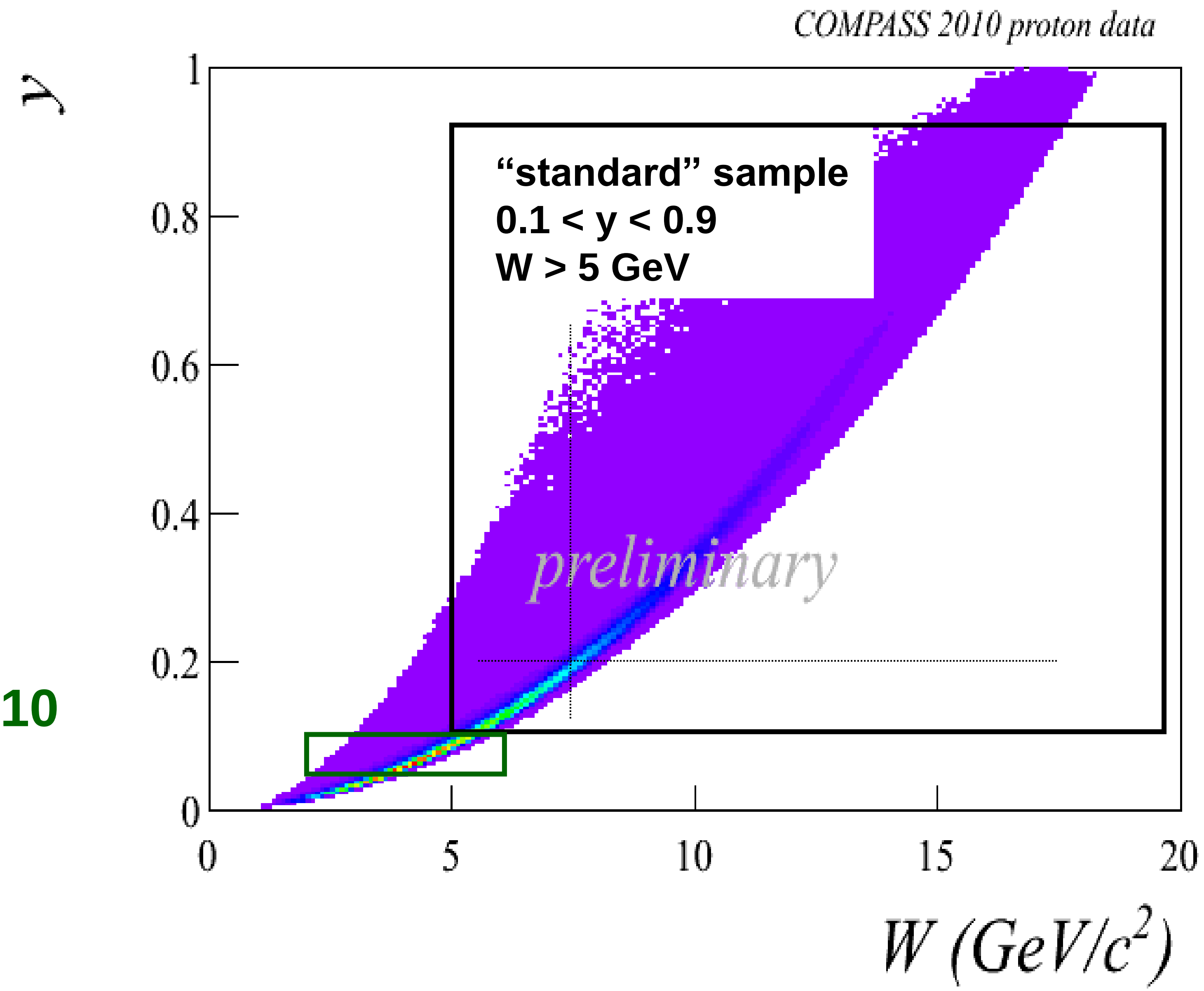


h+

h-

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

low y

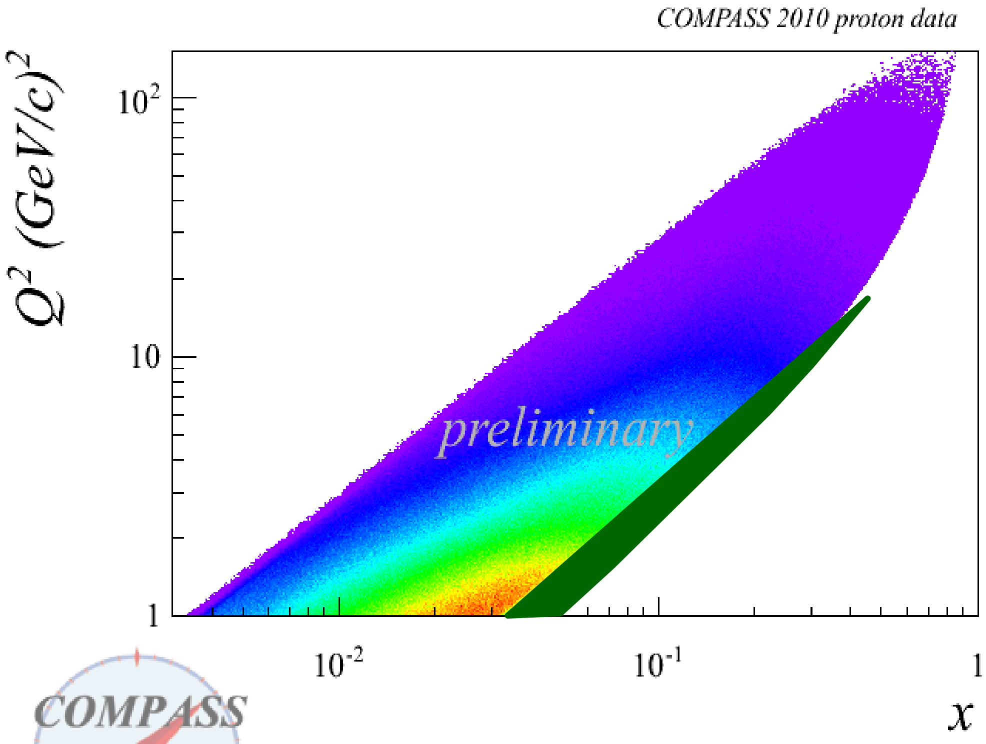


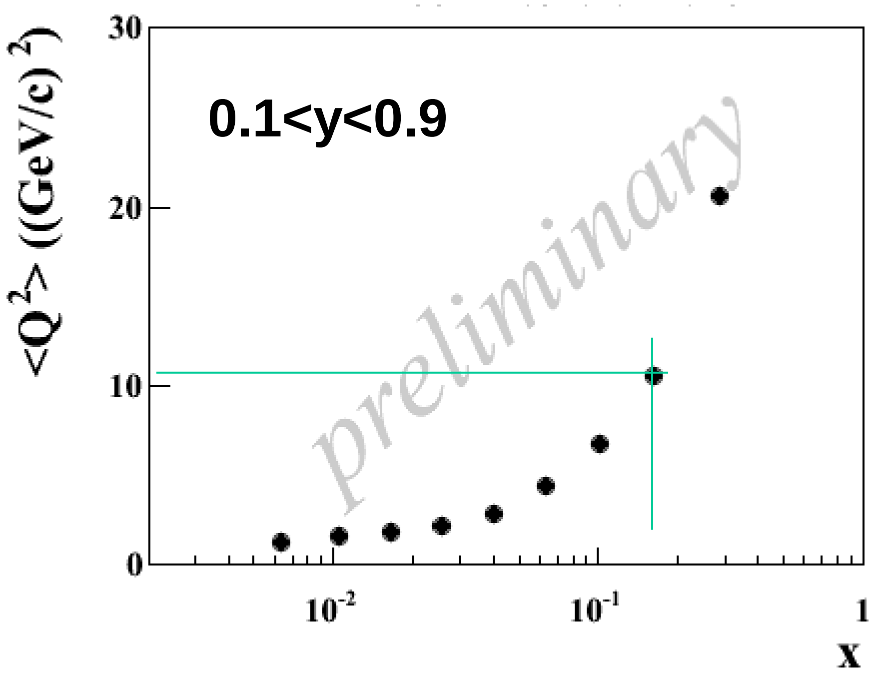
“standard” sample
0.1 < y < 0.9
W > 5 GeV

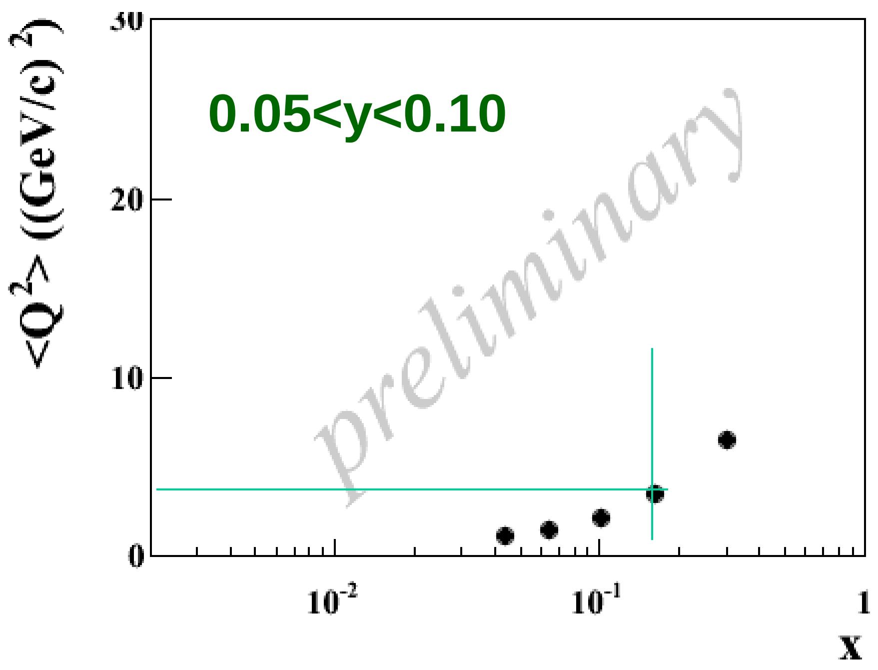
0.05 < y < 0.10 sample

low y

0.05 < y < 0.10 sample

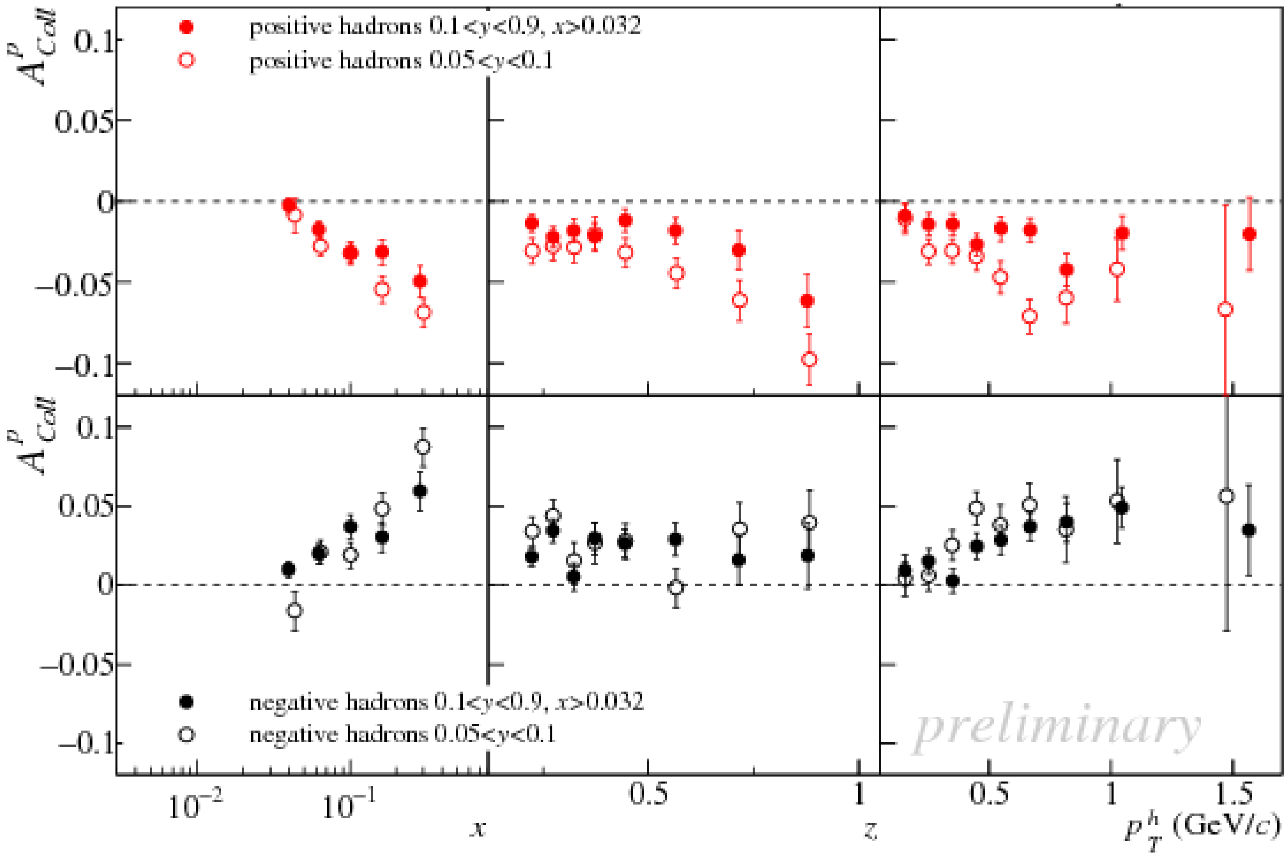






0.05 < y < 0.10 - Collins asymmetry

COMPASS 2010 p data

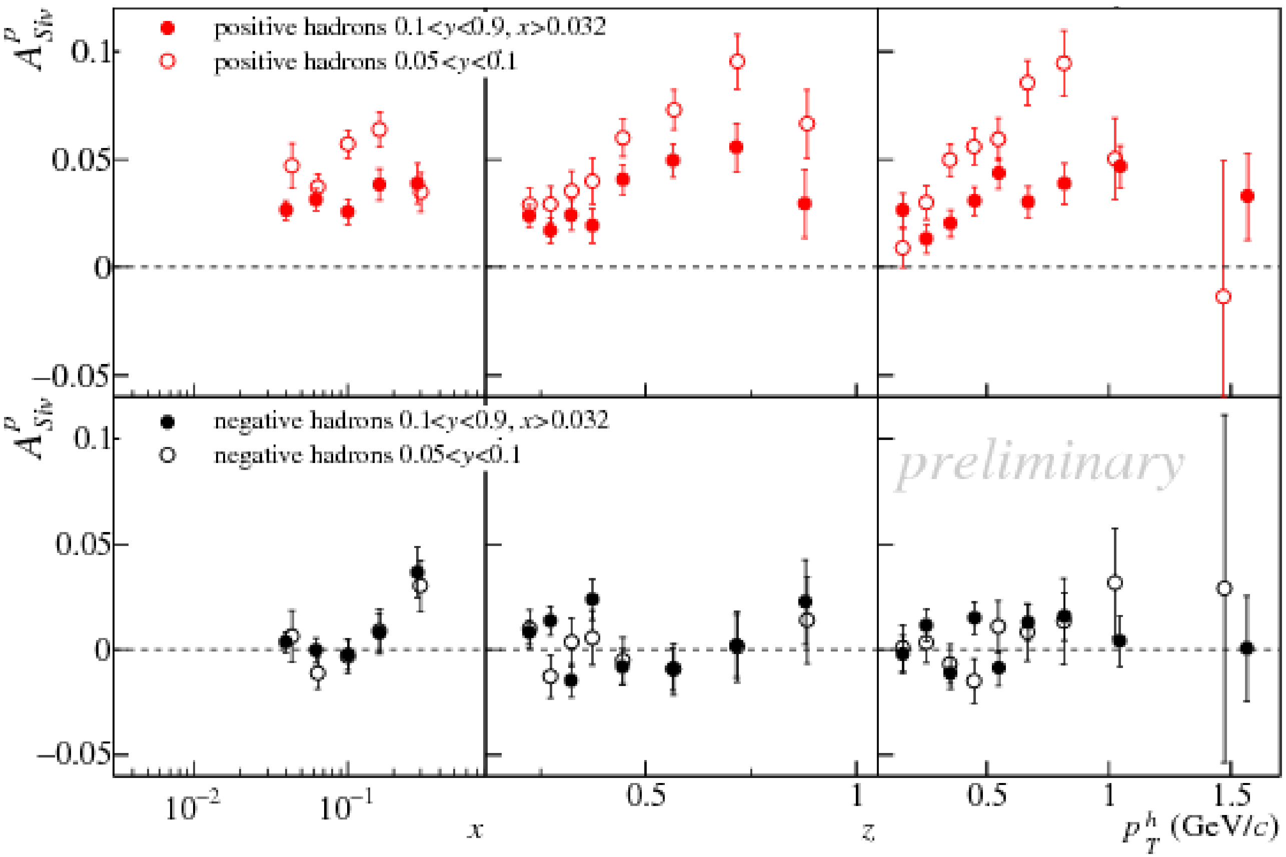


h+

h-

a small effect is visible for h+

0.05 < y < 0.10 - Sivers asymmetry



COMPASS 2010 p data

h+

h-

a clear enhancement of the asymmetry for h+ is observed

in agreement with Q^2 evolution?

summary

COMPASS has produced many important results on SIDIS
transverse momentum and transverse spin asymmetries

- **for unpolarised deuteron,**
  the **cosϕ** and the **cos2ϕ** have been measured to be different from zero and have a strong dependence on kinematic variables

- **polarised deuteron:**
  all the azimuthal spin asymmetries have been found to be compatible with zero

- **transversely polarised proton:**
  all the azimuthal spin asymmetries have been found to be compatible with zero, but:
  - **h^+ and h^- Collins asymmetry** in the valence region (opposite sign)
    no strong dependence on Q^2 / y (LT)
  - **di-hadron asymmetry** ~ Collins asymmtery
  - **h^+ Sivers asymmetry** over all the x range
    dependence on Q^2 / y (Q^2 evolution?)

  high precision measurements exist

future

from existing data COMPASS will produced new results on SIDIS transverse momentum and transverse spin asymmetries

- **unpolarised deuteron**:
  dependence on the kinematical variables of
  cosϕ and **cos2ϕ** asymmetries
  multiplicities

- **longitudinally polarised proton and deuteron**:
  - precise measurement of all the **azimuthal asymmetries**

- **transversely polarised proton**:
  - precise measurement of all the **other azimuthal asymmetries**
  - further studies of the dependence on the different kinematical variables of **Collins and Sivers asymmetries** (multidimensional analysis)

- **particle identification**

future

on a longer scale, new measurements:

COMPASS phase 2

- **Drell-Yan in $\pi^- p^\uparrow$** **2014**
- **Deeply Virtual Compton Scattering with**
  - LH target
  - 160 GeV muons

  2015-2016

  to access **GPDs**

  in parallel: precise measurements of **SIDIS off unpolarised protons**

in waiting for the collider, CERN is the only lab where to measure high energy SIDIS,
in a phase space complementary to that of JLab12 experiments:

it would be important to make a few urgent measurements e.g. SIDIS off transversely polarized deuterons