COMPASS Results on Transverse Spin and Transverse Momentum Effects

Anna Martin
Trieste University & INFN (Italy)
on behalf of the COMPASS Collaboration

DIS 2010

OUTLOOK

- the COMPASS experiment
- Collins asymmetry
- Sivers asymmetry

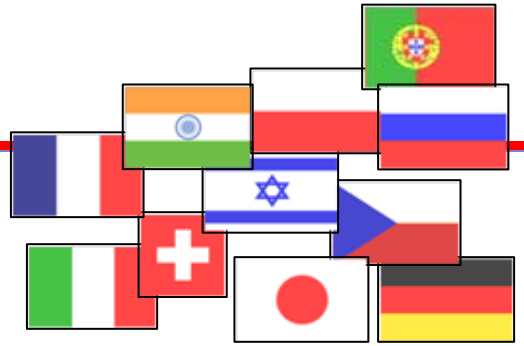
} new results !

many topics not covered ...

- future measurement

COMPASS

a long story of measurements….



fixed target experiment at the CERN SPS
broad physics programme

SIDIS measurements: the spin structure of the nucleon

2002
2003 } **deuteron** (^{6}LiD) **polarised target — L & T**
2004

2006 **deuteron** (^{6}LiD) **polarised target — L only**
2007 **proton** (NH_3) **polarised target — L & T**

muon beam: 160 GeV/c longitudinal polarisation -80%
intensity $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)

Spectroscopy with hadron beams

2008
2009

COMPASS SET-UP for muon running

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

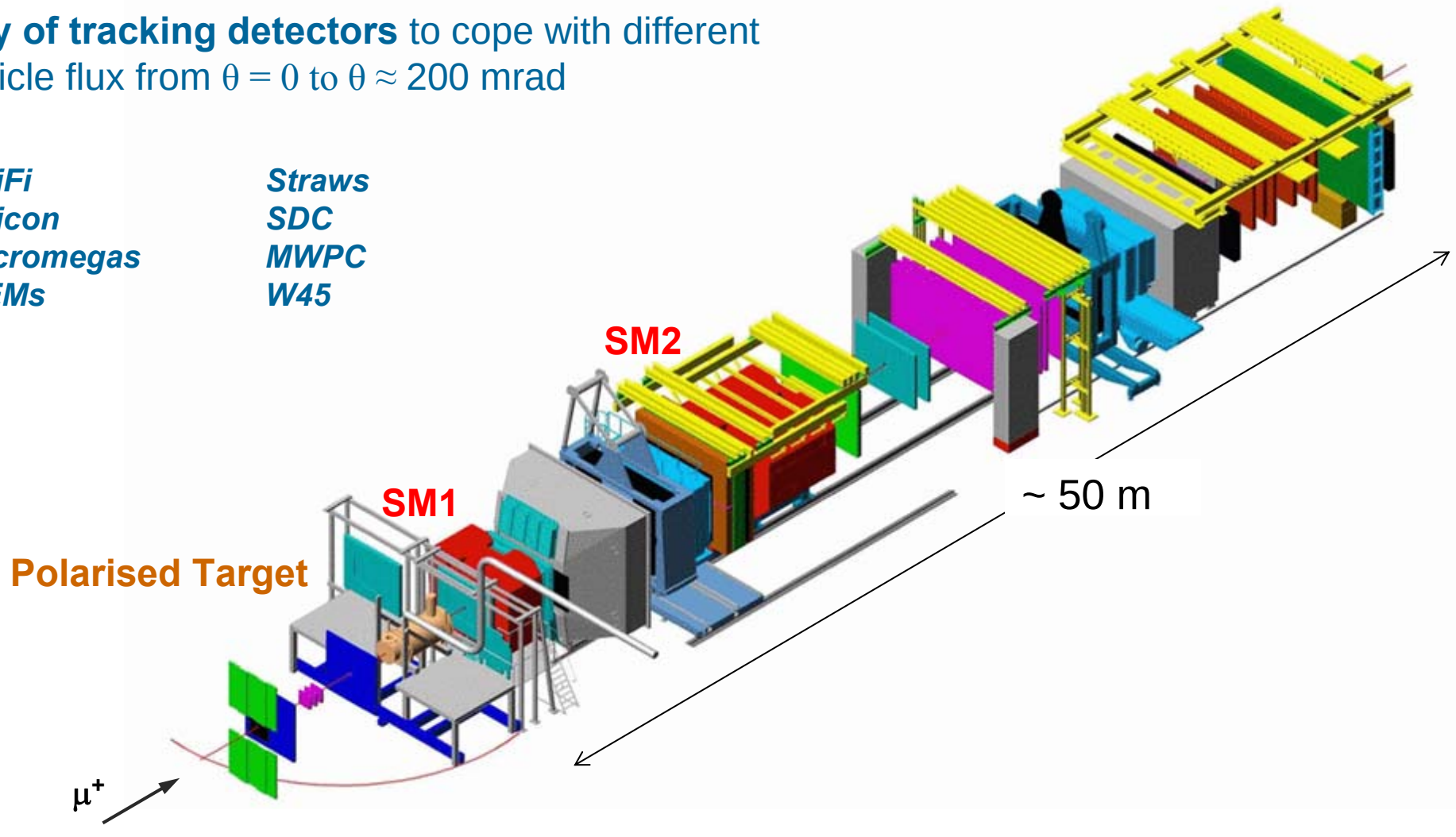
two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

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

SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*



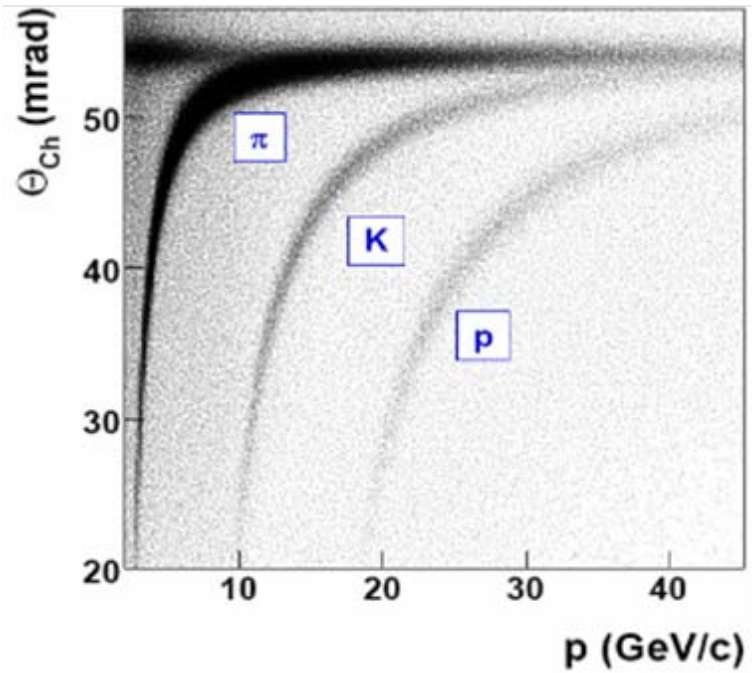
COMPASS SET-UP for muon running

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

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)



calorimetry, PID

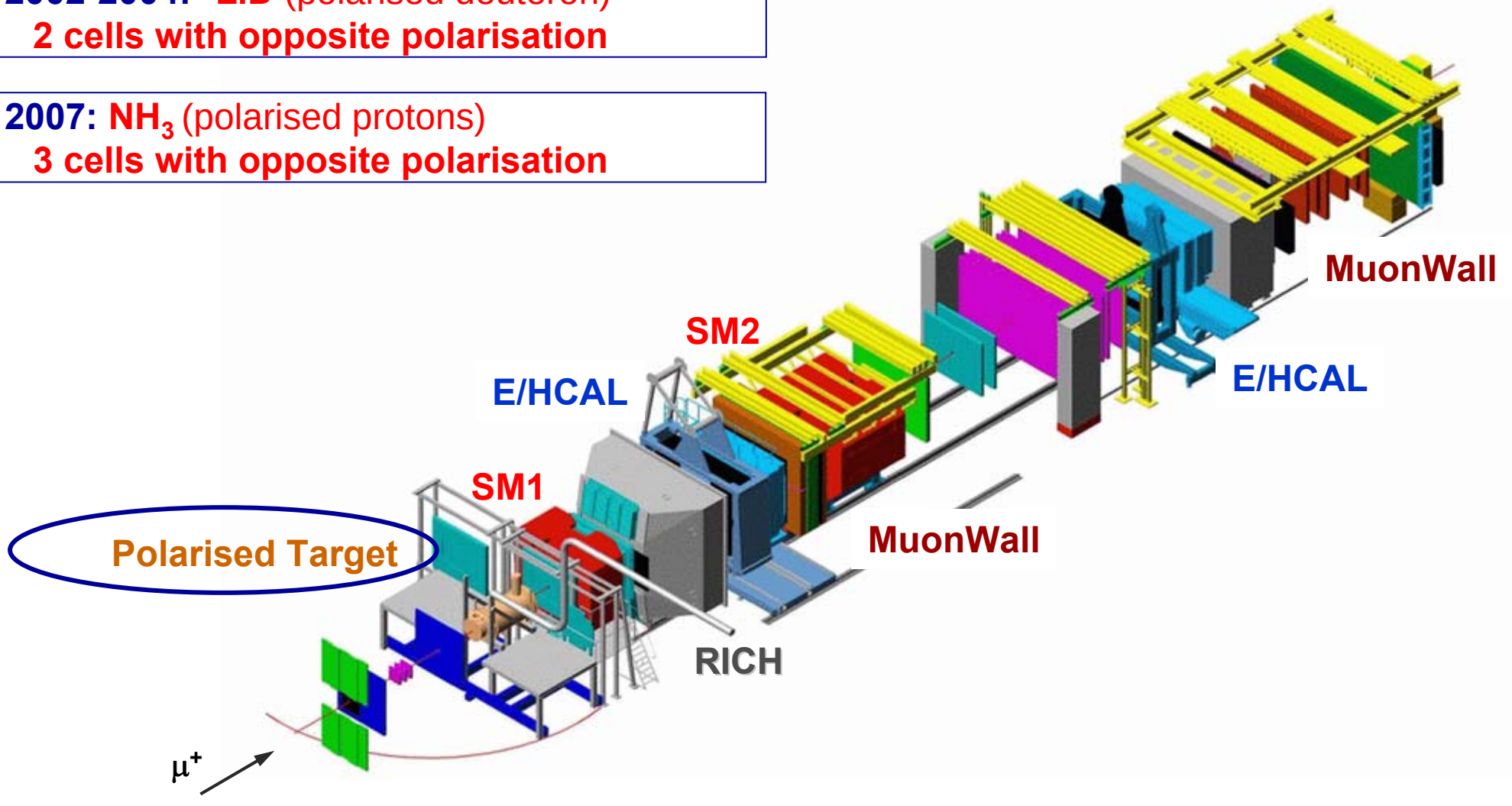
RICH detector

COMPASS SET-UP for muon running

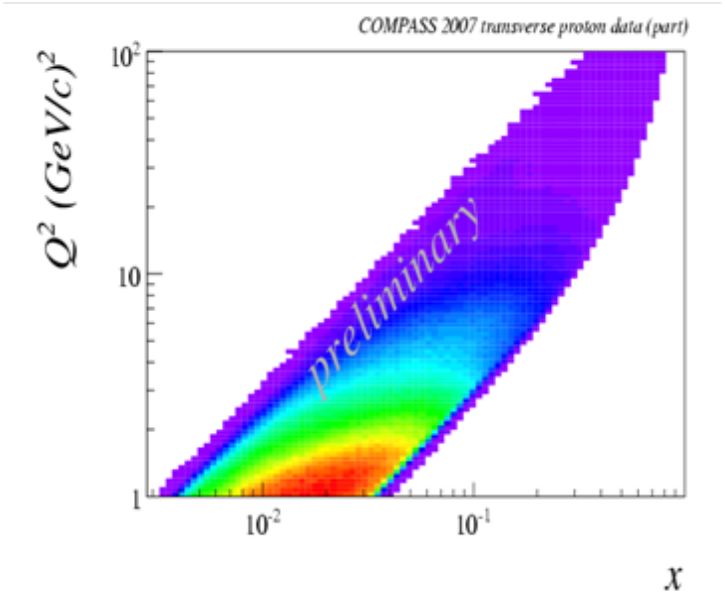
solid state target operated in frozen spin mode, 120 cm long

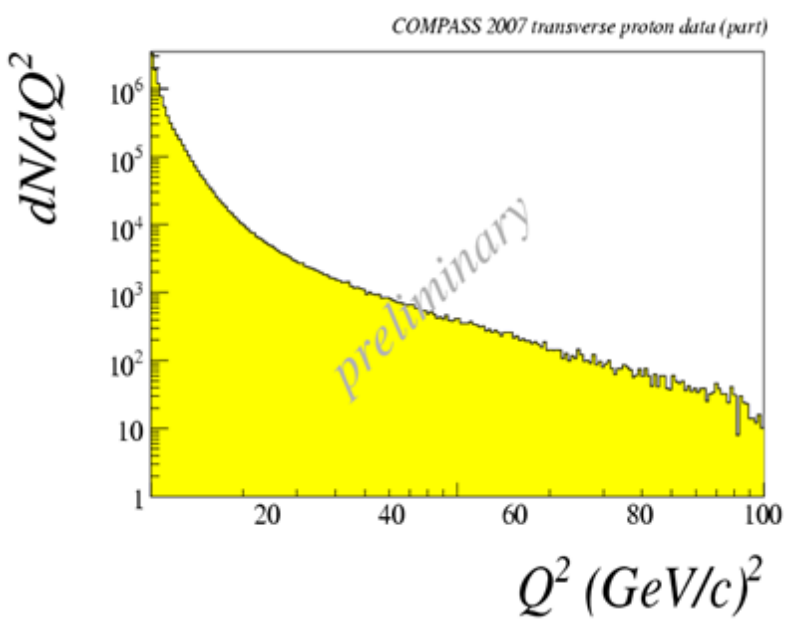
2002-2004: ^{6}LiD (polarised deuteron)
2 cells with opposite polarisation

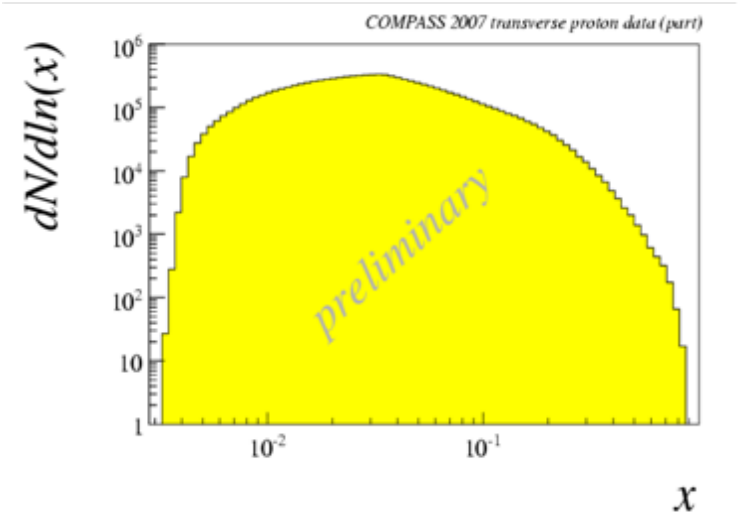
2007: NH_3 (polarised protons)
3 cells with opposite polarisation

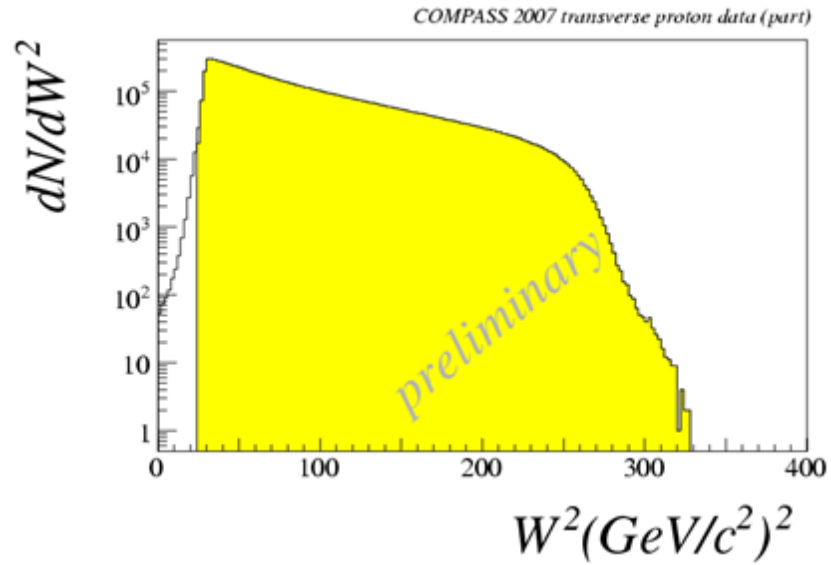


SIDIS event selection









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

hadron selection: p^h > 1.5 GeV/c, $p_T{}^h$>0.1 GeV/c, z>0.2

- the COMPASS experiment
- **Collins asymmetry**
- Sivers asymmetry

The Structure of the Nucleon

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

nucleon polarization

quark polarization	U	L	T
U	f_1  *number density*		
L		g_1  *helicity*	
T			h_1  *transversity*

$\Delta_T q$

Transversity PDF

is chiral-odd:

- **cannot be measured in inclusive DIS**
- **observable effects are given only by the product of $\Delta_T q\,(x)$ and an other chiral-odd function**

can be measured in SIDIS off transversely polarised targets via "quark polarimetry"

$l\,N^{\uparrow} \to l'\,h\,X$ **"Collins" asymmetry**
"Collins" Fragmentation Function

$l\,N^{\uparrow} \to l'\,hh\,X$ **"two-hadron" asymmetry**
"Interference" Fragmentation Function

$l\,N^{\uparrow} \to l'\,\Lambda X$ **Λ polarisation**
Fragmentation Function of $q^{\uparrow} \to \Lambda$

D. Kang

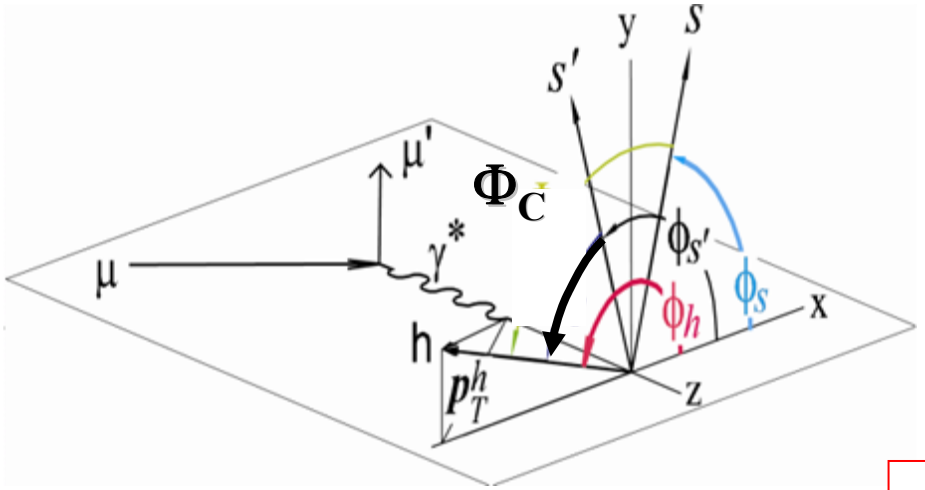
all explored in COMPASS

Collins asymmetry

if transversity PDF and Collins FF different from zero

modulation in the azimuthal distribution of the final state hadrons

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



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

ϕ_h azimuthal angle of the hadron,

ϕ_S azimuhtal angle of the spin of the nucleon

transversity

"Collins FF"

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

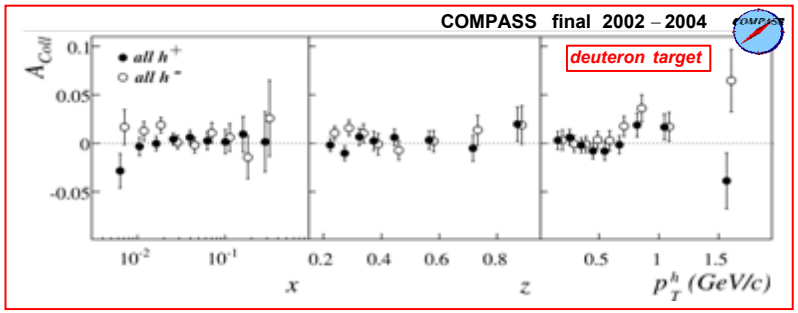
first measured by HERMES (proton target) and COMPASS (deuteron target)

Collins asymmetry

- **clear non-zero effects seen by HERMES on proton**
  evidence that both transversity PDF and Collins FF are non zero

- **~ zero asymmetries measured by COMPASS on deuteron over the whole x-range**

  understood as u – d cancellation

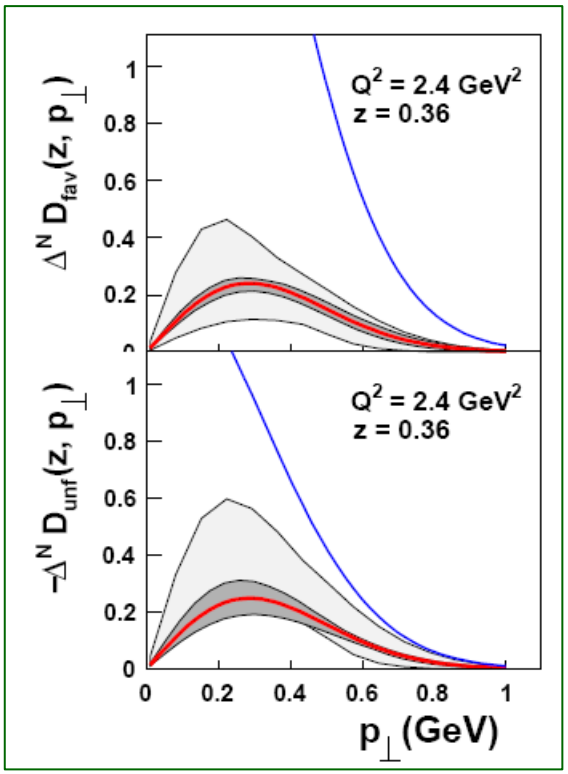


- **independent measurement of Collins effect from BELLE** $e^+e^- \to \pi^+\pi^- X$ **data**
  (first measurements from LEP data)

all these data are well described in global fits
[M. Anselmino et al.]

and allowed for first extractions of the Collins FFs and of transversity PDFs

a major result !



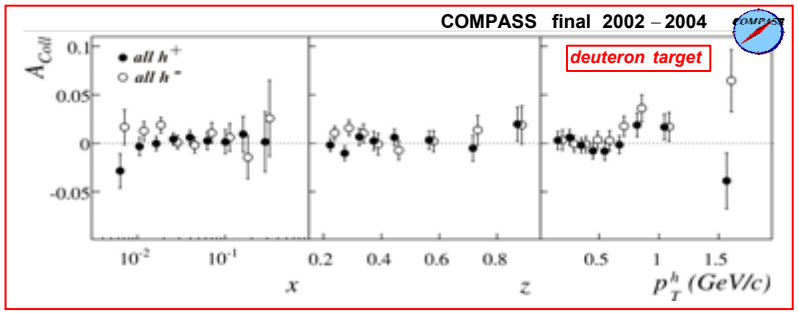
still, a lot of interest for the higher energy COMPASS proton measurement

Collins asymmetry

- **clear non-zero effects seen by HERMES on proton**
  evidence that both transversity PDF and Collins FF are non zero

- **~ zero asymmetries measured by COMPASS on deuteron over the whole x-range**

  understood as u – d cancellation

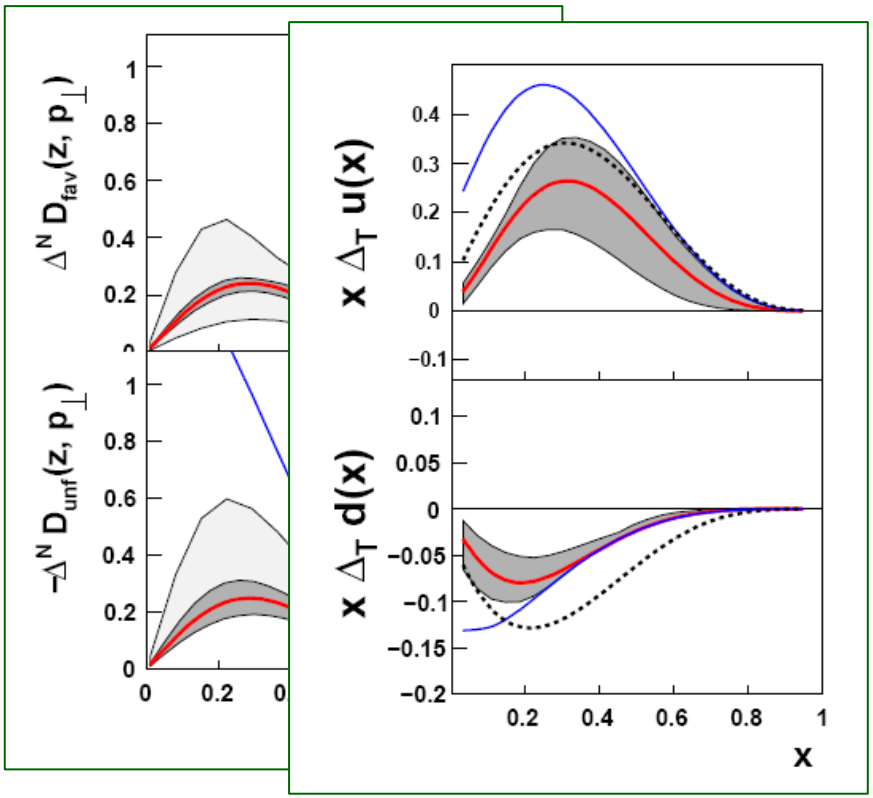


- **independent measurement of Collins effect from BELLE** $e^+e^- \to \pi^+\pi^- X$ **data**
  (first measurements from LEP data)

all these data are well described in global fits
[M. Anselmino et al.]

and allowed for first extractions of the Collins FFs and of transversity PDFs

a major result !



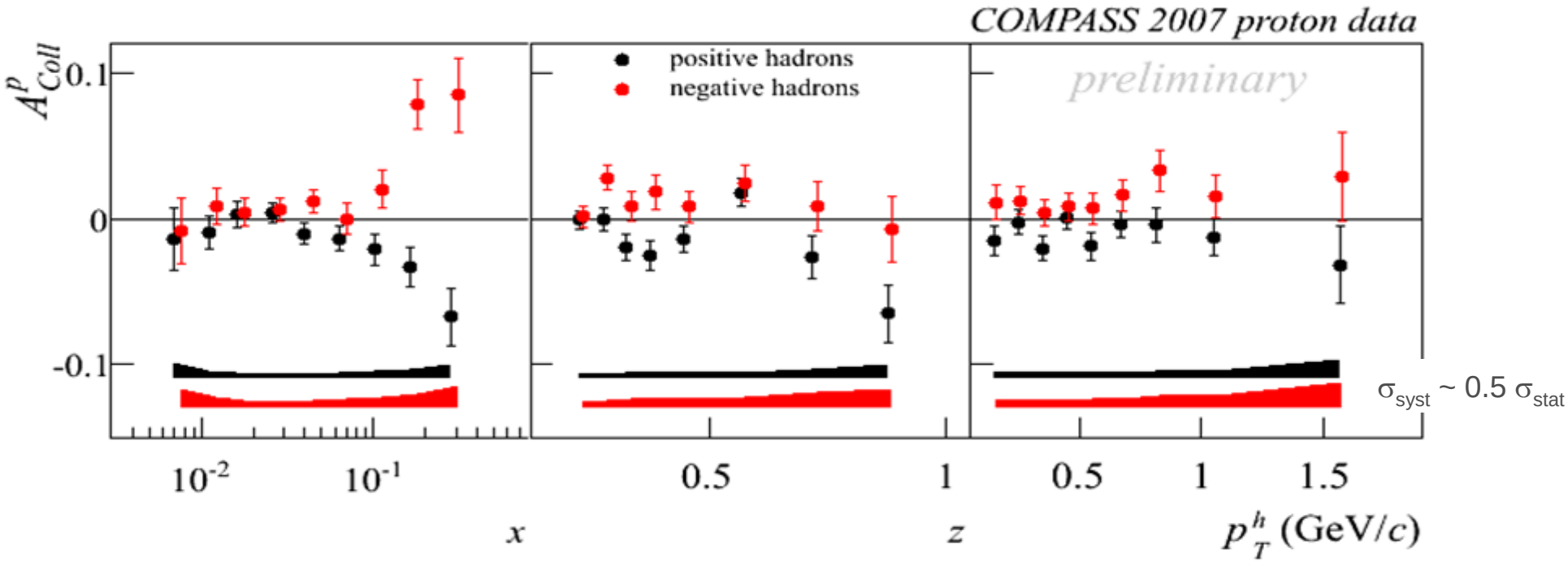
still, a lot of interest for the higher energy COMPASS proton measurement

Collins asymmetry – proton data

COMPASS proton results from 2007 run

the analysis is over and the paper almost ready to be sent

new results very much the same as presented at DIS 2009



- **at small x, the asymmetries are compatible with zero**
- **large signal in the valence region**
  of opposite sign for positive and negative hadrons

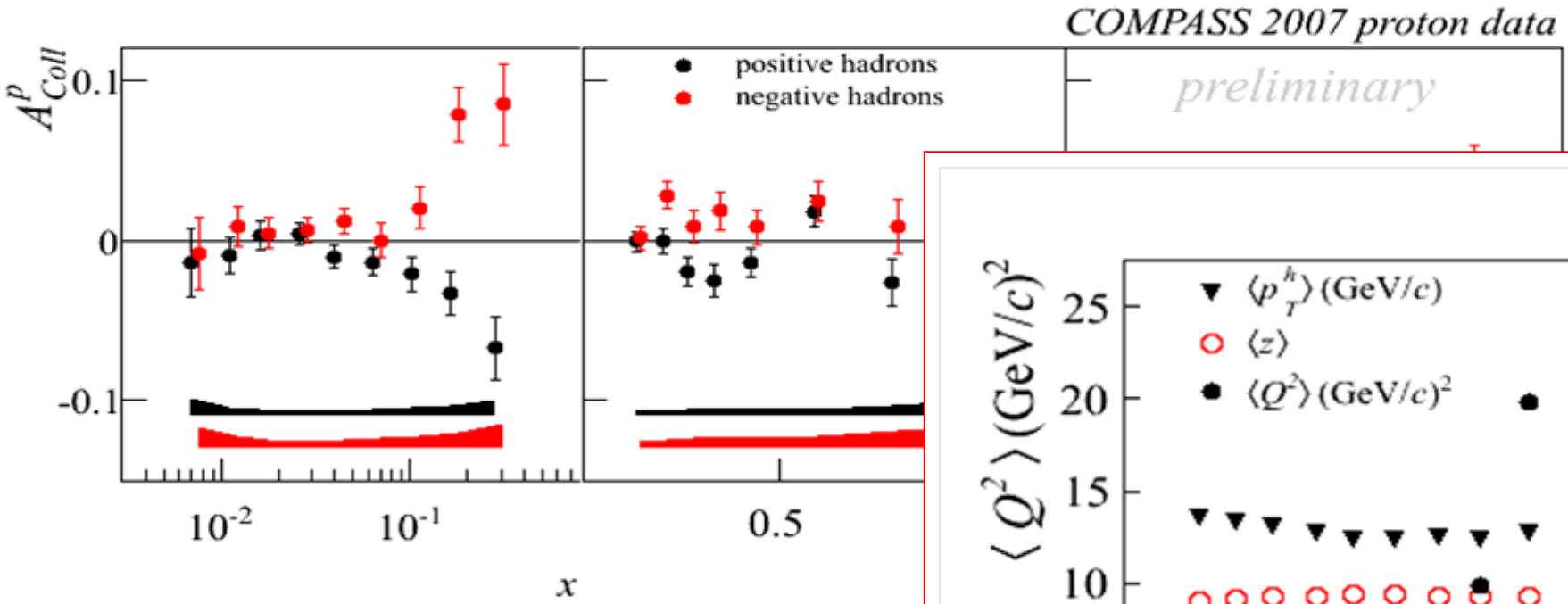
same sign and
~ strength as HERMES

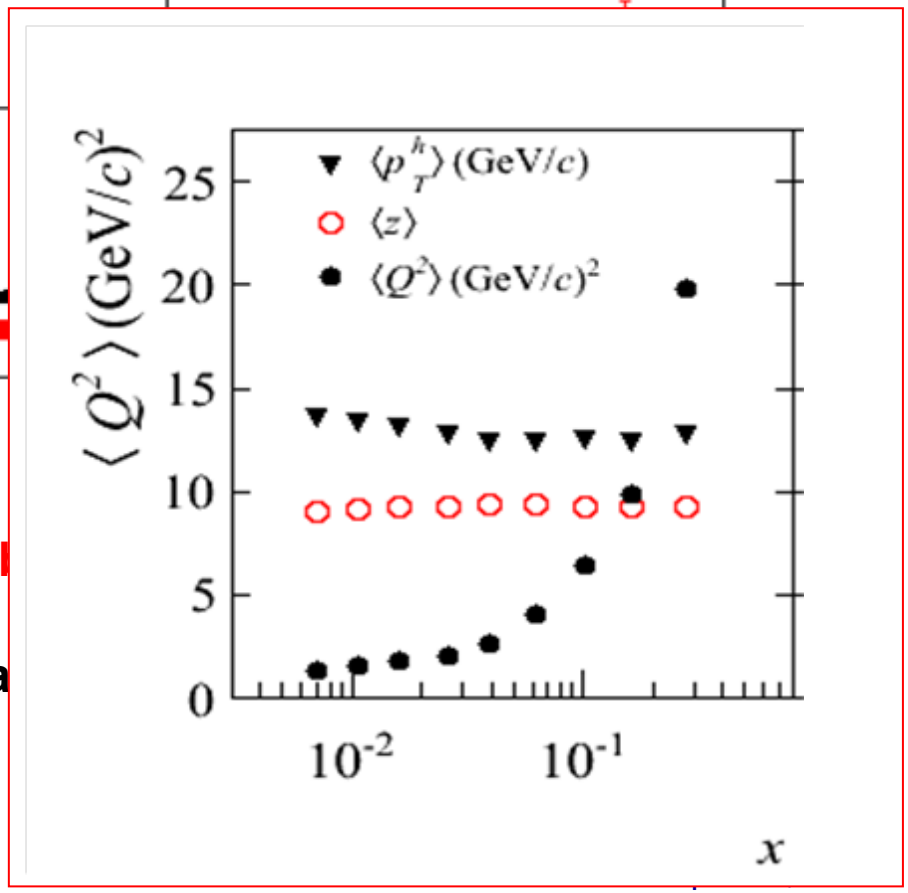
Collins asymmetry – proton data

COMPASS proton results from 2007 run

the analysis is over and the paper almost ready to be sent

new results very much the same as presented at DIS 2009



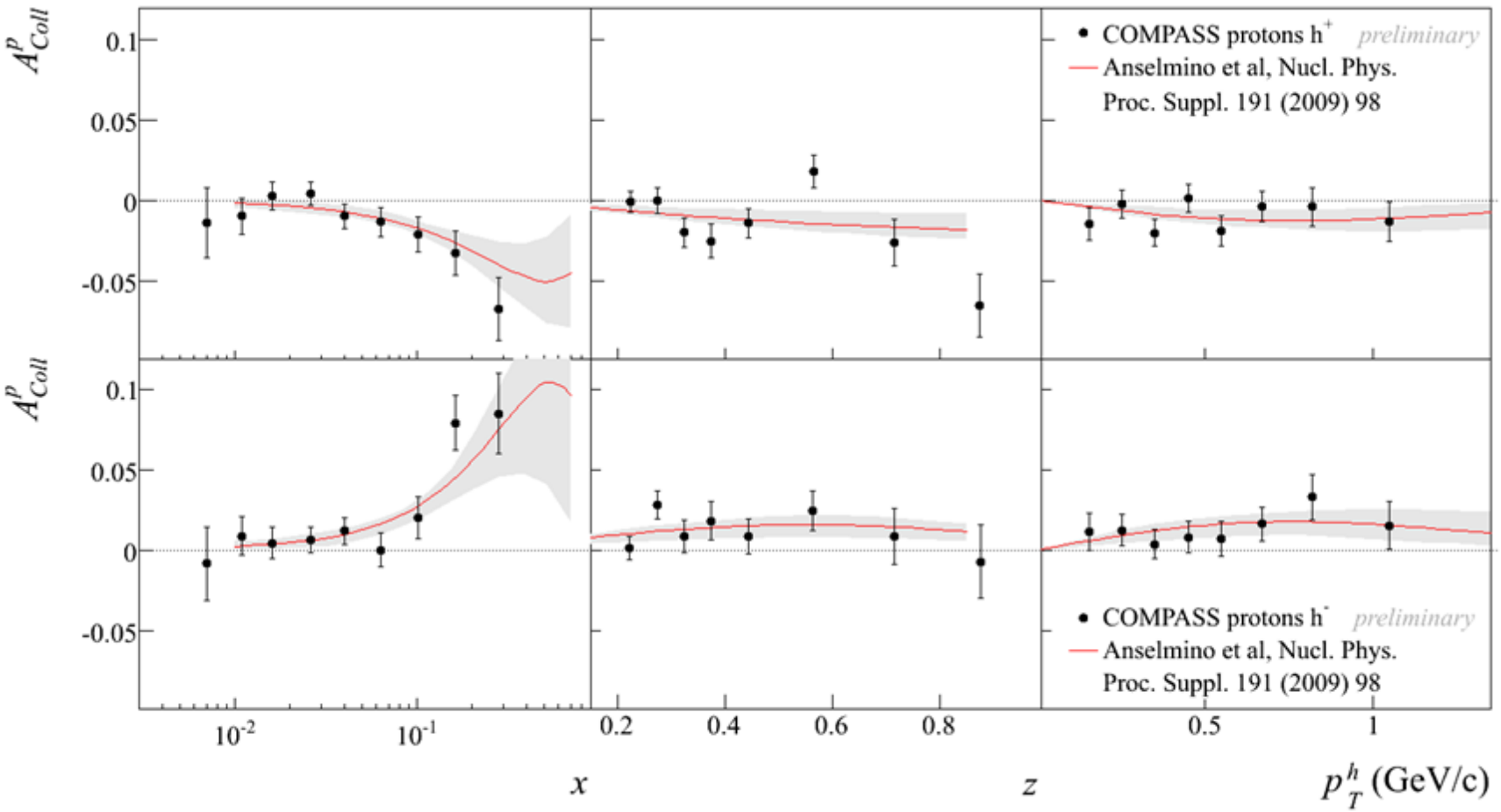


- **at small x**, the asymmetries are **compatil**
- **large signal** in the **valence region**
  of opposite sign for positive and nega

  same sign and
  ~ strength as HERMES

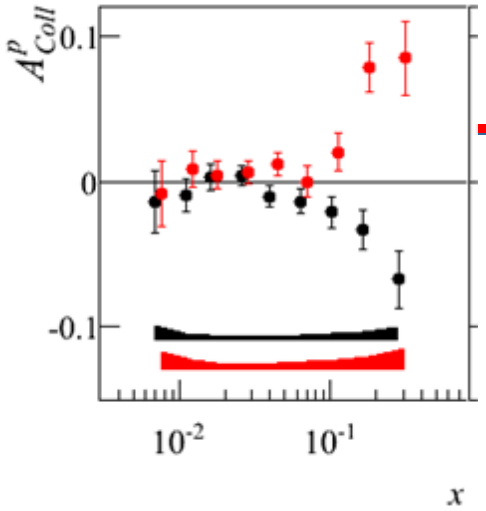
Collins asymmetry

comparison with predictions from fit to the HERMES proton, COMPASS deuteron, BELLE data



our data **support the assumption of a weak Q^2 dependence in the present energy range**

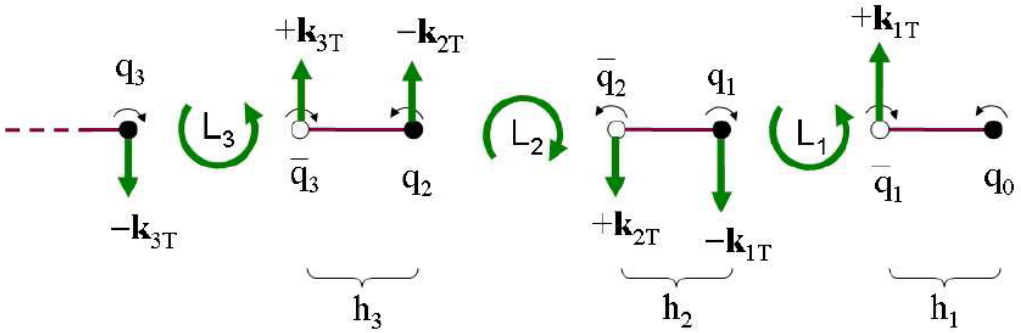
Collins asymmetry

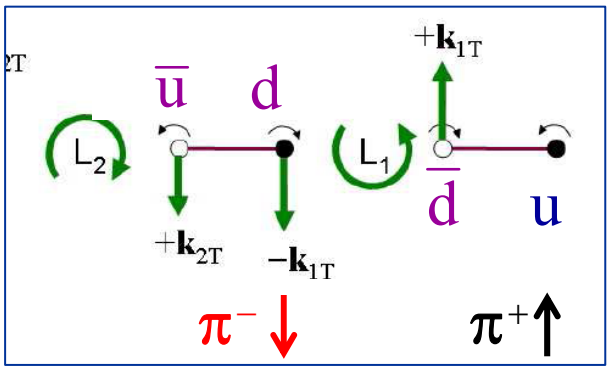


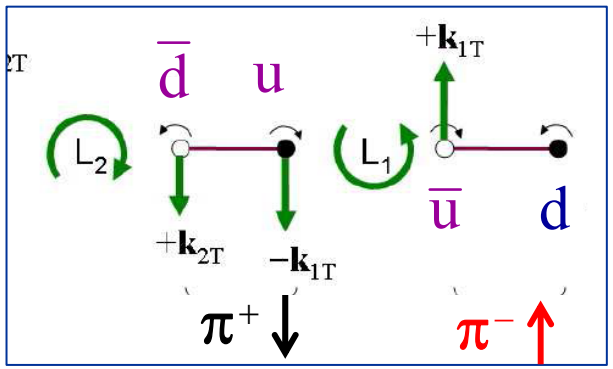
SIGN in agreement with the

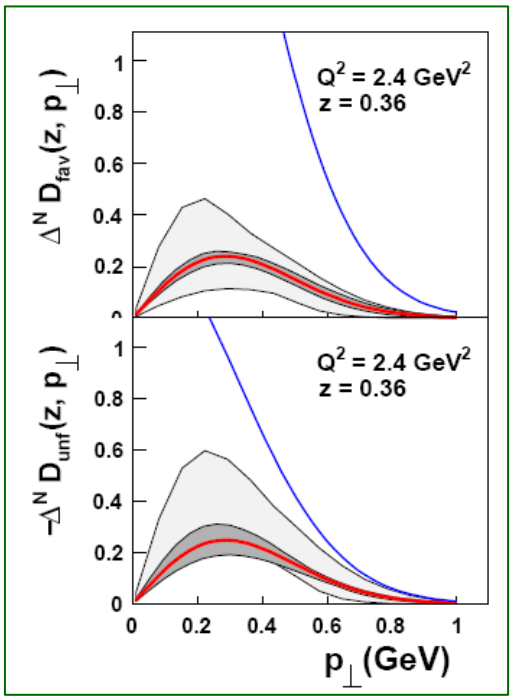
"recursive fragmentation model with quark spin"

[X. Artru, arXiv:1001.1061]



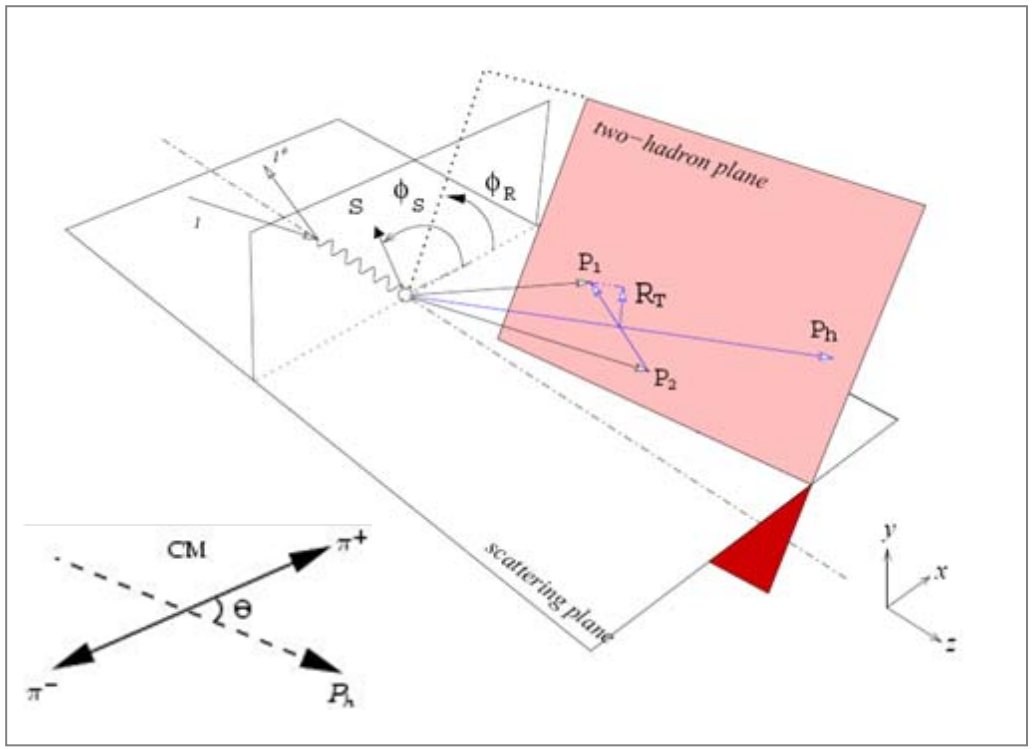






can also describe the two-hadron asymmetries

Two Hadron Asymmetry



azimuthal asymmetry in

$$\phi_{RS} = \phi_{R\perp} - \phi_S,$$

$\phi_{R\perp}$ **is the azimuthal angle of the plane defined by the two hadrons**

$R = (z_1 p_2 - z_2 p_1)/(z_1 + z_2)$

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \{1 \pm A_{RS} \cdot \sin\Phi_{RS}\}$$

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309

Interference Fragmentation Function

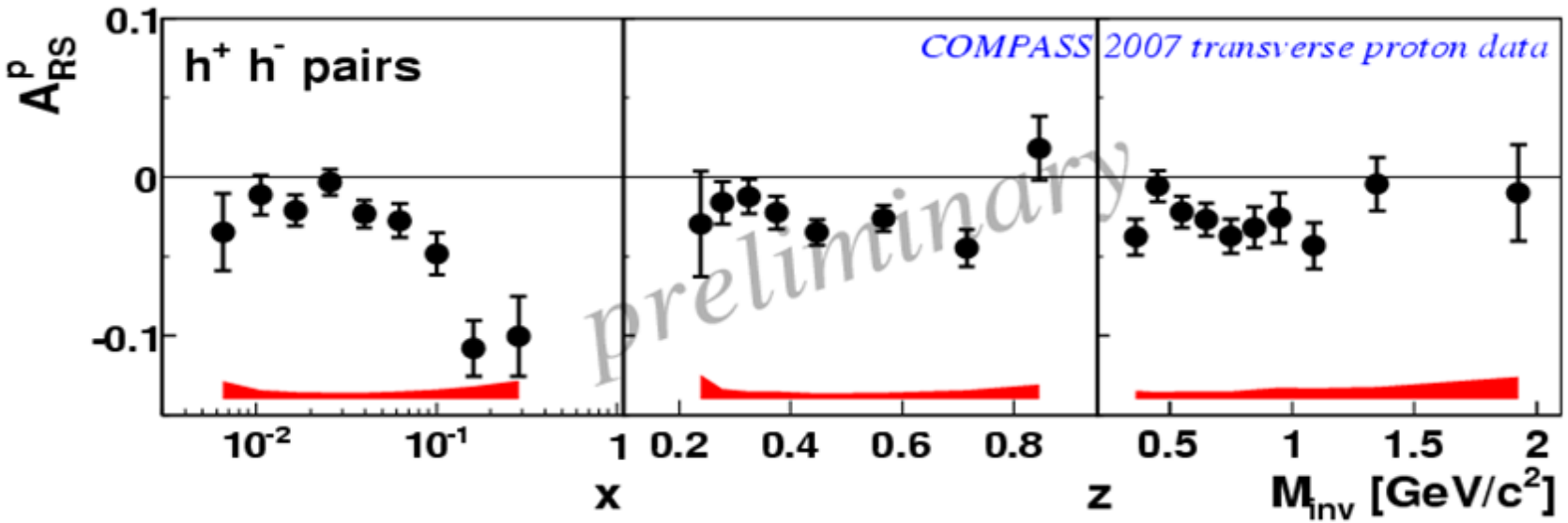
BELLE → A. Vossen

$$A_{RS} = \frac{1}{f \cdot P_T \cdot D_{NN}} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{2h}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_h^2)}$$

Two Hadron Asymmetry

deuteron: compatible with zero all x

proton: DIS2009



$x_F > 0.1$
$z_{1,2} > 0.1$
$Z = z_1 + z_2 < 0.9$
$R_T > 0.07$ GeV/c

in the valence region the asymmetry is
~ larger than the Collins asymmetry

larger than measured by HERMES

difficult to describe both sets of results at the same time
[Bacchetta et al., Mah et al.]

it will be interesting to analyse these data in the framework of the "recursive model"

- the COMPASS experiment
- Collins asymmetry
- **Sivers asymmetry**

The Structure of the Nucleon

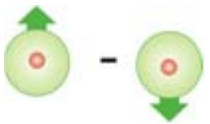
three distribution functions are necessary to describe
the quark structure of the nucleon at LO in the collinear case

taking into account the quark intrinsic transverse momentum k_T,
at leading order 8 PDFs are needed for a full description

"TMDs"

nucleon polarisation

quark polarisation

	U	L	T
U	f_1  *number density*		$f_{1T}^{\perp}$ 
L		g_1  *helicity*	g_{1T} 
T	$h_1^{\perp}$ 	$h_{1L}^{\perp}$ 	h_1  *transversity* $h_{1T}^{\perp}$ 

$\Delta_T q$

SIDIS gives access to all of them

SIDIS cross-section

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

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

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

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

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

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

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

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

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

3 modulations
with unpol target

3 modulations
with L pol target

→ *I. Savin*

8 modulations
(4 LO)
with T pol target

Collins

A Bacchetta, M Diehl, K Goeke, A Metz, P Mulders, M Schlegel (06)

all measured by COMPASS on deuteron

The Structure of the Nucleon

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

taking into account the quark intrinsic transverse momentum k_T,
at leading order 8 PDFs are needed for a full description

"TMDs"

nucleon polarisation

quark polarisation

	U	L	T	
U	f_1 *number density*		$f_{1T}^{\perp}$	$\Delta_0^T q$ ***Sivers function***
L		g_1 *helicity*	g_{1T}	
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 *transversity*, $h_{1T}^{\perp}$	$\Delta_T q$

SIDIS gives access to all of them

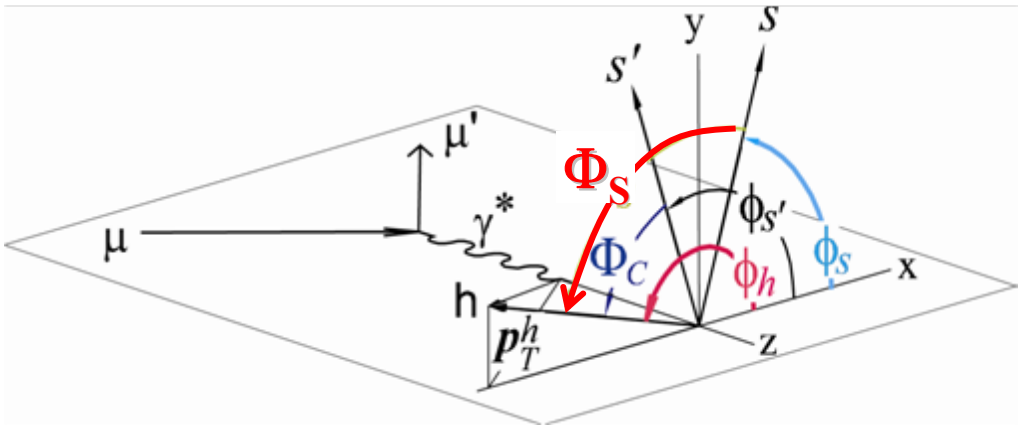
The Sivers PDF

$f_{1T}^{\perp}$  gives the correlation between the nucleon transverse spin and the quark k_t

- requires final/initial state interactions to survive time-reversal invariance
- time-reversal invariance implies:

$$f_{1T}^{\perp}\big|_{SIDIS} = -f_{1T}^{\perp}\big|_{DY}$$ … to be checked → *O. Denisov*

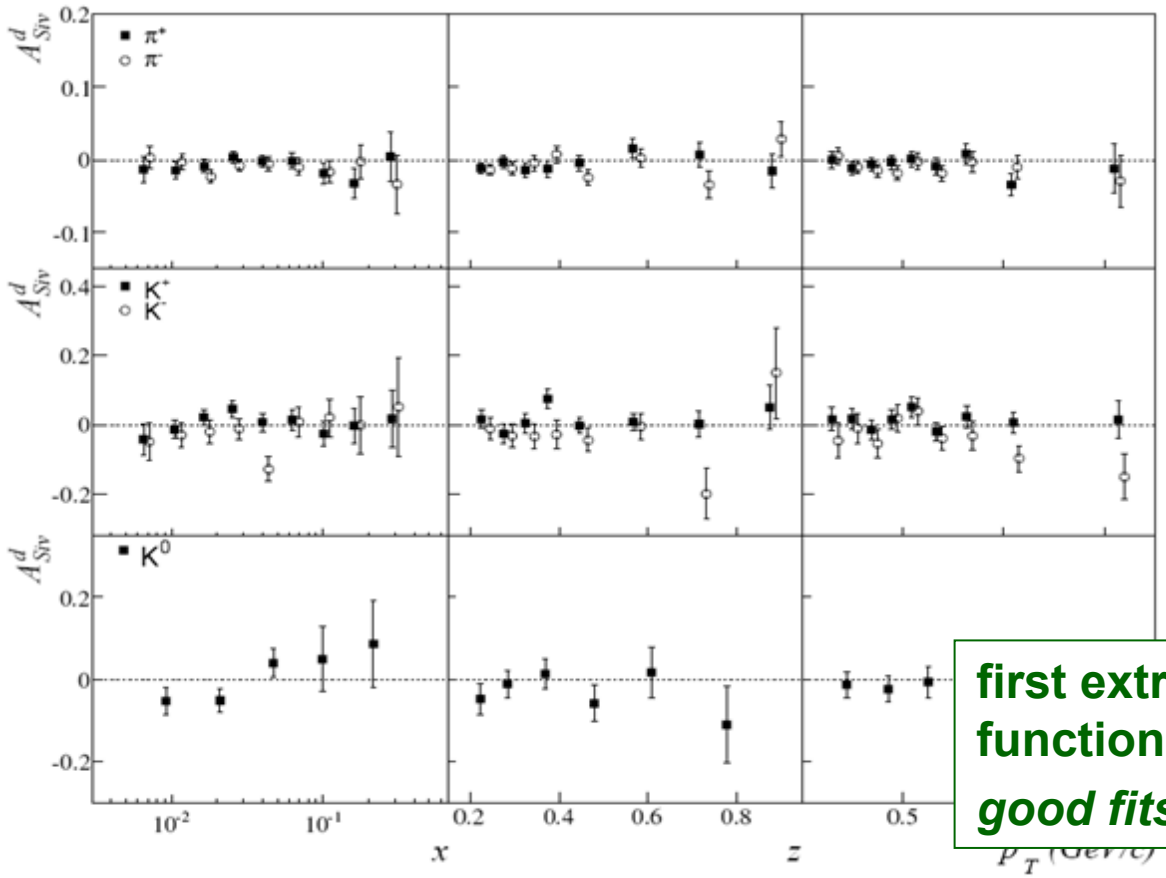
- in SIDIS, it is responsible of a modulation in $\Phi_S = \phi_h - \phi_S$ of the hadron produced inclusively on a transversely polarized target



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

Sivers asymmetry

- strong signal seen by HERMES for π^+ and K^+ producted on transversely polarized protons
- no signal seen by COMPASS on transversely polarized deuterons, interpreted as u- and d-quark cancellation (as for the Collins asymmetry)



PLB 673 (2009) 127

$\pi^{\pm}$

COMPASS

$K^{\pm}$

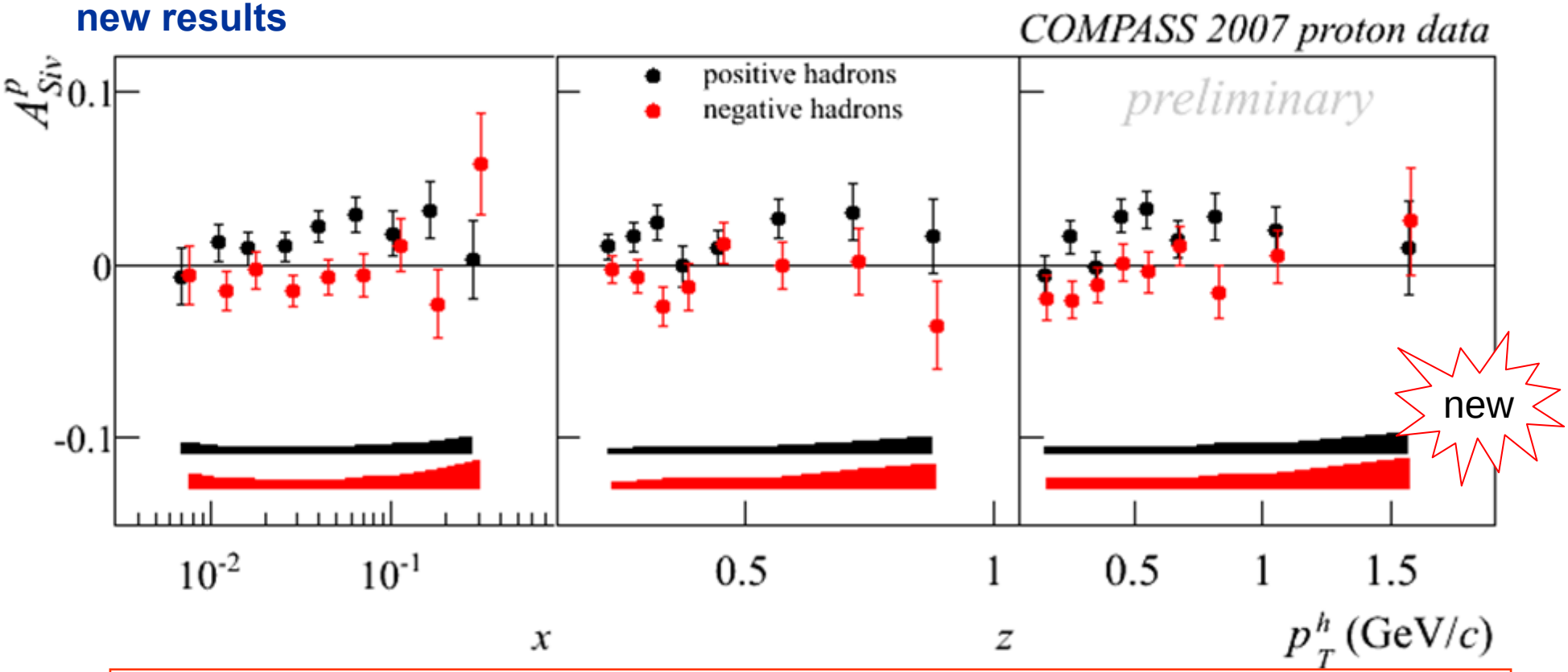
first extractions of the Sivers function from pion SIDIS data

good fits to the data

Sivers asymmetry – proton data

the analysis of the 2007 data is over

new results

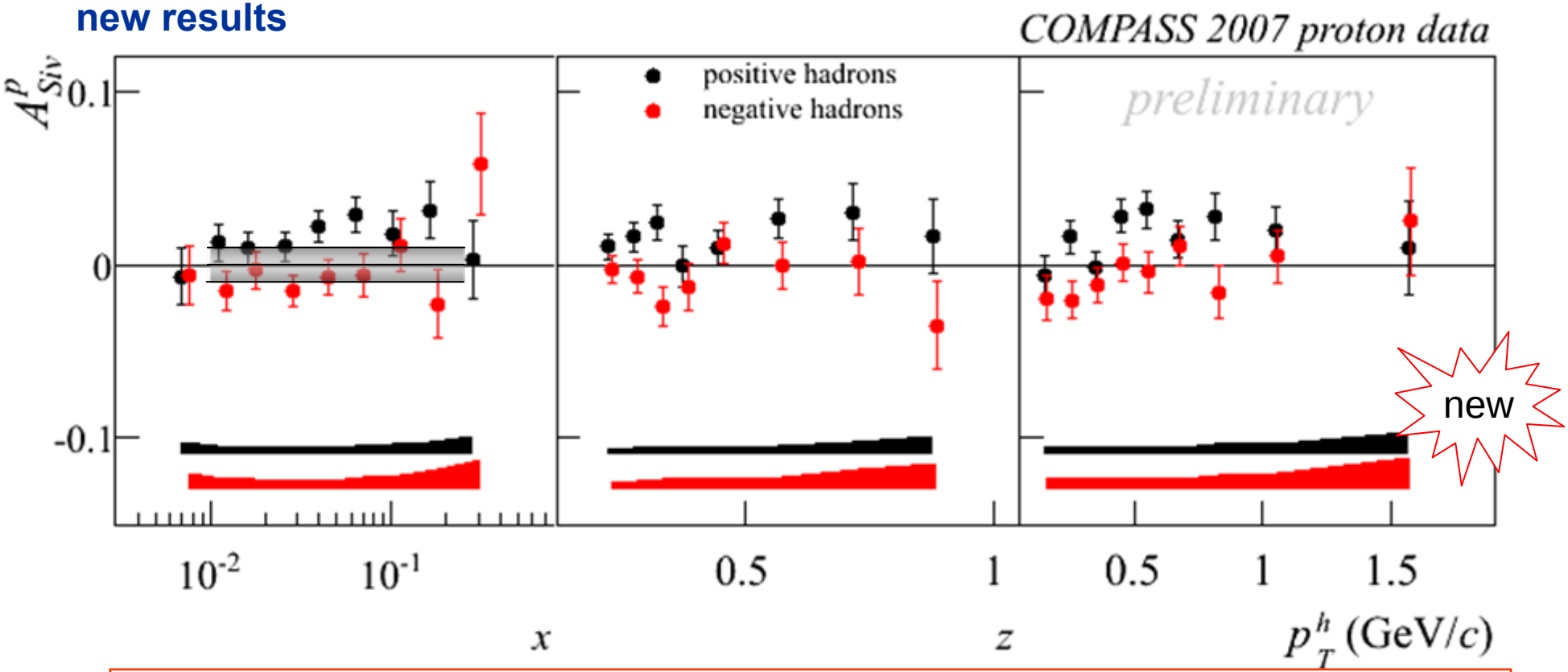


evidence for a positive signal for h^+,
which extends to small x, in the region not measured before

Sivers asymmetry – proton data

the analysis of the 2007 data is over

new results



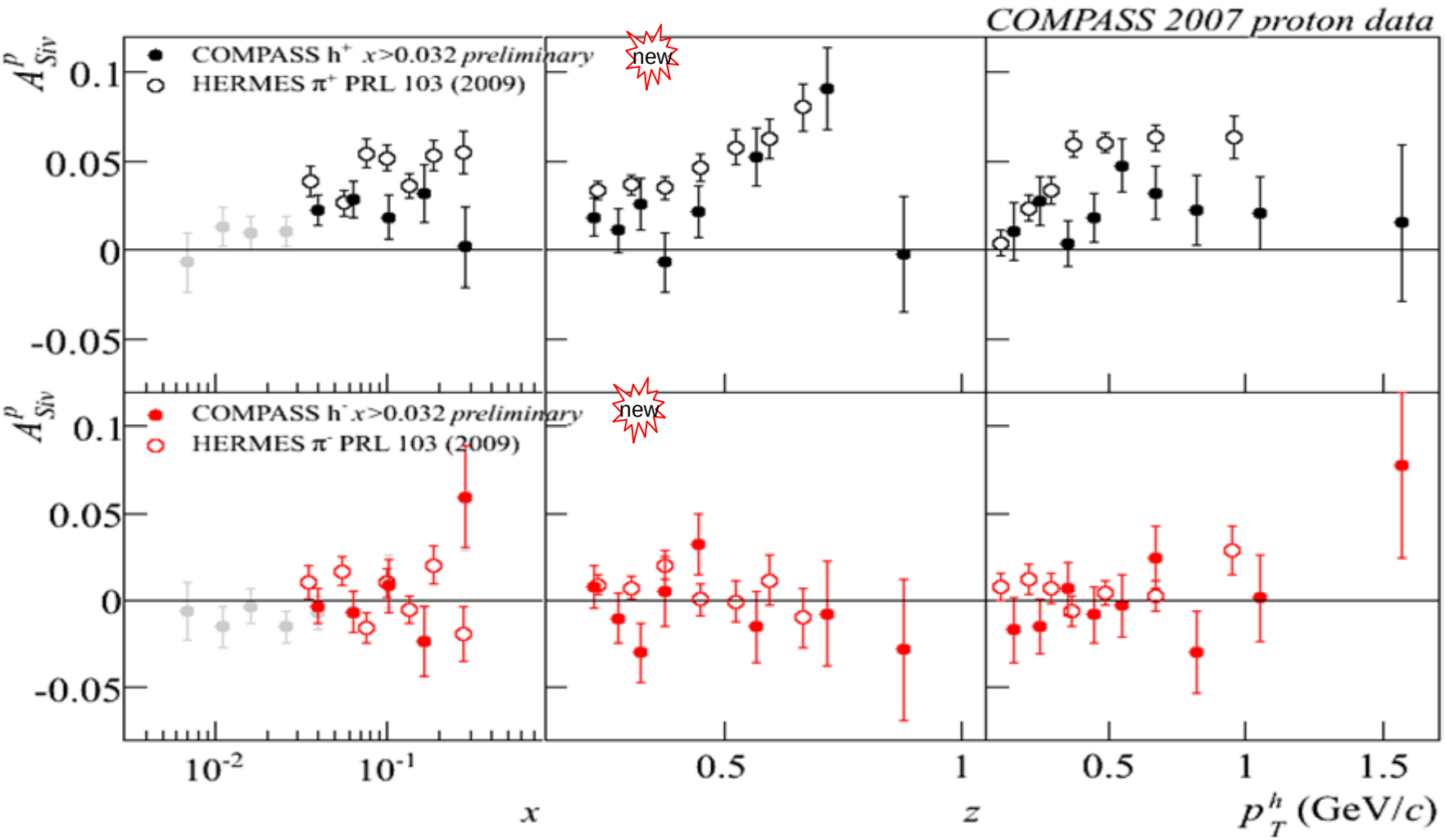
evidence for a positive signal for h^+,
which extends to small x, in the region not measured before

systematic errors h^- ~ 0.5 σ_{stat}
h^+ ~ 0.8 σ_{stat} plus a scale (abs) uncertainty of ± 0.01

different results from data collected in the first and in the second half of the run

Sivers asymmetry – proton data

comparison with the HERMES final results

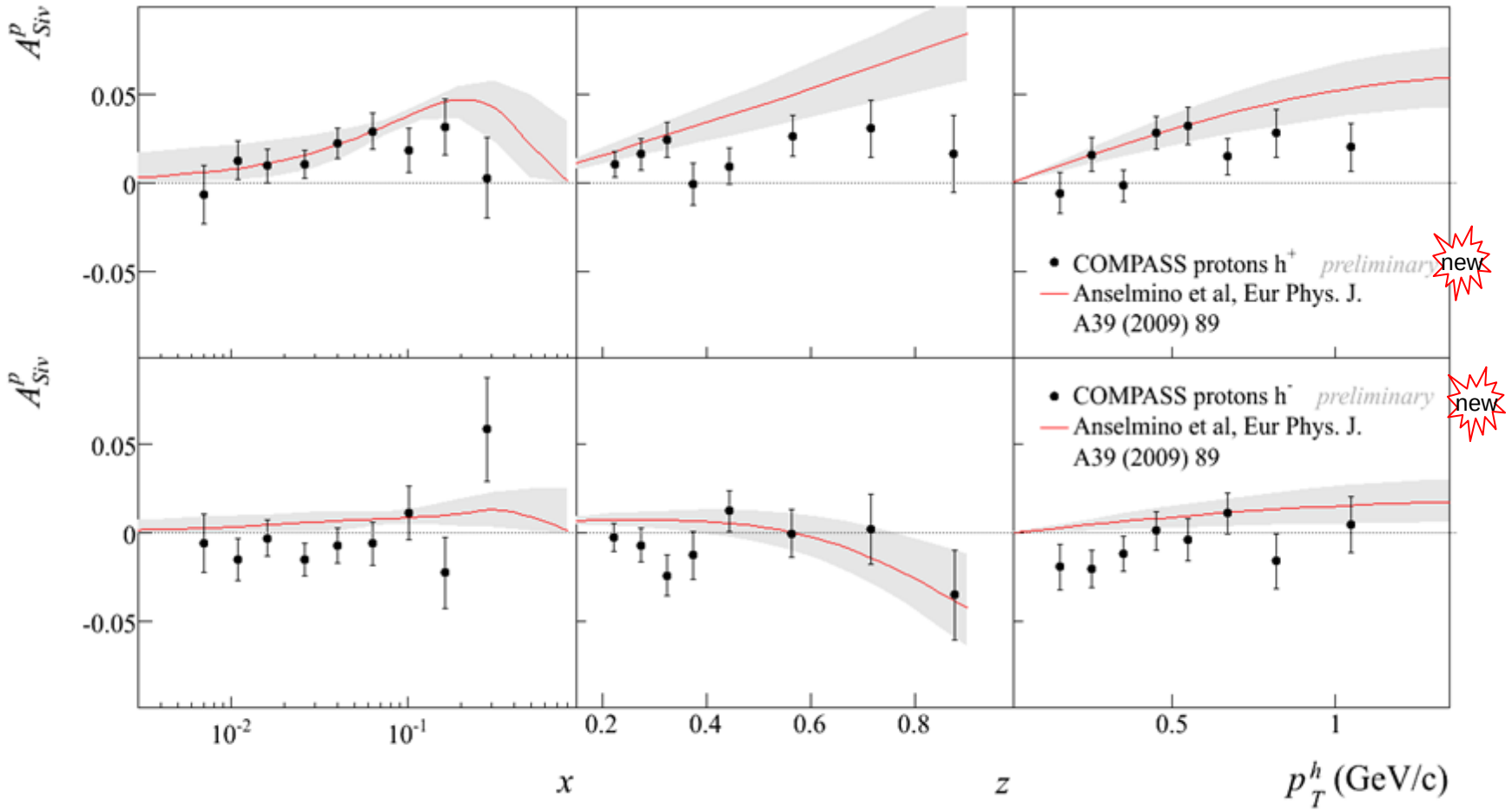


h⁺ COMPASS asymmetry **same sign**
smaller by a factor ~ 2

Sivers asymmetry – proton data

comparison with the most recent predictions from *M. Anselmino et al.*

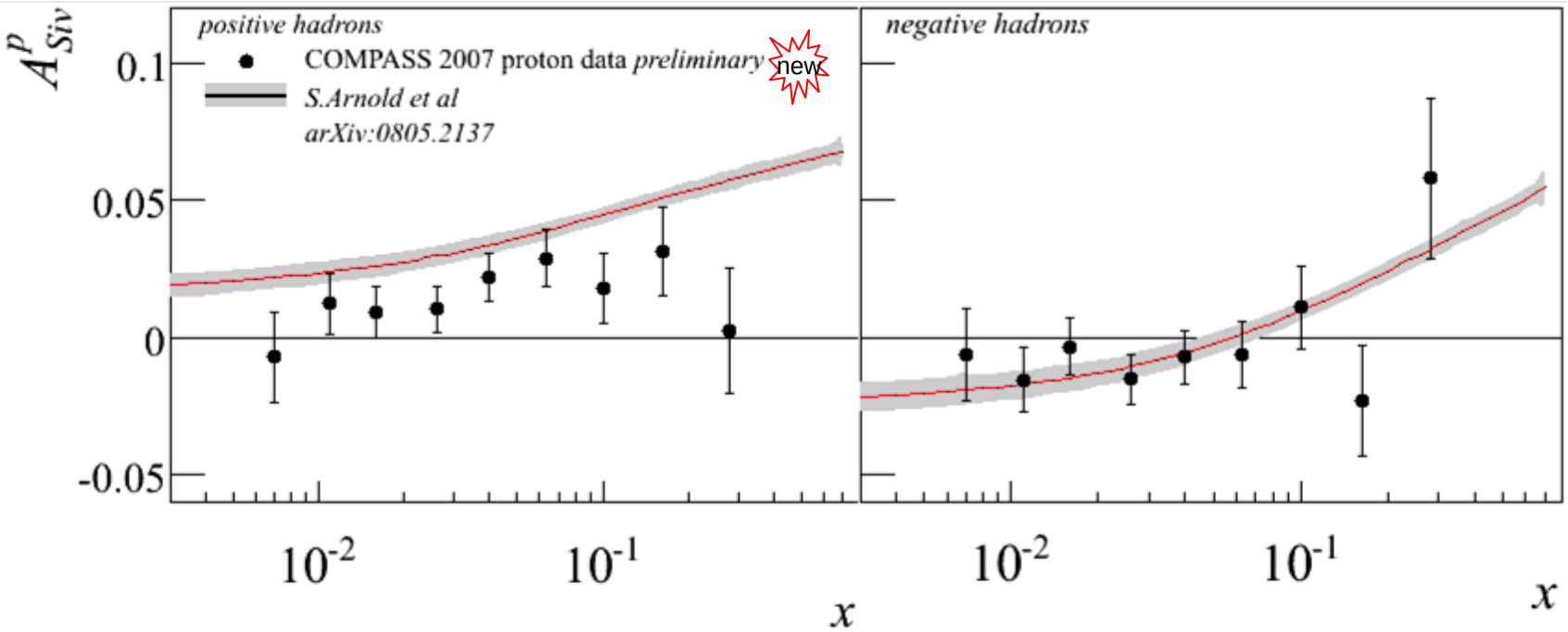
based on the fit of HERMES proton and COMPASS deuteron data



Sivers asymmetry – proton data

comparison with calculations from S.Arnold et al. [arXiv:0805.2137]

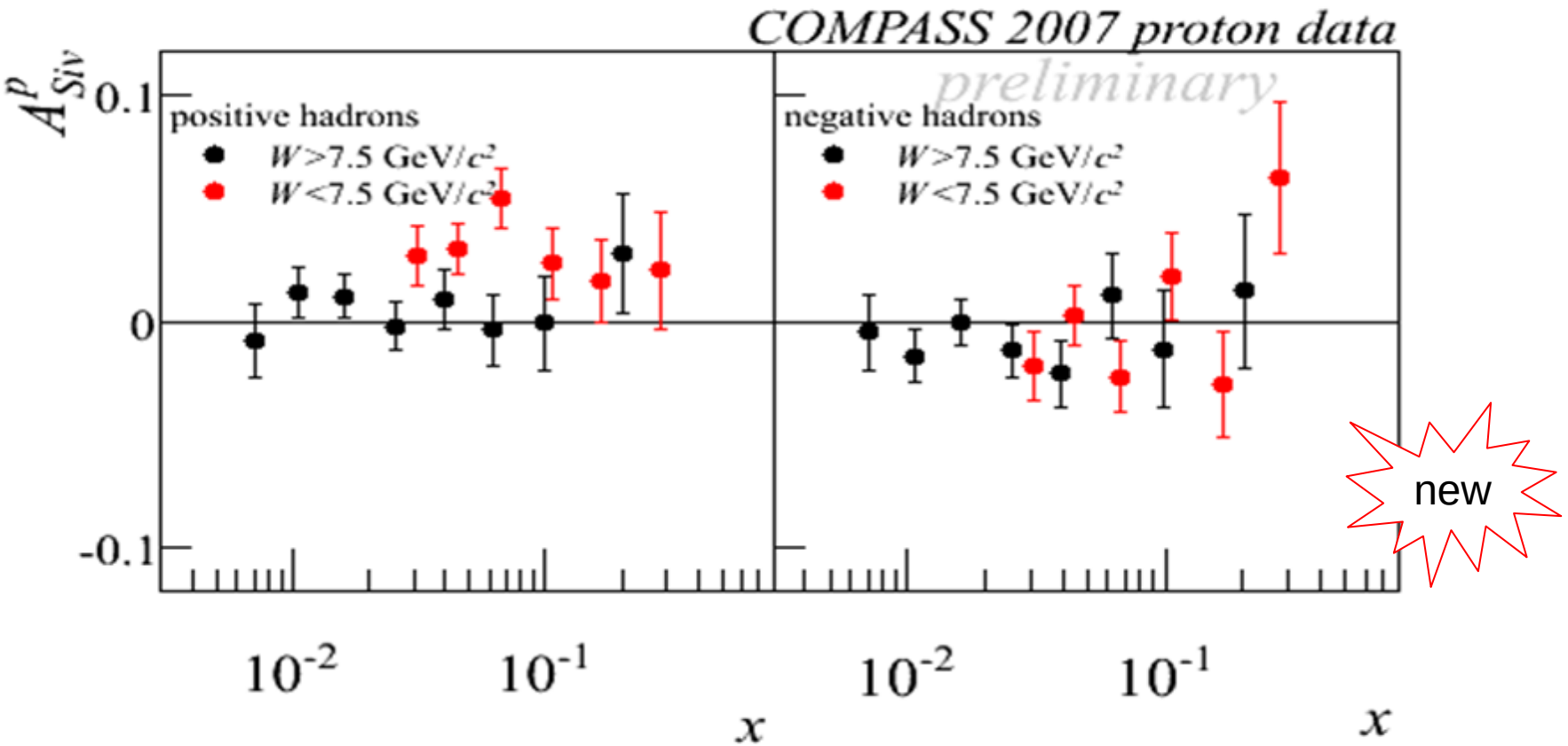
in agreement with HERMES preliminary results



Sivers asymmetry – proton data

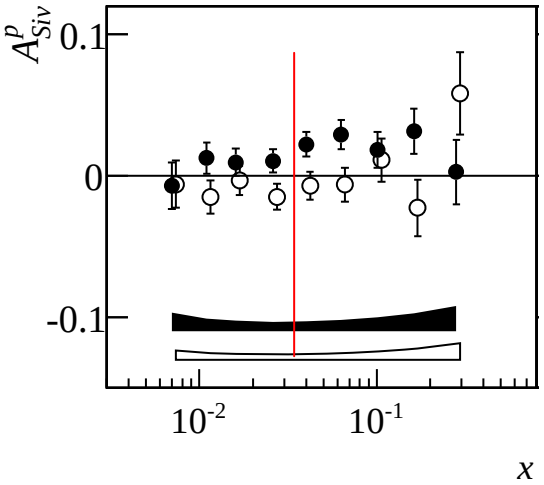
various investigations to understand the results

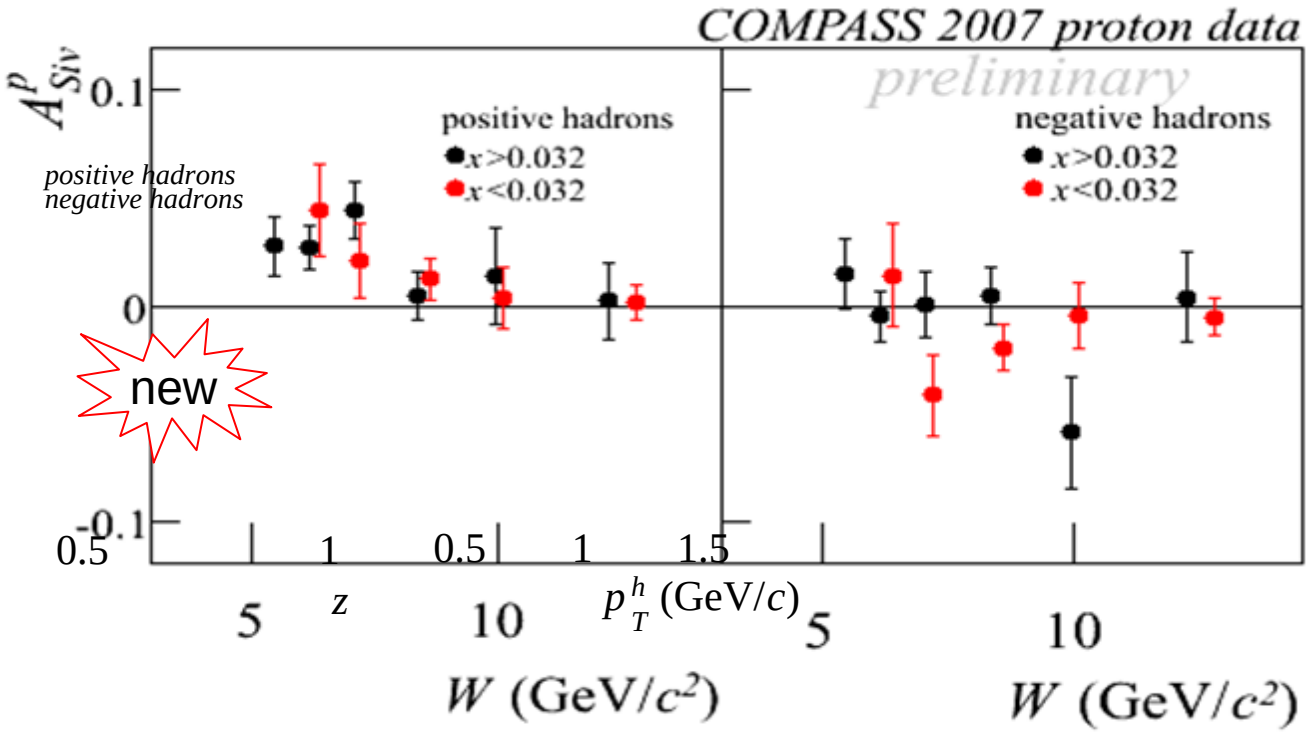
possible W dependence

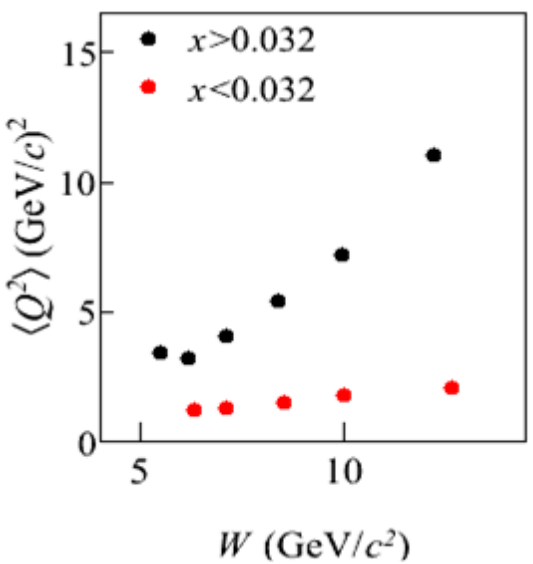


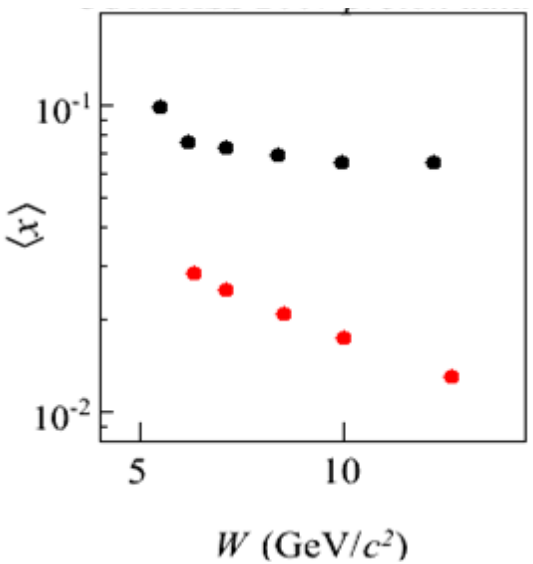
Sivers asymmetry – proton data

W dependence



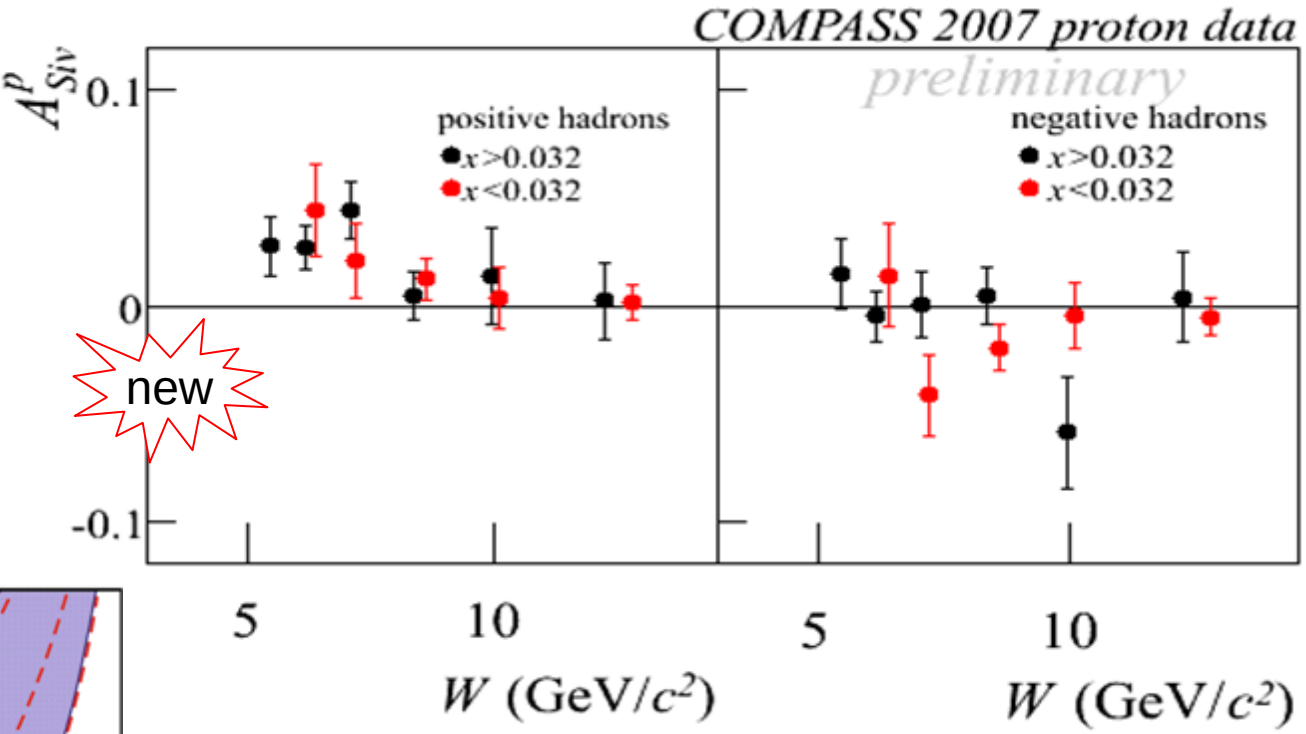


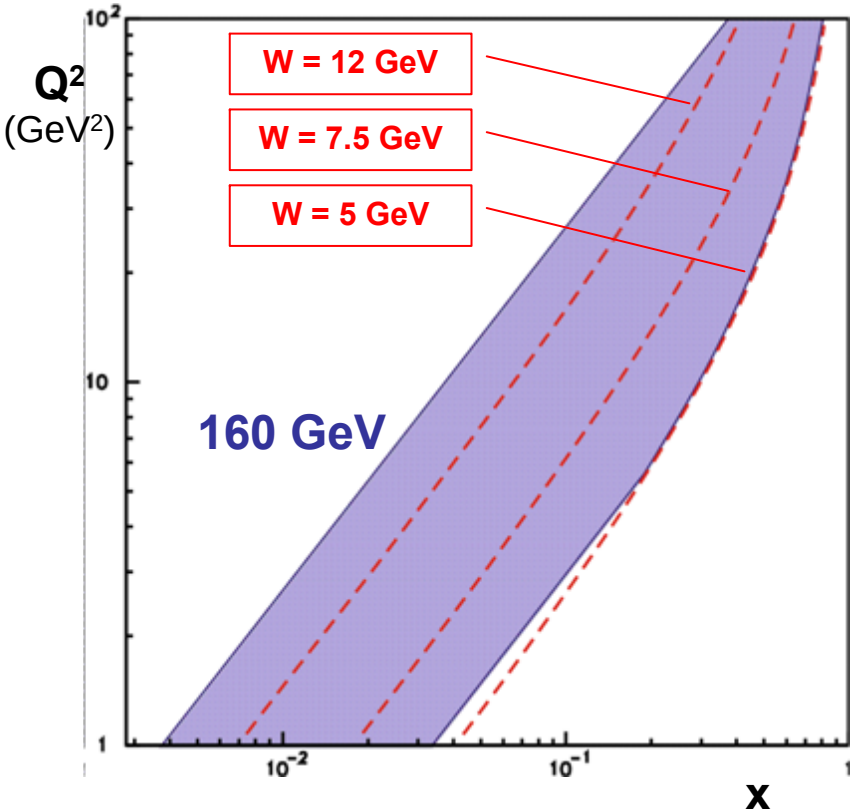




Sivers asymmetry – proton data

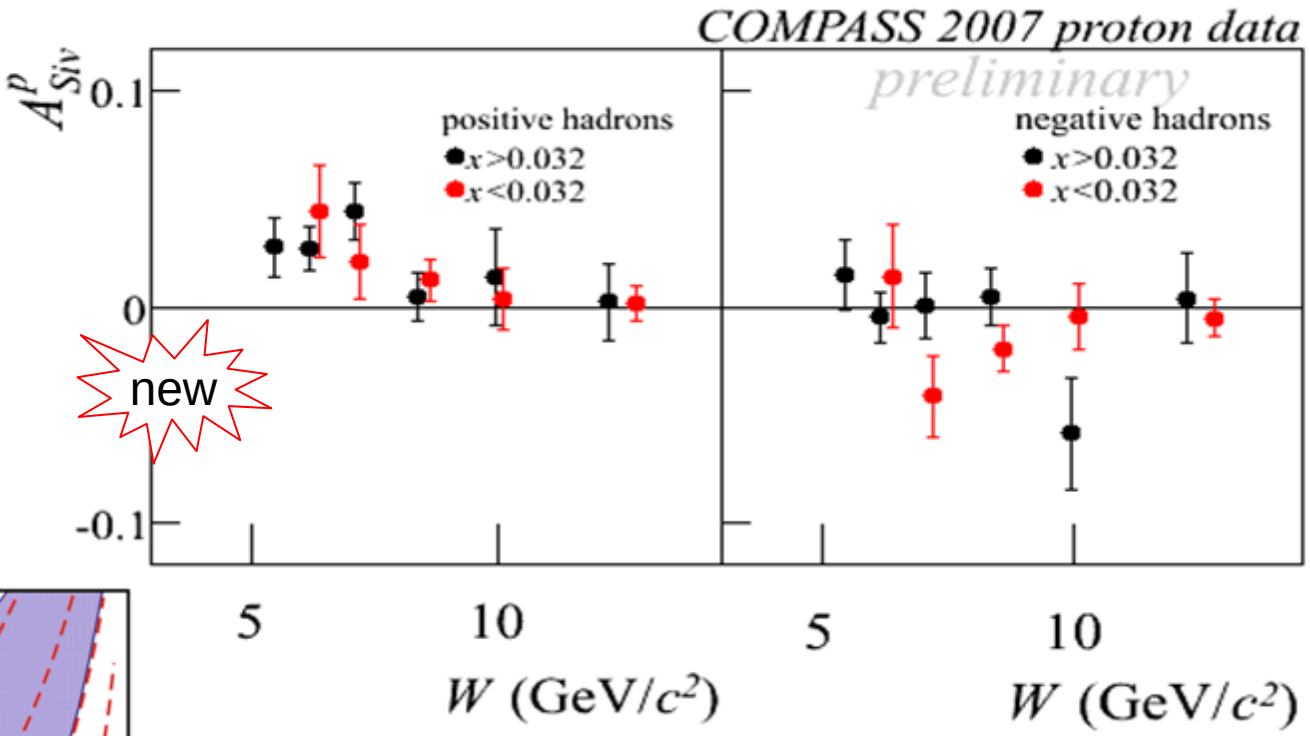
W dependence

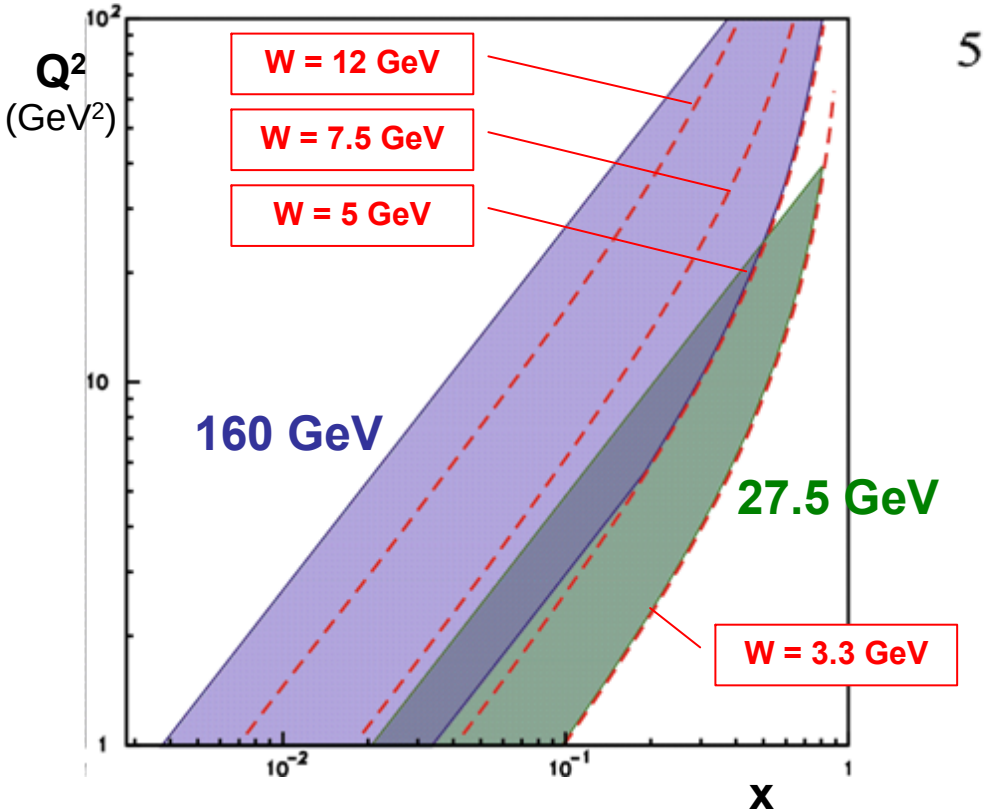




Sivers asymmetry – proton data

W dependence





no evidence of dependence of the Collins asymmetry on W

Summary

the Collins and Sivers asymmetries of the proton have been measured at high energy

- Q^2 and W ranges extended at large values
- x range extended to considerably smaller values

Collins asymmetry:

- clear signal both for positive and negative hadrons in the valence region
- SIDIS as appropriate tool to investigate the transversity PDF

Sivers asymmetry:

- signal for positive hadrons, also at small x values
- indication for a possible (and unexpected) W dependence

much more can be done in SIDIS off transversely polarised nucleons

COMPASS near future

2010: one full SPS year of run
with the transversely polarised NH_3 target
and the 160 GeV muon beam

the run will start in 2 weeks

projected statistical errors for the Sivers asymmetry