Transverse Spin and Momentum Effects in SIDIS

experimental overview

Anna Martin
Trieste University & INFN (Italy)

IWHSS'11
Paris
4-6 April 2011

Transverse Spin and Momentum Effects in SIDIS

experimental overview

- introduction
- the experiments
- azimuthal asymmetries:

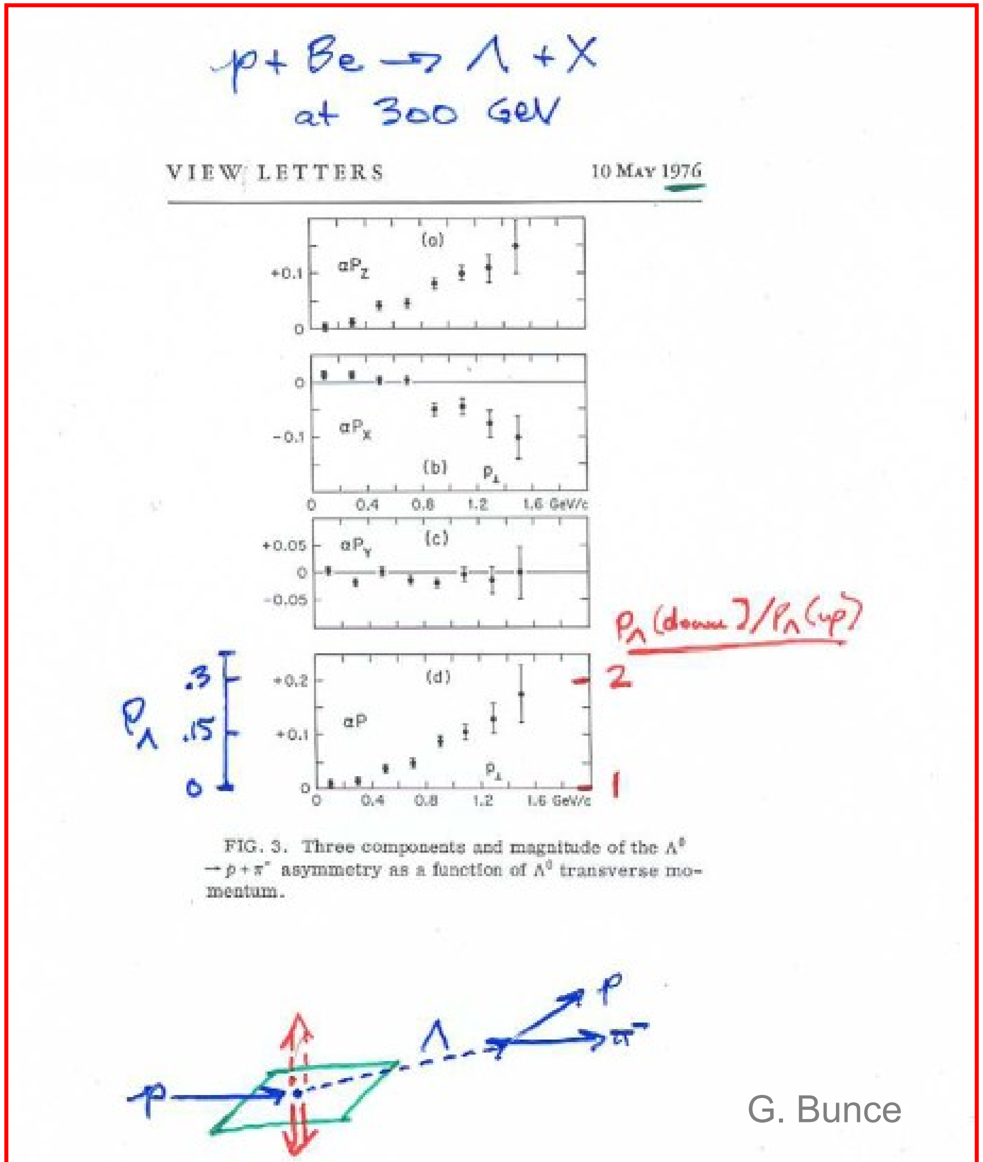
  some recent results

  transversity, Sivers and Boer-Mulders PDFs

the beginning

large transverse spin effects observed in hadronic interactions

$A_N \sim 10^{-1}$



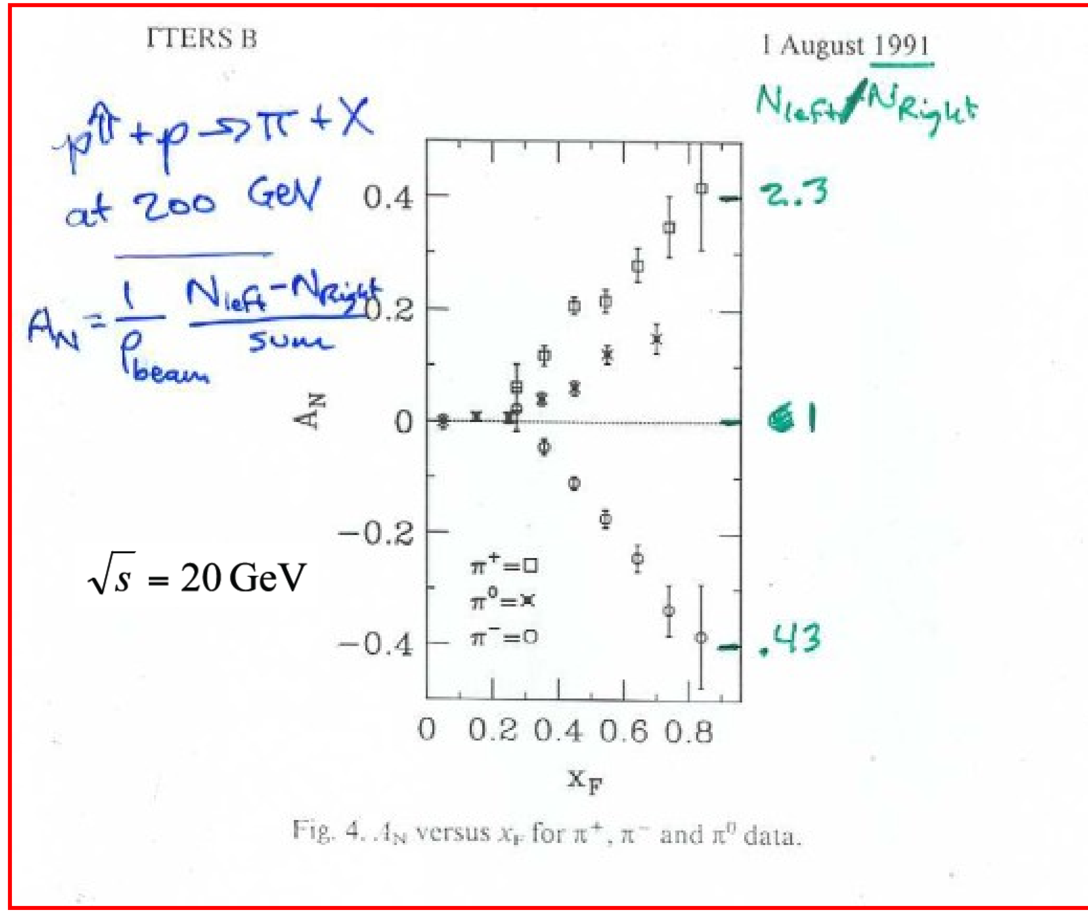
theory:

expected to be very small at high energies

(Kane, Pumplin, Repko, PRL 41 (1978) 1689)

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

$A_N \sim 10^{-4}$



Transverse Spin and Momentum Structure of the Nucleon

a large international theoretical and experimental effort

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

transversity PDF $\Delta_T q$ or h_1 : correlation between the transverse spin of the nucleon and the transverse spin of the quark

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

"TMDs"

nucleon polarisation / **quark** polarisation

quark \ nucleon	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*; $h_{1T}^{\perp}$ -	$\Delta_T q$

Anna Martin

Transverse Spin and Momentum Structure of the Nucleon

a large international theoretical and experimental effort

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

transversity PDF $\Delta_T q$ or h_1 : correlation between the transverse spin of the nucleon and the transverse spin of the quark

Sivers function $f_{1T}^{\perp}$
correlation between the transverse spin of the nucleon and the transverse momentum of the quark

Boer-Mulders function $h_1^{\perp}$
correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

T-odd TMDs

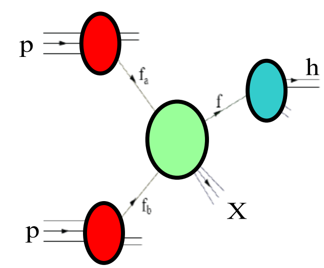
nucleon polarisation (columns); **quark** polarisation (rows)

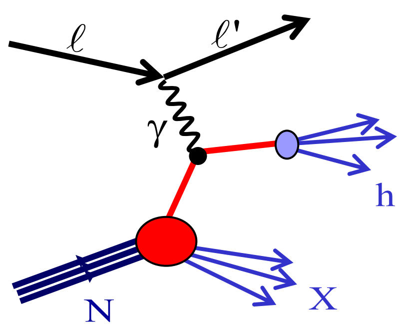
	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*	$\Delta_0^T q$
L		g_1 *helicity* Δq	g_{1T}	
T	$h_1^{\perp}$ *Boer Mulders*	$h_{1L}^{\perp}$	h_1 *transversity* $h_{1T}^{\perp}$	$\Delta_T q$

Transverse Spin and Momentum Structure of the Nucleon

a large international theoretical and experimental effort

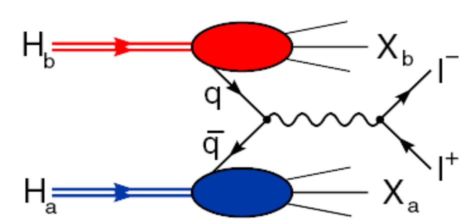
hard polarised pp scattering
RHIC / BNL
→ *M. Grosse-Perdekamp*



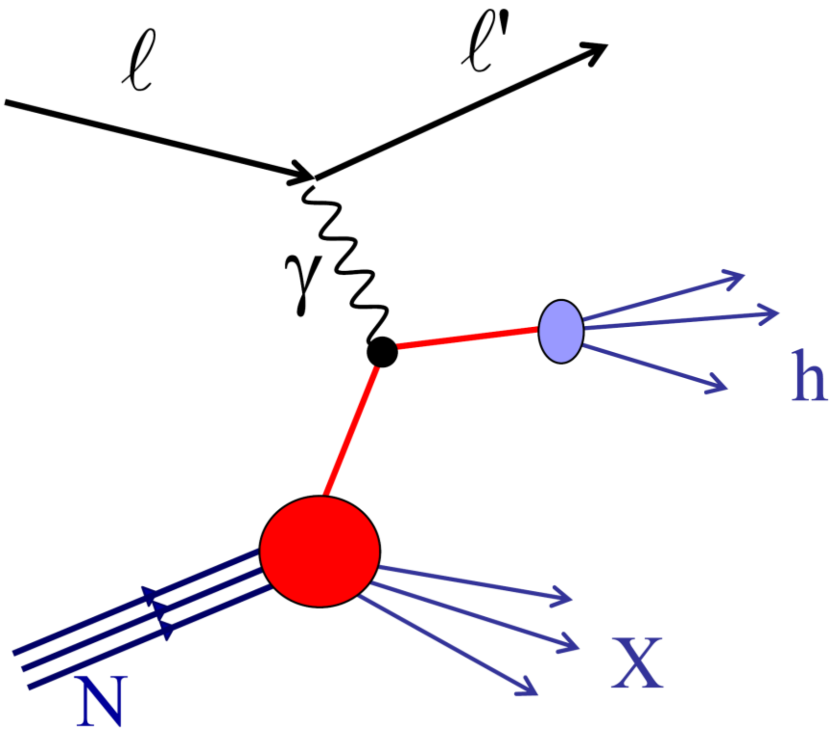


SIDIS off transversely polarised targets:
DESY (HERMES)
CERN (COMPASS)
JLab → *Z.-E. Meziani*
*and **eRHIC, EIC, ENC***

and several (future) projects for (polarised) Drell-Yan:
CERN *(COMPASS)*
FNAL, *JParc, RHIC, JINR, IHEP, GSI*
→ *J.-C. Peng, A. Ogawa, A. Ferrero*



Semi-Inclusive Deep Inelastic Scattering



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

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

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

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

- **the FFs must be known**
- **allows to disentangle the effects related to the different TMD PDFs and to access all of them**
- **by identifying the final state hadrons allows for flavor separation**

Semi-Inclusive Deep Inelastic Scattering

18 structure functions

14 azimuthal modulations

$\phi_{h\,(S)}$ hadron (nucleon spin) azimuthal angle in GNS

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

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

3 with unpolarised target

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

3 with L polarised target

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

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

8 with T polarised target

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

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

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

they can be measured from the same data

A Bacchetta et al., 2006

18 structure functions

14 azimuthal modulations

$\phi_{h\,(S)}$ hadron (nucleon spin) azimuthal angle in GNS

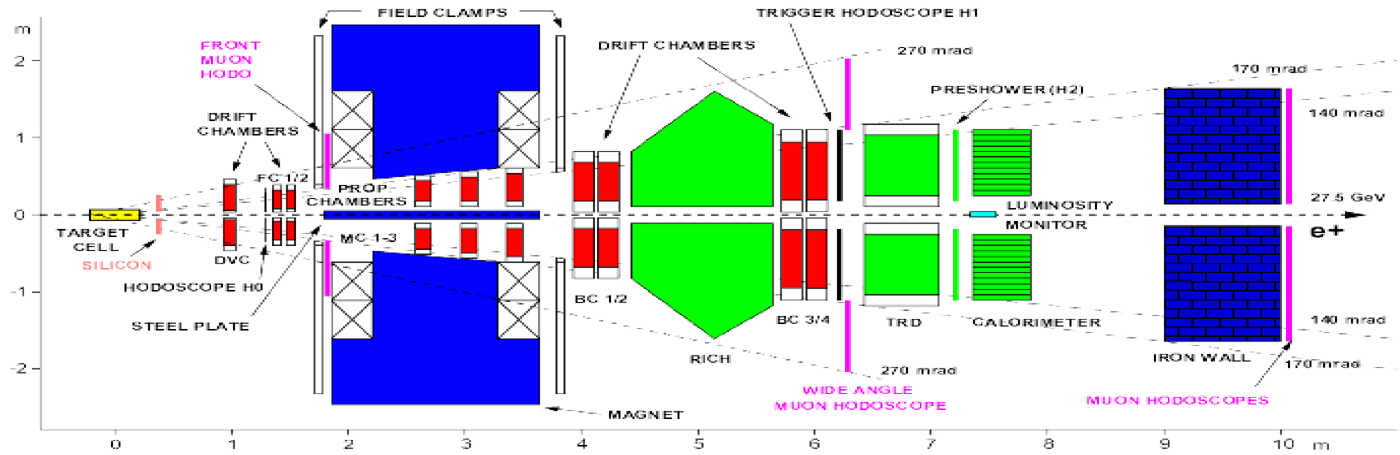
$$F_{BT}^{mod} \propto x \sum_q e_q^2 \; f^q \otimes D_q^h$$

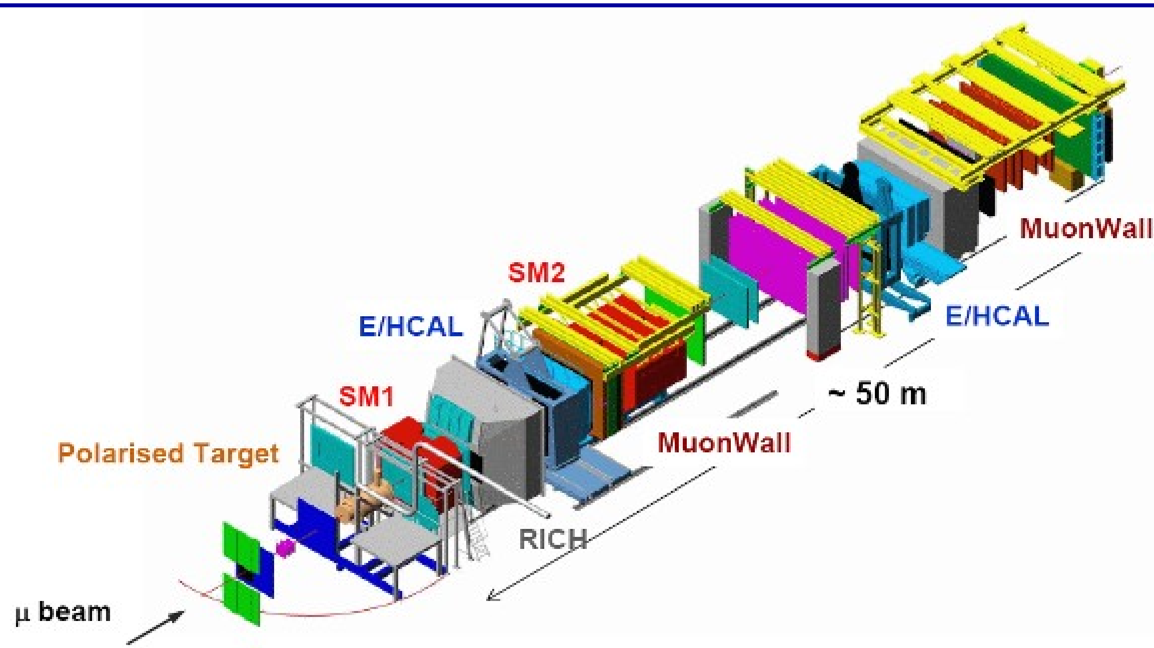
any TMD PDF

corresponding FF

the measurements of the structure functions using
different targets with different polarisations and
looking at different final state hadrons
give information on the different TMD PDFs for the different quark flavours q

the experiments

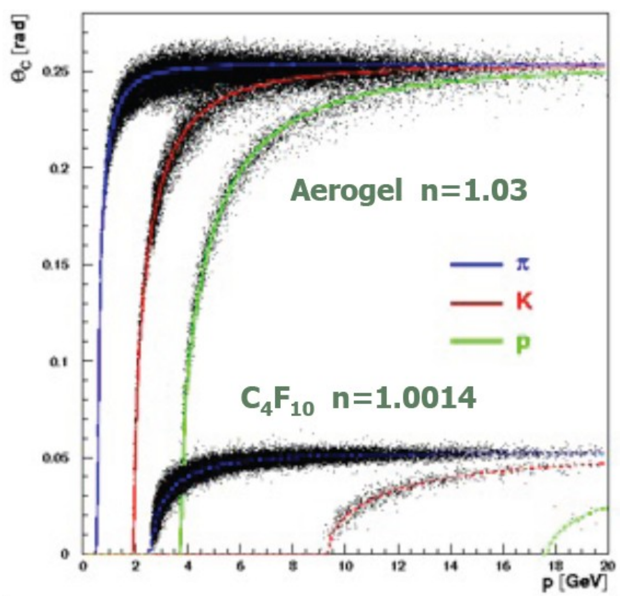

FIELD CLAMPS
TRIGGER HODOSCOPE H1
DRIFT CHAMBERS
270 mrad
170 mrad
PRESHOWER (H2)
140 mrad
FRONT MUON HODO
DRIFT CHAMBERS
FC 1/2
PROP. CHAMBERS
MC 1-3
TARGET CELL
SILICON
DVC
HODOSCOPE H0
STEEL PLATE
BC 1/2
RICH
BC 3/4
TRD
LUMINOSITY MONITOR
CALORIMETER
IRON WALL
27.5 GeV
e+
140 mrad
170 mrad
270 mrad
WIDE ANGLE MUON HODOSCOPE
MUON HODOSCOPES
MAGNET
m
2
1
0
-1
-2
0
1
2
3
4
5
6
7
8
9
10
m


MuonWall
SM2
E/HCAL
E/HCAL
SM1
~ 50 m
Polarised Target
MuonWall
RICH
μ beam

data taking with
T polarised target:
2002-2005 (p)

hermes

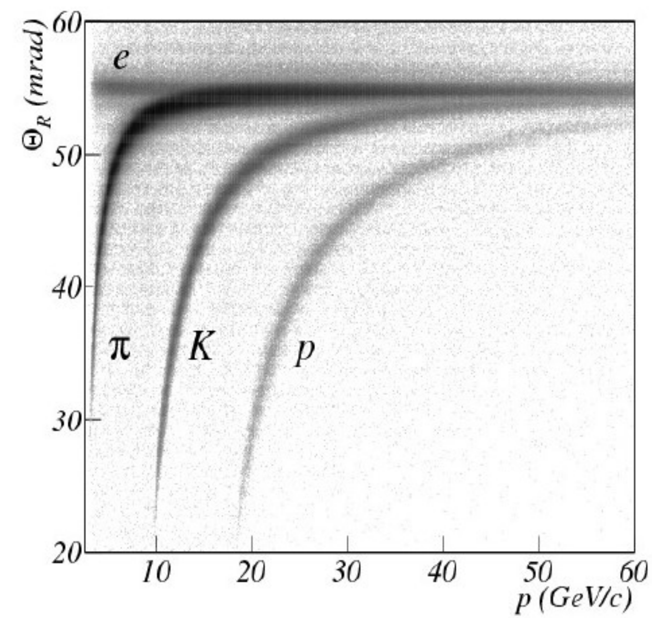
- polarized (<60%) e^+/e^- beam
  of **27 GeV**, both helicity states
- pure gas targets with T (**p**) and L (**p,d**) polarization,
  fast spin-flip of target
- RICH PID K: 2-15 GeV



COMPASS

data taking with
T polarised target:
2002-2004 (d)
2007 (p)
2010 (p)

- polarized (~-80%) μ^+
  of **160 GeV**
- **NH_3** (p) and **^{6}LiD** (d) targets with T and L polarization, 2 (3) cells with opposite P, polarisation reversal every ~8h
- RICH PID K: 9-50 GeV



data taking with
T polarised target:
2002-2005 (p)

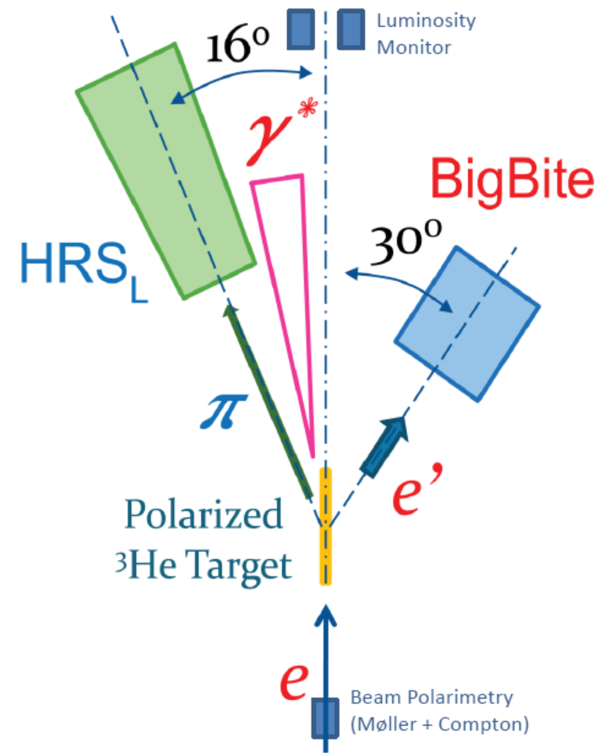
data taking with
T polarised target:
2002-2004 (d)
2007 (p)
2010 (p)

- polarized (<60%) e^+/e^- beam of **27 GeV**, both helicity states
- pure gas targets with T (**p**) and L (**p,d**) polarization, fast spin-flip of target
- RICH PID K: 2-15 GeV

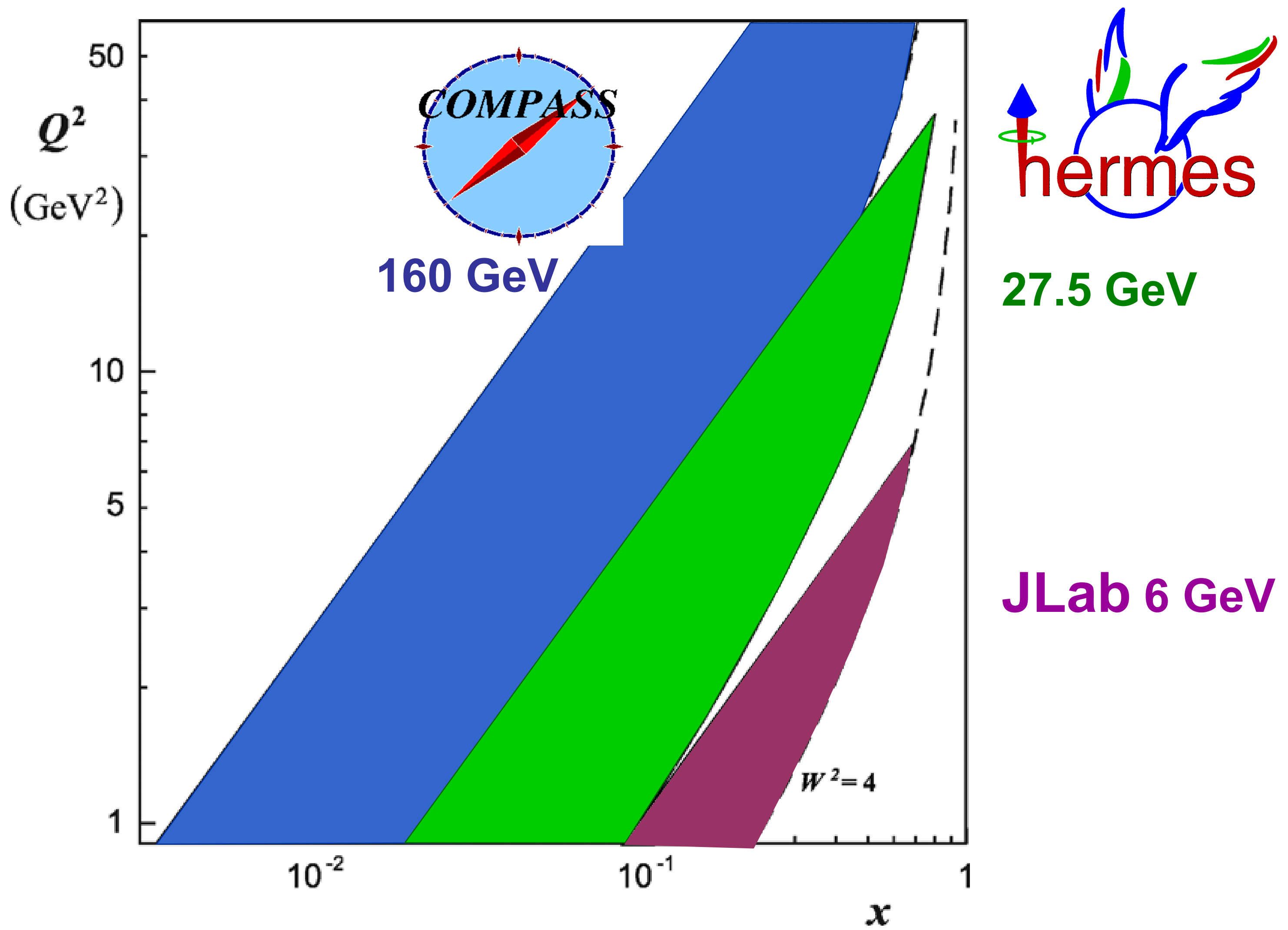
- polarized (~-80%) μ^+ of **160 GeV**
- **NH_3** (p) and **^{6}LiD** (d) targets with T and L polarization, 2 (3) cells with opposite P, polarisation reversal every ~8h
- RICH PID K: 9-50 GeV

Jefferson Lab E06-010 Collaboration

- **6 GeV** electron beam
- transversely polarised **^{3}He** target
- identified final state hadrons



kinematical region



results

azimuthal asymmetries

transverse target polarisation

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

Collins asymmetry

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

$h_1 H_1^\perp$

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

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

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

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

Collins asymmetry

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

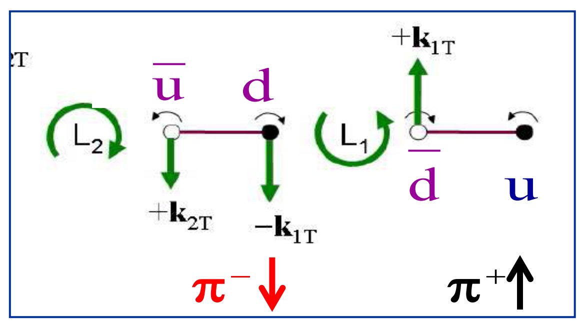
amplitude of the $\sin(\phi_h+\phi_S-\pi)$ modulation
in the azimuthal distribution of the final state hadrons

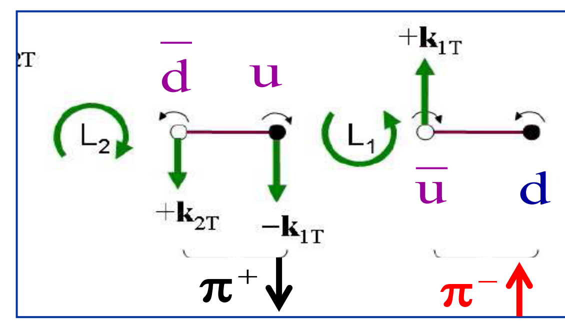
transversity   "Collins FF"

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

"recursive fragmentation model with quark spin"
[X. Artru, arXiv:1001.1061]

D. Sivers, TMD2010





data from Belle (and BaBar)

Collins asymmetry

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

amplitude of the $\sin(\phi_h+\phi_S-\pi)$ modulation
in the azimuthal distribution of the final state hadrons

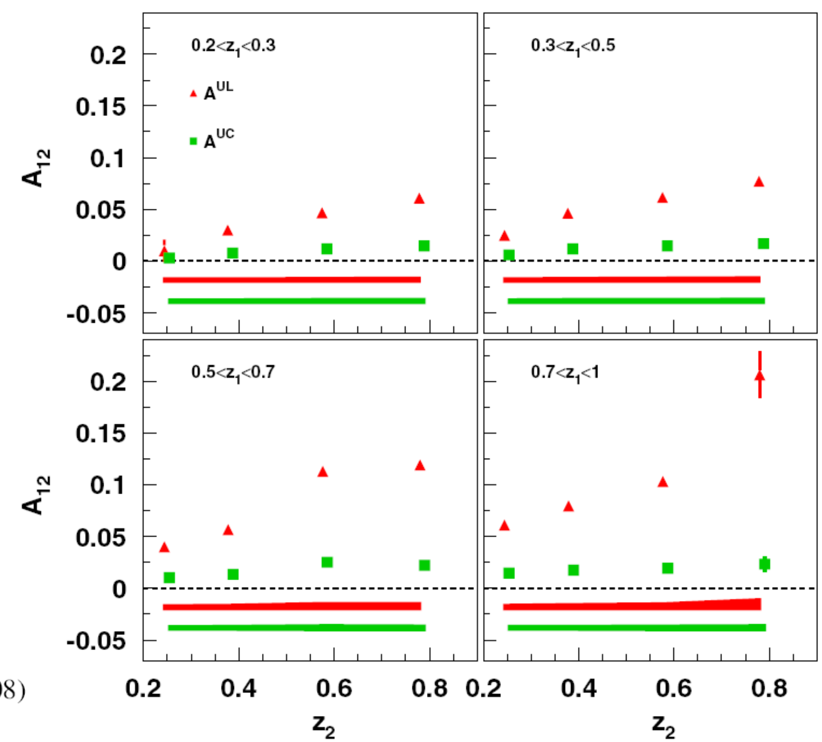
transversity

"Collins FF"

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

data from Belle

$$e^+e^- \rightarrow \pi^+\pi^- X$$



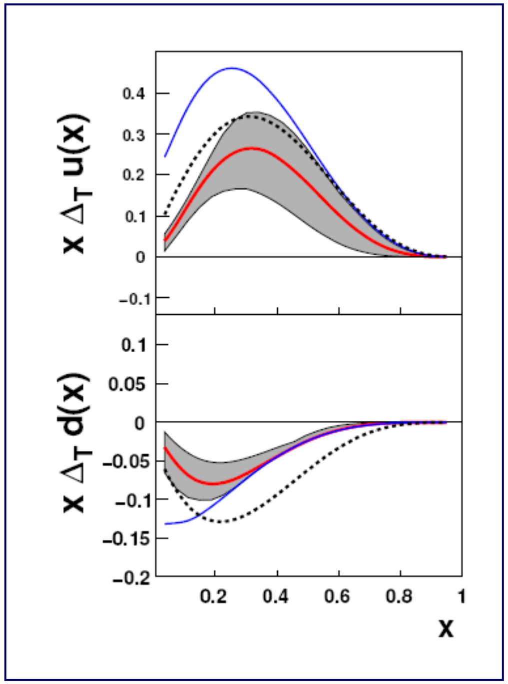
PHYSICAL REVIEW D **78,** 032011 (2008)

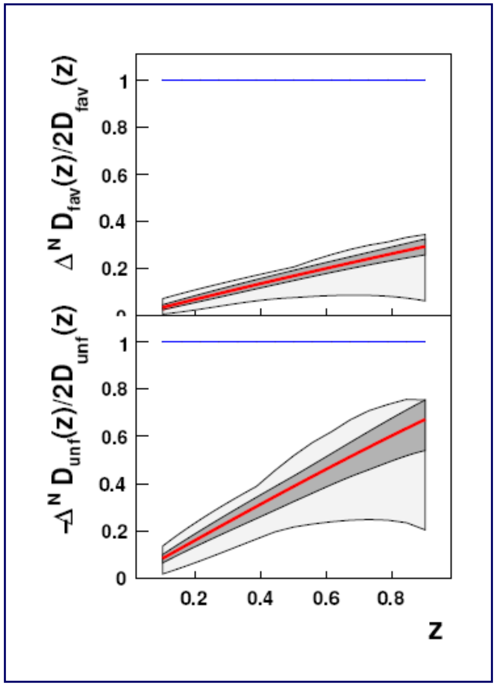
Collins asymmetry

2005

- **first strong signals seen by HERMES on protons: MILESTONE!**
- **no signal seen by COMPASS on deuterons**

the COMPASS d, HERMES p, and BELLE data are well described in global fits
→ *first extractions of the Collins FFs and the transversity PDFs, and tensor charge*

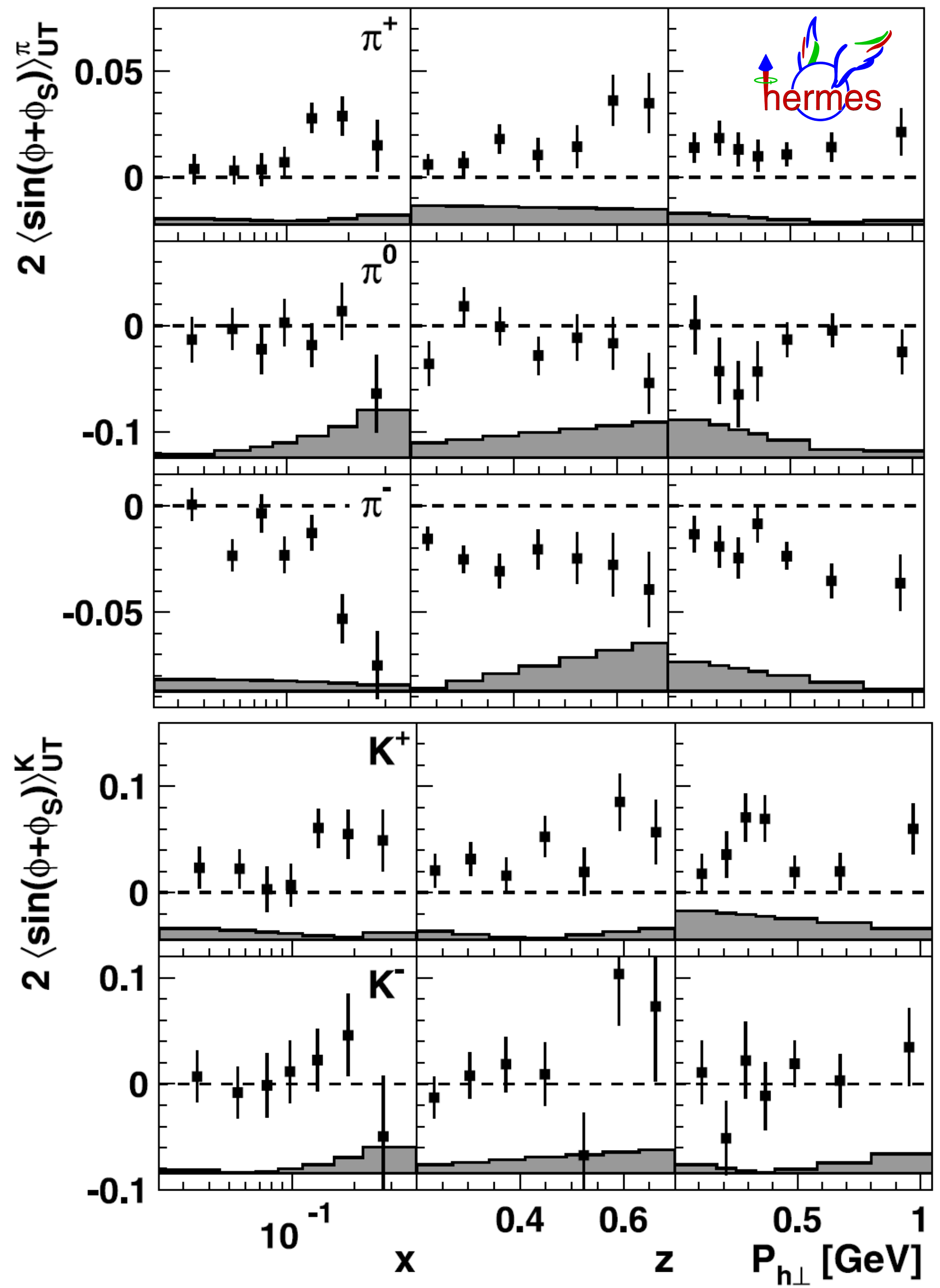




M. Anselmino et al.,
Nucl.Phys.Proc.Suppl.191 (2009) 98

Collins asymmetry - proton

PLB 693 (2010) 11



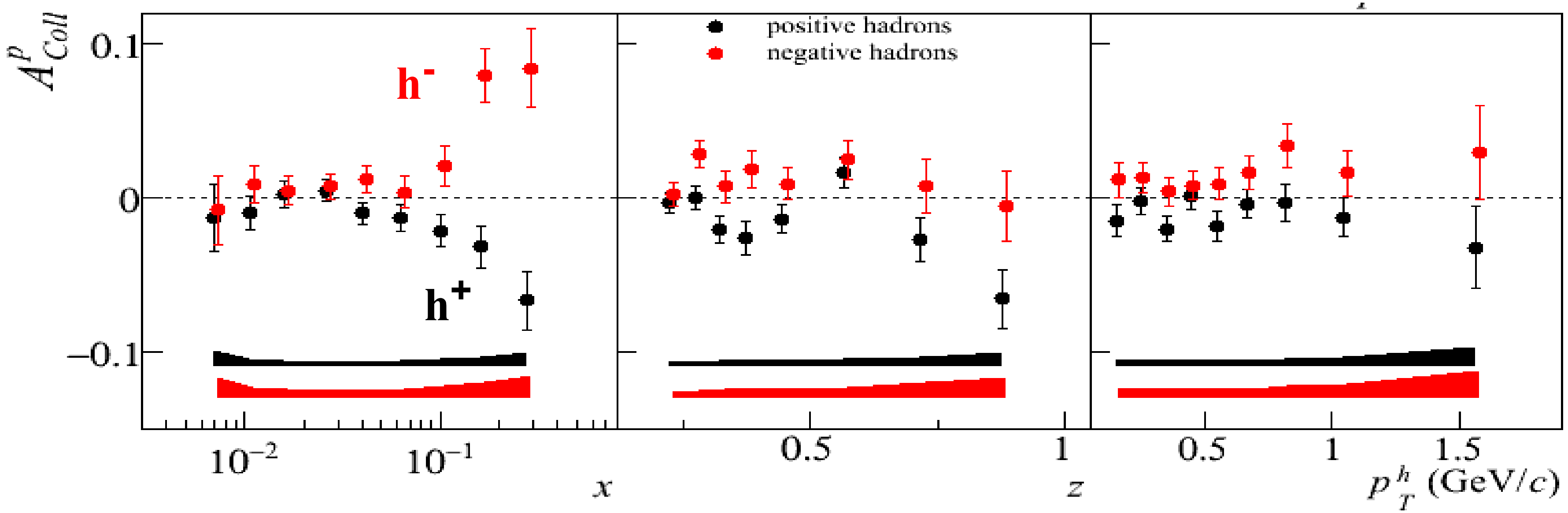
final HERMES results

- clear signal for π^+ and π^- x>0.1 opposite sign
- K^+ signal larger than π^+: role of sea quarks?
- *higher twist effects? limited statistics and range to study the Q^2 dependence*

Collins asymmetry - proton

final COMPASS results from 2007 data

PLB 692 (2010) 240

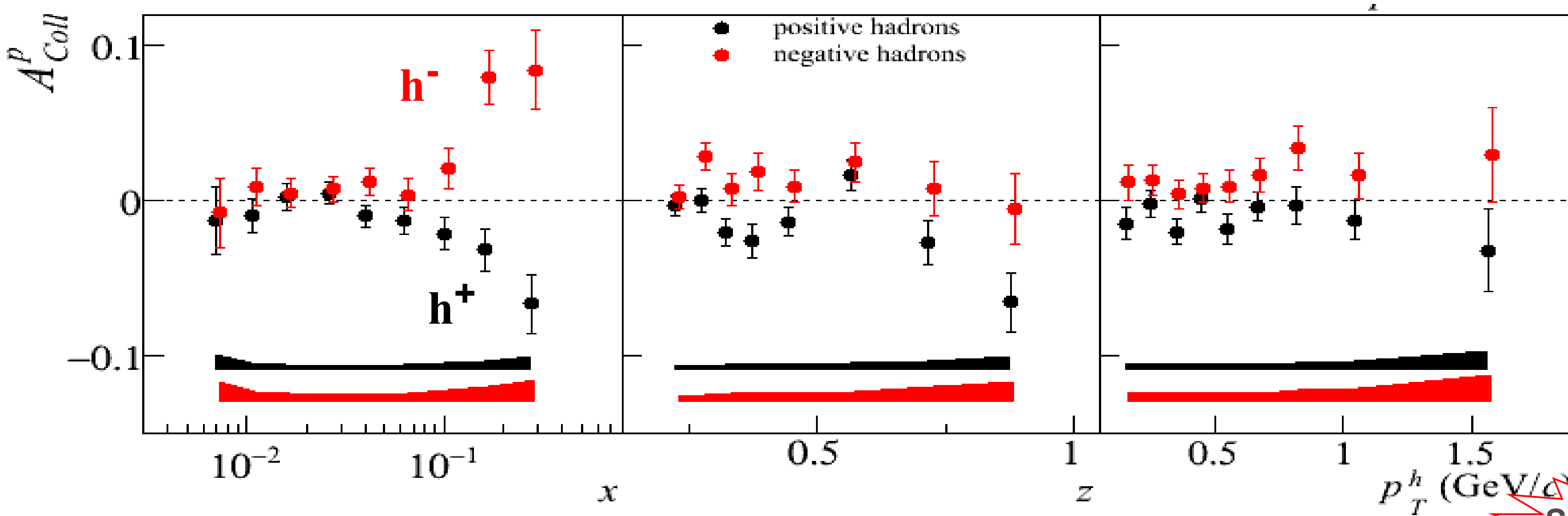


- **at small x,** the asymmetries are **compatible with zero**
- **large signal in the valence region**
  of opposite sign for positive and negative hadrons

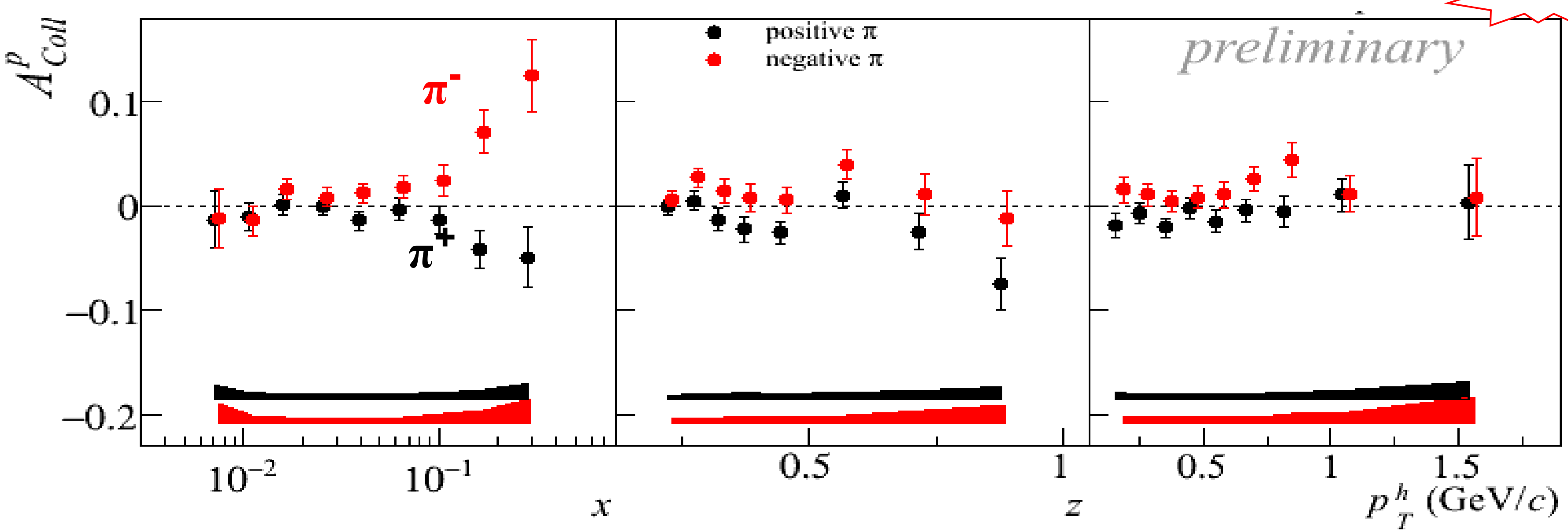
Collins asymmetry - proton

final COMPASS results from 2007 data

PLB 692 (2010) 240

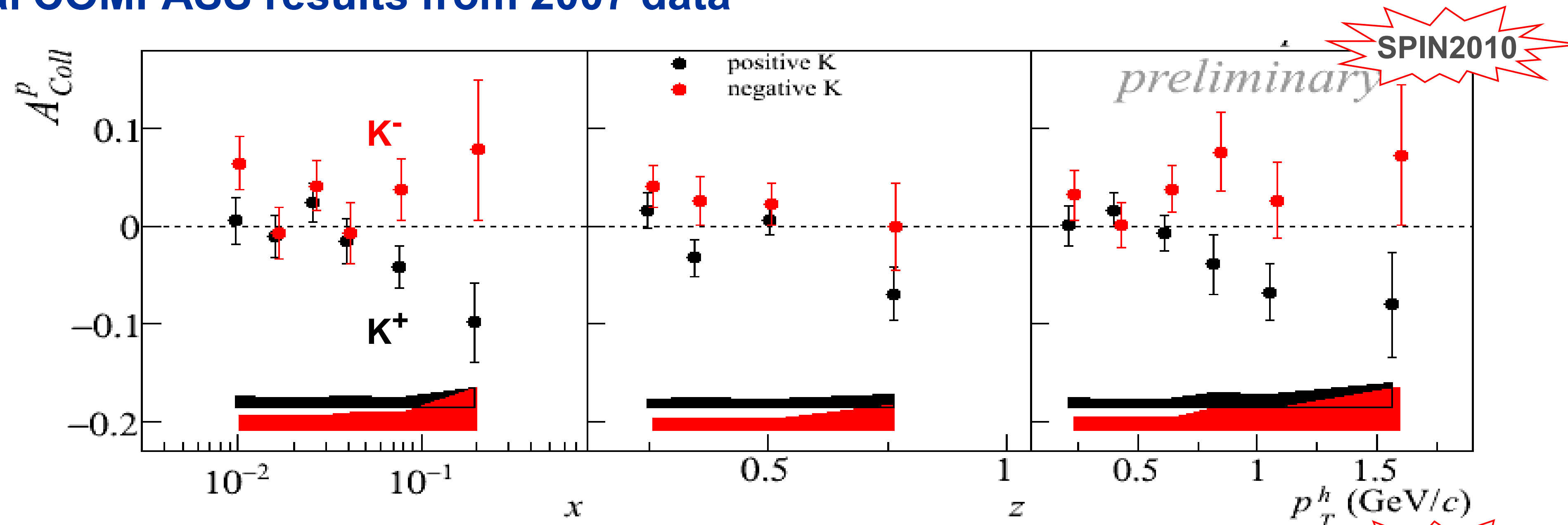


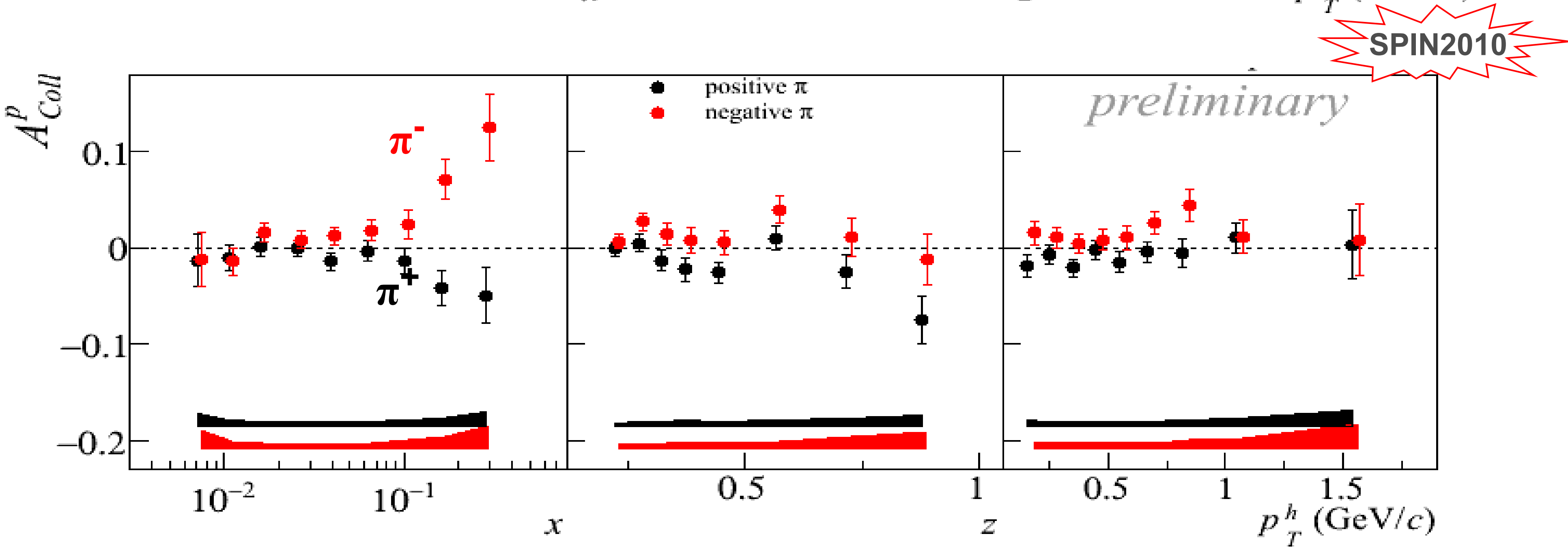
SPIN2010



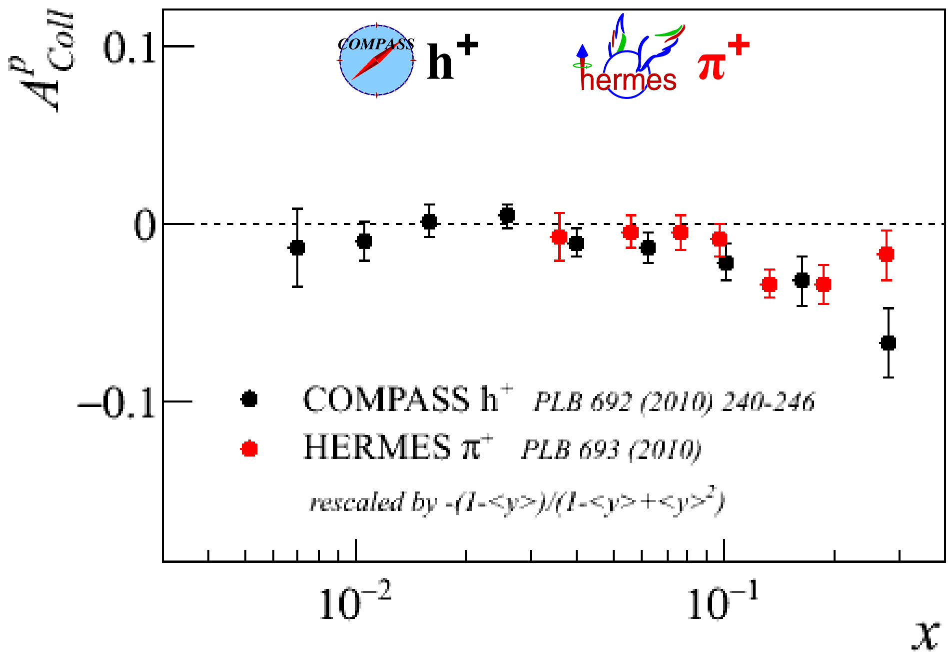
Collins asymmetry - proton

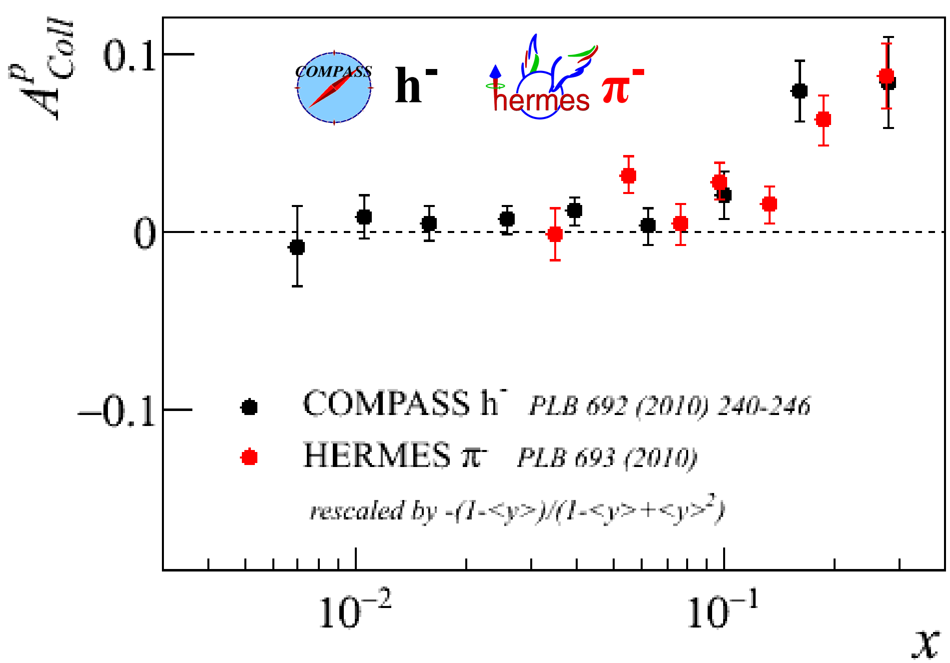
final COMPASS results from 2007 data





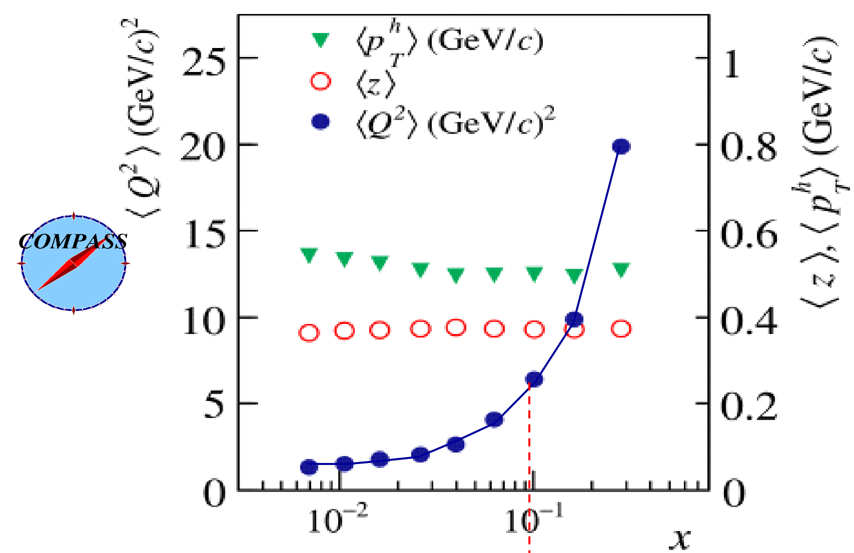
Collins asymmetry - proton

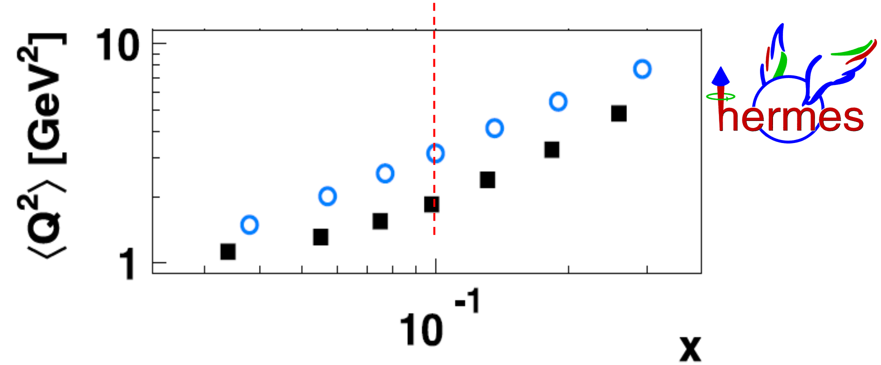




same sign and strength:
a very important, not obvious result!

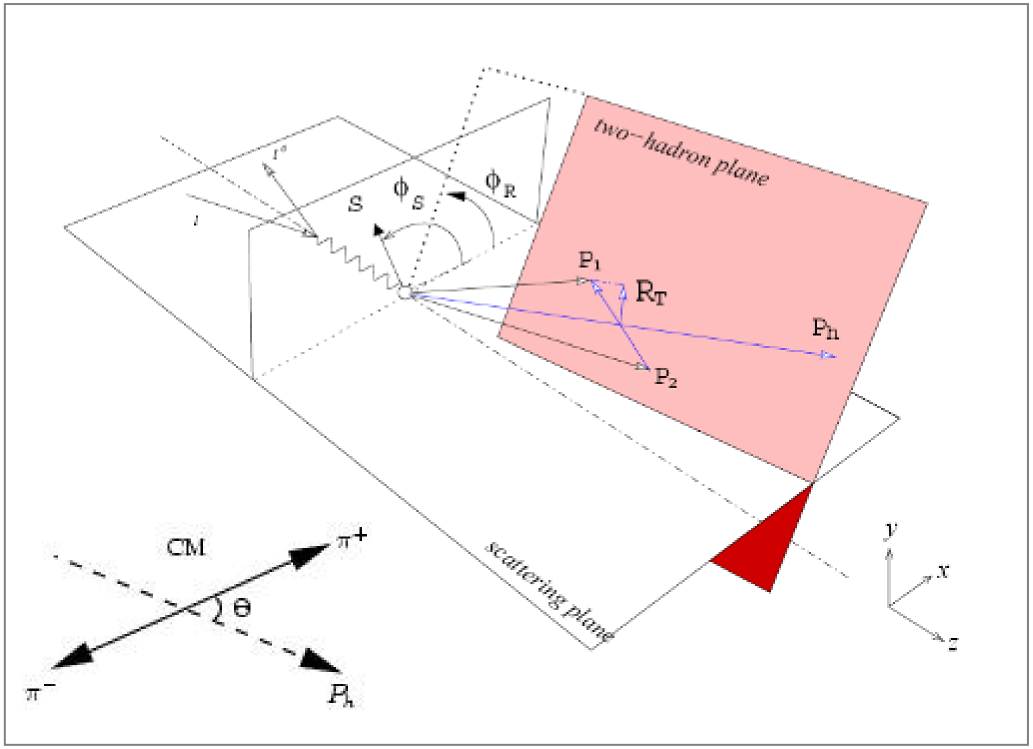
indication for: not a higher twist effect,
weak Q^2 dependence of the Collins FF





COMPASS sign convention

Two Hadron Asymmetry



azimuthal asymmetry in

$\phi_{RS} = \phi_{R\perp} - \phi_{S'}$

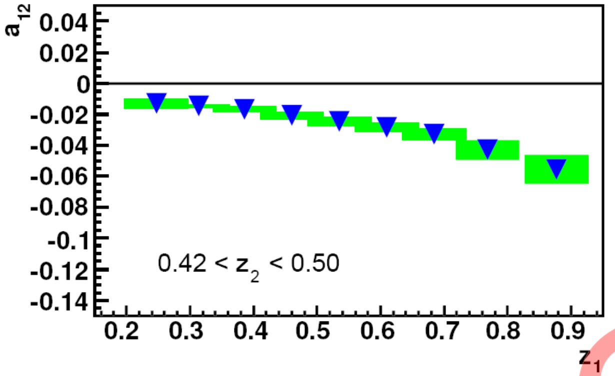
$\phi_{R\perp}$ **is the azimuthal angle of the plane defined by the two hadrons**

$\boldsymbol{R} = (z_1 \boldsymbol{p}_2 - z_2 \boldsymbol{p}_1)/(z_1 + z_2)$

Interference Fragmentation Function

BELLE

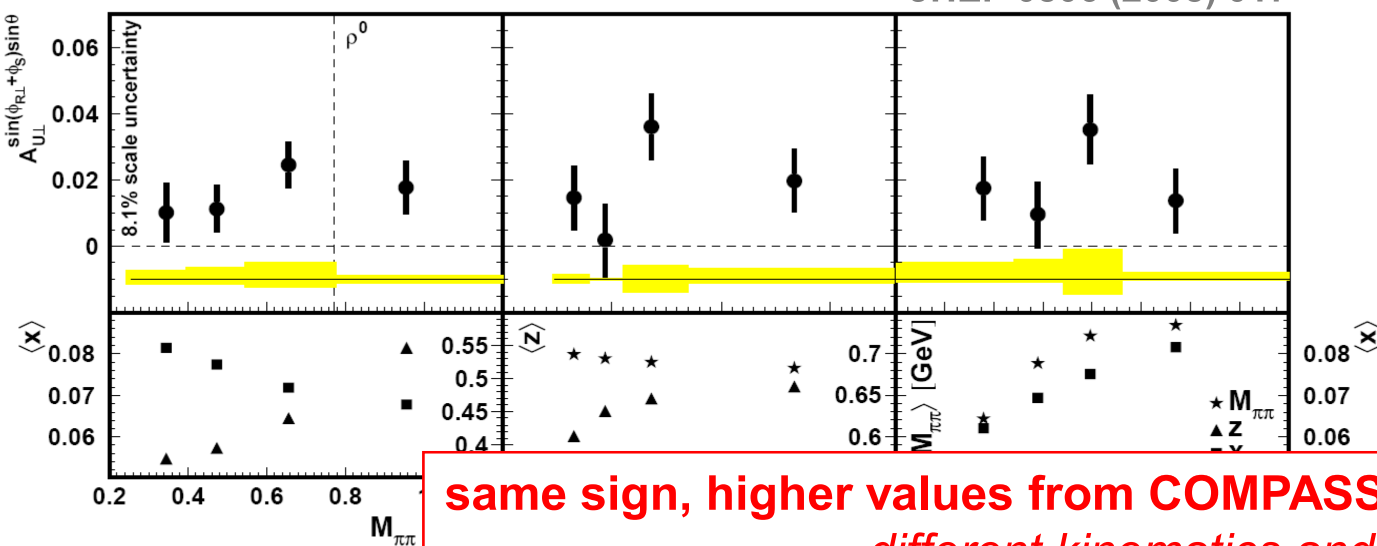
$$A_{RS} = \frac{1}{f \cdot P_T \cdot D_{NN}} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{2h}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_h^2)}$$



Anna Martin

Two Hadron Asymmetry

JHEP 0806 (2008) 017



transversely polarised protons:

first evidence for a different from zero interference FF

same sign, higher values from COMPASS than from HERMES

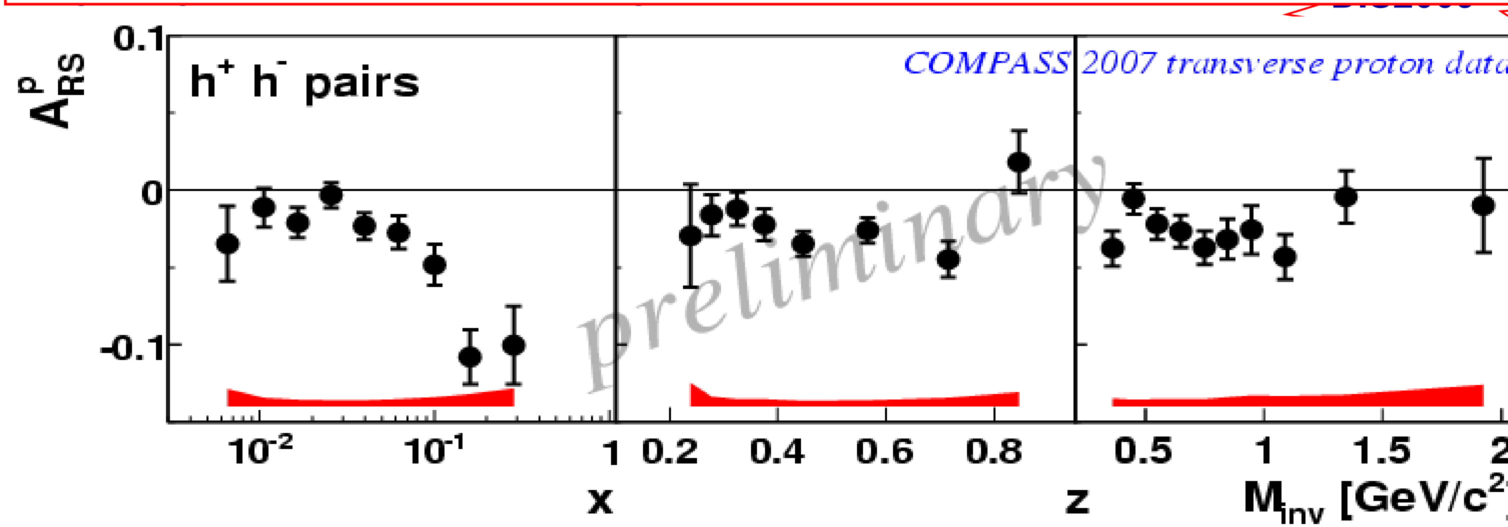
different kinematics and extraction

difficult to describe both sets of data at the same time

[Bacchetta et al., Mah et al.]

deutero

proton:

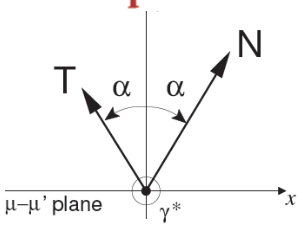


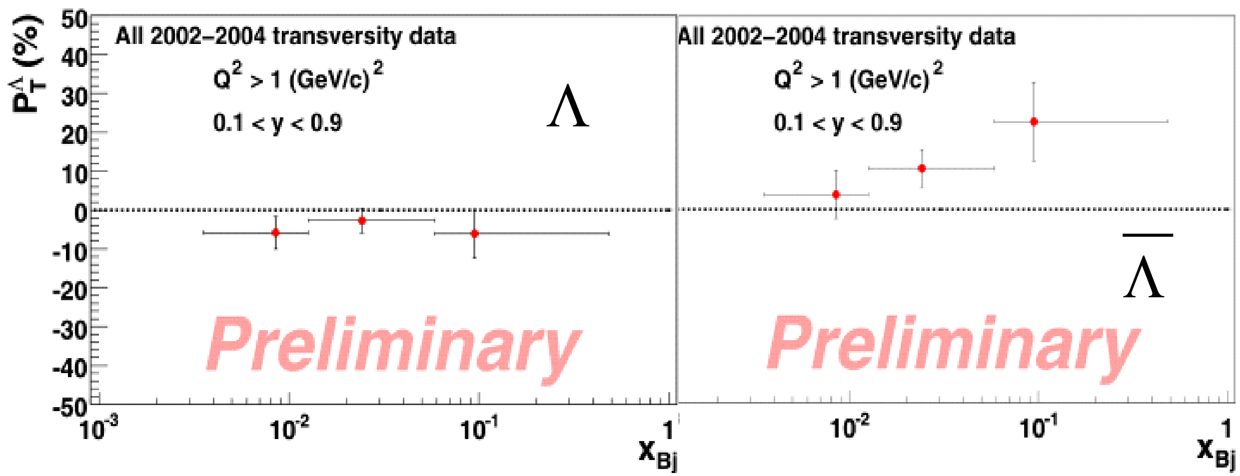
- sign in agreement with the Collins asymmetry
- strength ~ larger than the Collins asymmetry

Λ polarisation

[redacted] [redacted]

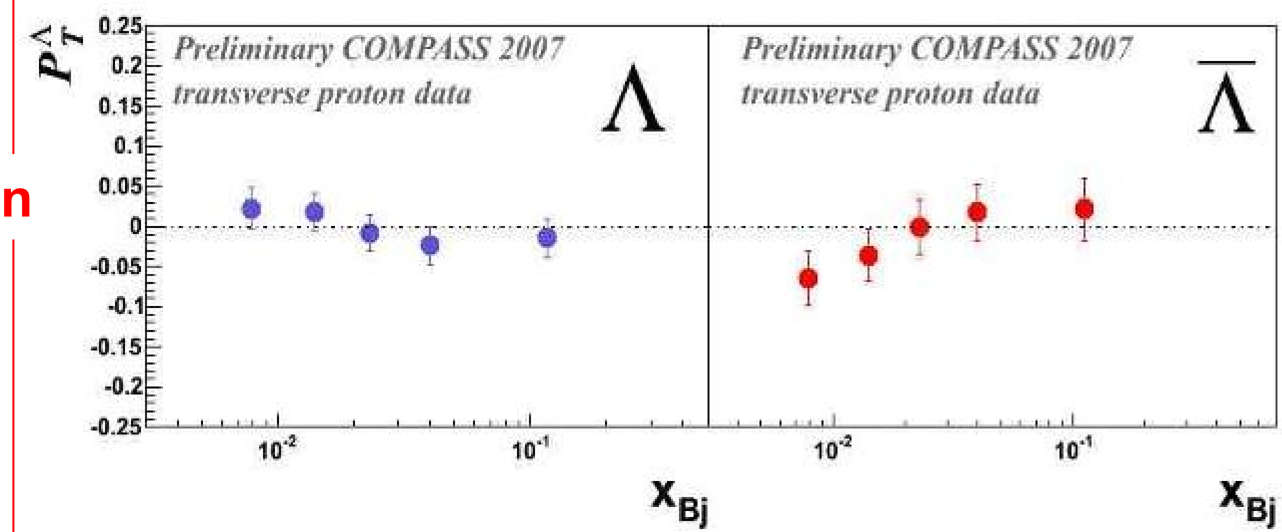
$$P^{\Lambda}_{T,exp} = f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$





deuteron

proton



compatible with zero

more statistics is needed

azimuthal asymmetries

transverse target polarisation

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

Sivers asymmetry

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

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

$h_1 H_1^\perp$ **Collins asymmetry**

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

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

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

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

Sivers asymmetry

$F_{UT,T}^{\sin(\phi_h - \phi_S)}$

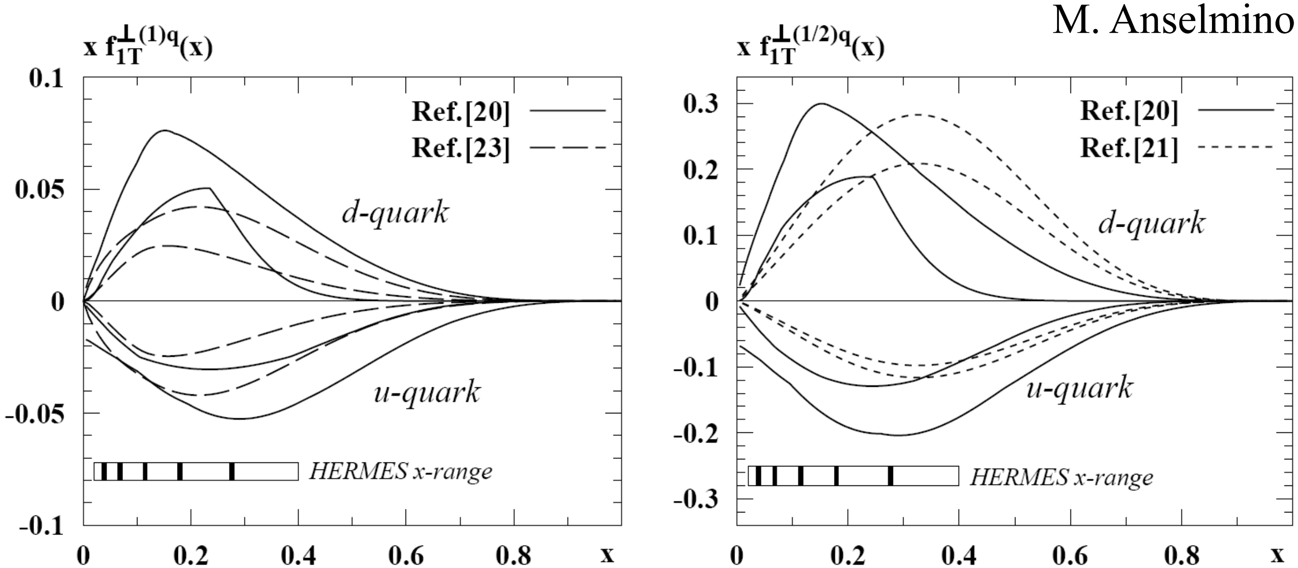
2005

- **first strong signal seen by HERMES for π^+ on protons**
- **no signal seen by COMPASS for h^+ and h^- on deuterons**

→ first extractions of the Sivers function from HERMES p (and COMPASS d) data

good description of the experimental results

M. Anselmino et al., Transversity2005

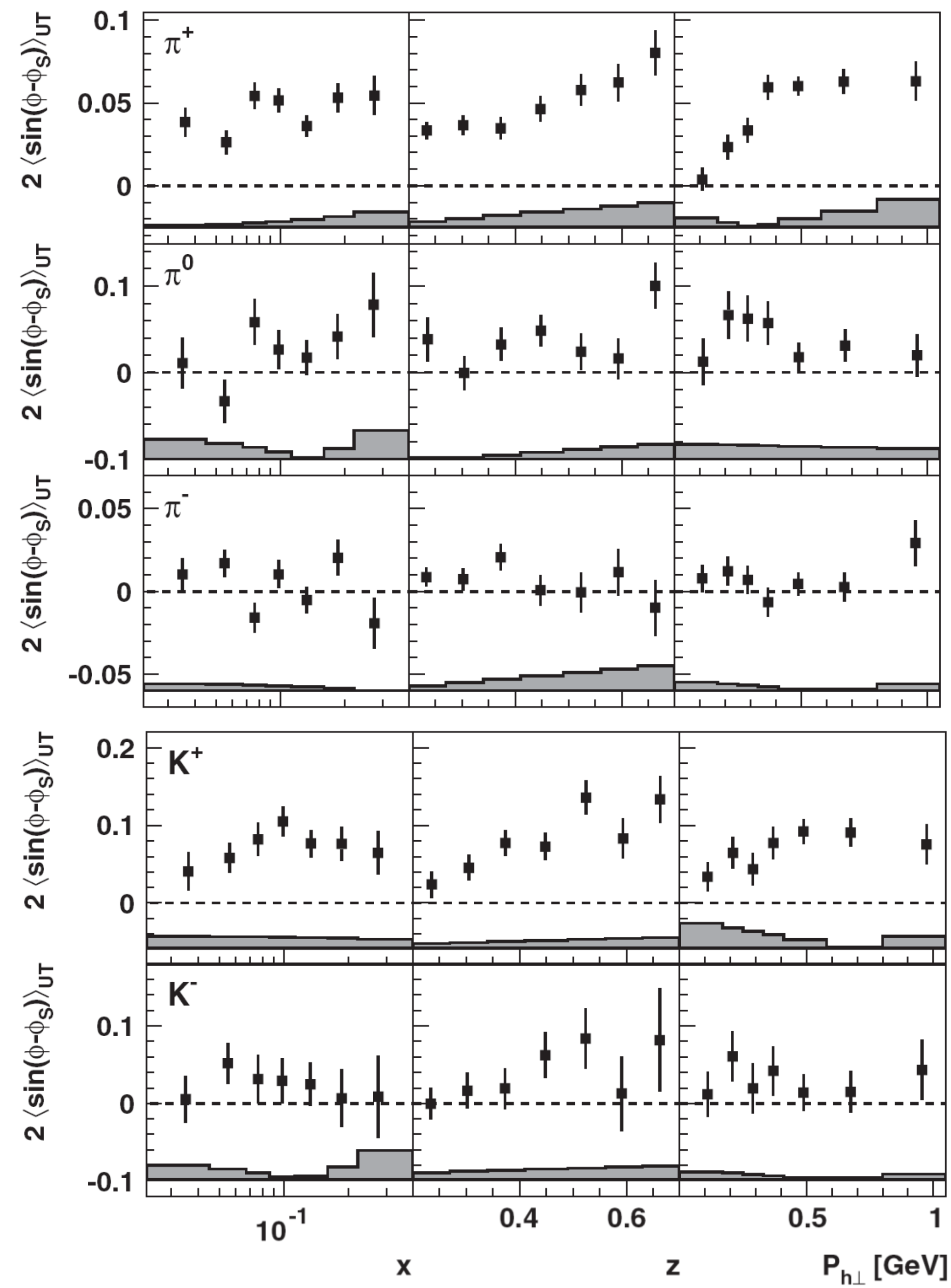


Sivers asymmetry - proton

final hermes results

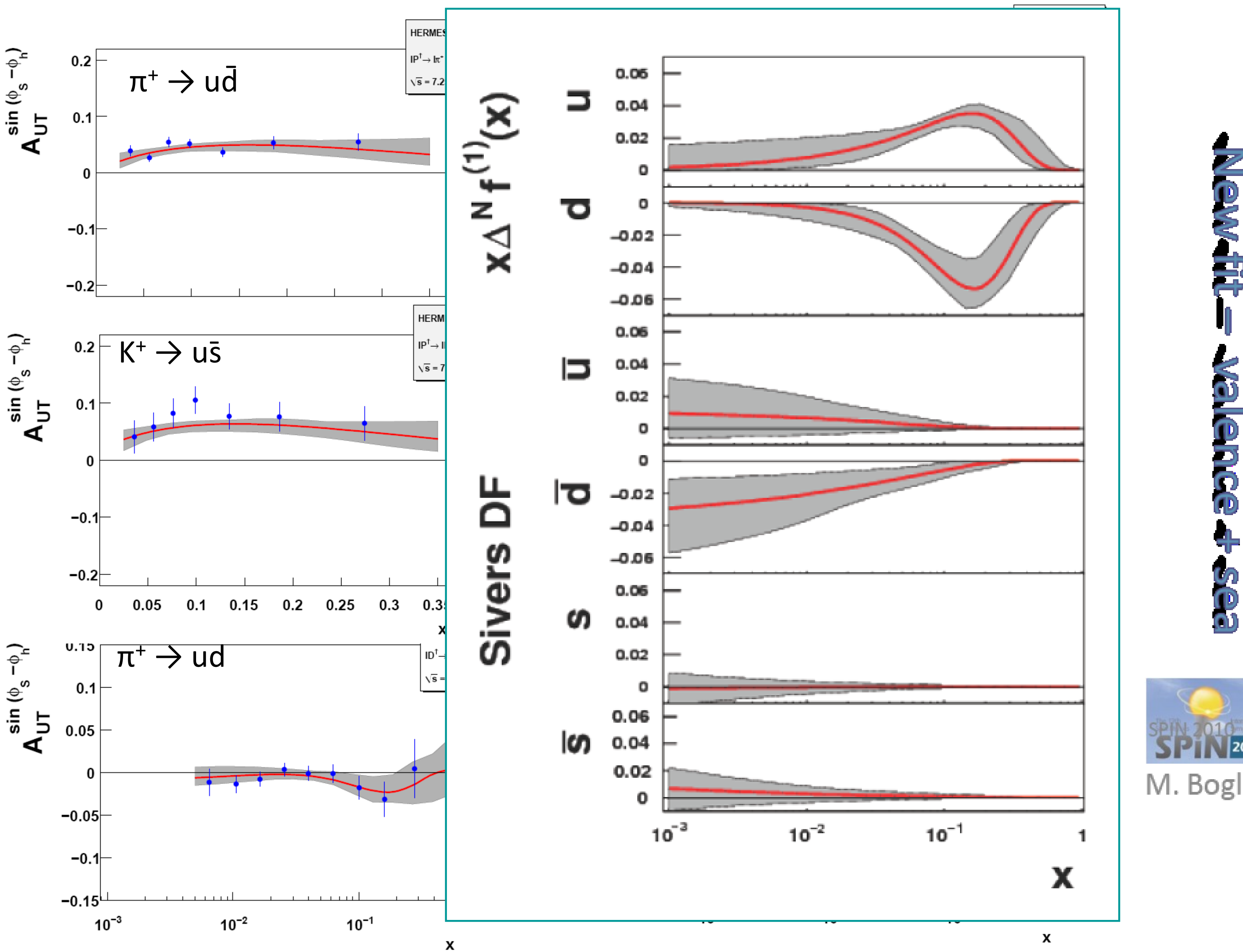
- **clear signal for π^+ and K^+ over all the measured x range**
- **saturation for $P_T^h > 0.4$ GeV/c**
- **difference between K^+ and π^+:**
  - role of sea quarks?

  larger at lower Q^2
  - higher twist effects in K production?



PRL **103,** 152002 (2009)

Sivers asymmetry



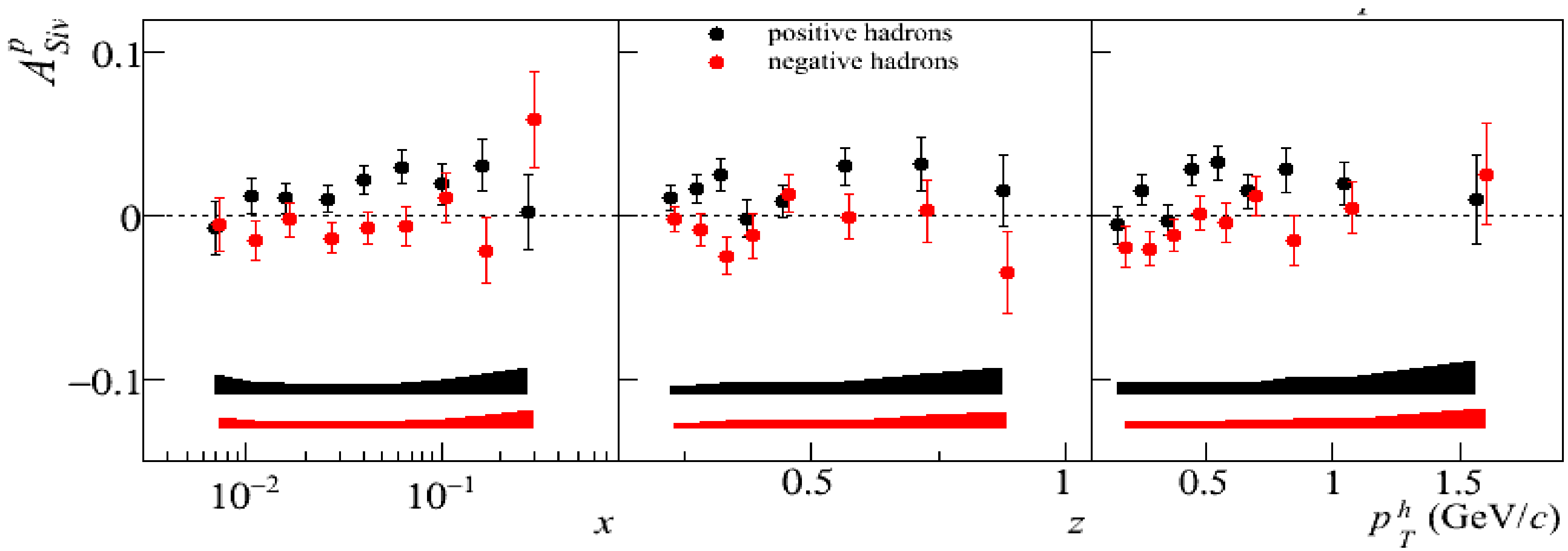
SPIN 2010

M. Boglione

Sivers asymmetry - proton

final COMPASS results from 2007 data

PLB 692 (2010) 240

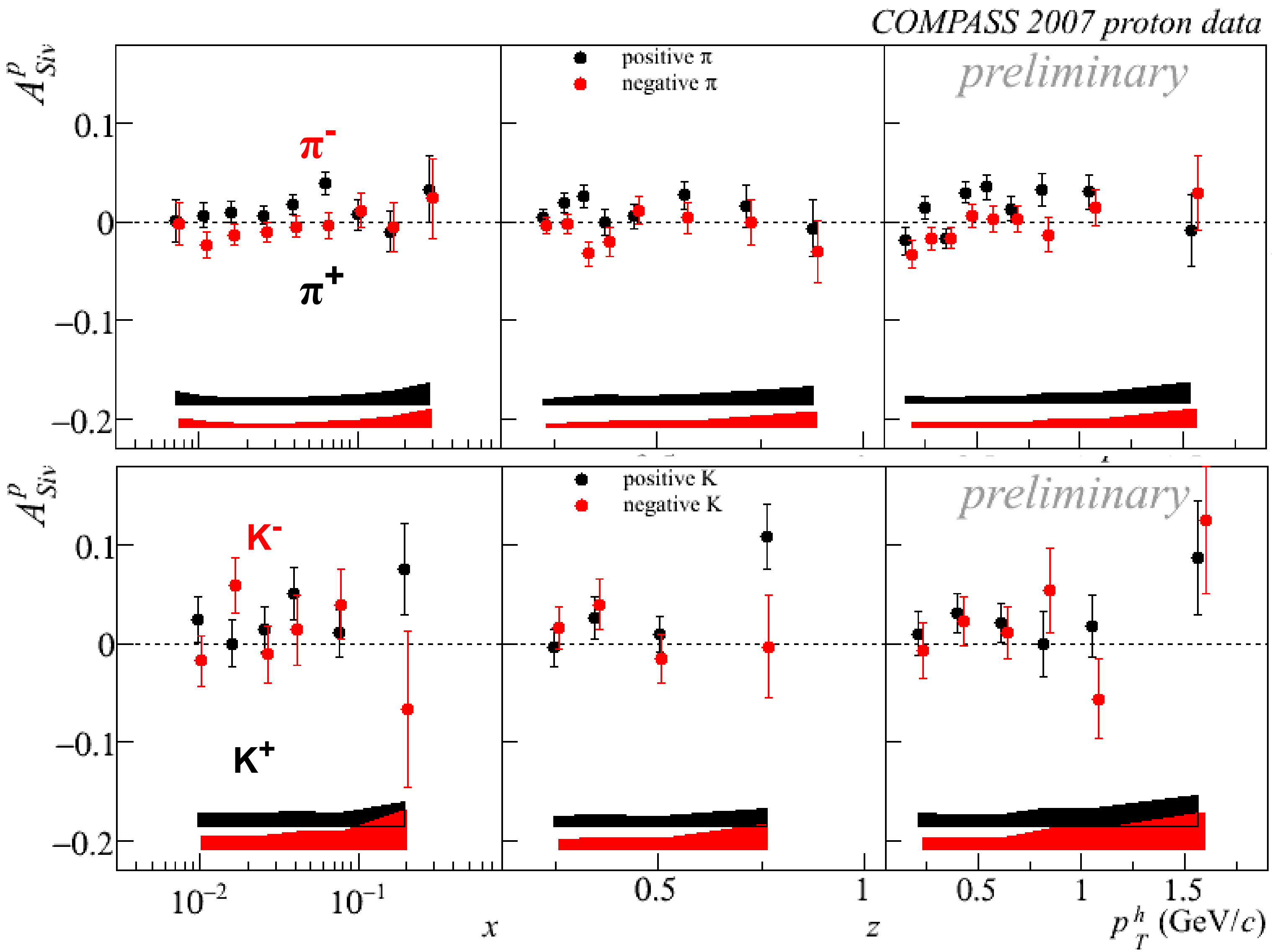


evidence for a positive signal for h^+,
which extends to small x, in the region not measured before

systematic errors $h^- \sim 0.5\ \sigma_{stat}$
$h^+ \sim 0.8\ \sigma_{stat}$ plus a scale (abs) uncertainty of ± 0.01

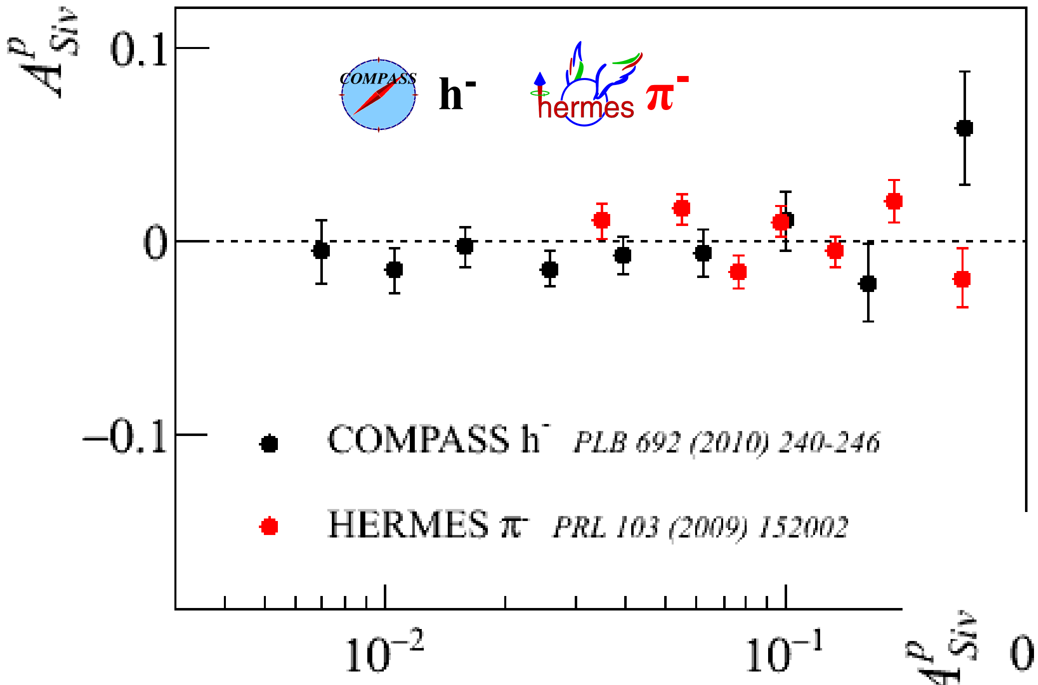
Sivers asymmetry - proton

COMPASS results from 2007 data

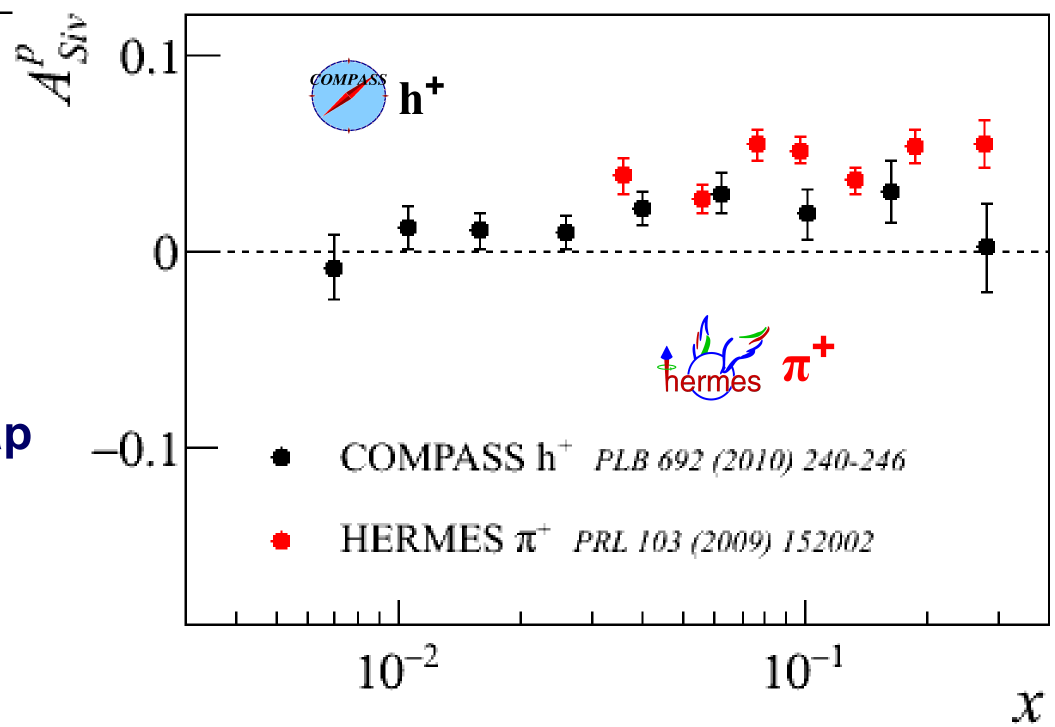


SPIN2010

Sivers asymmetry - proton

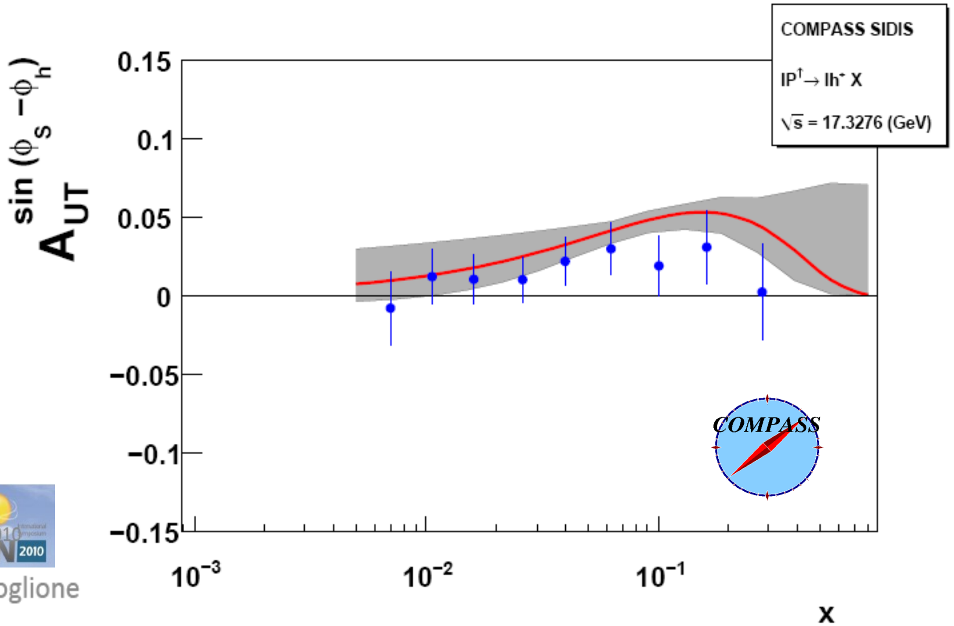


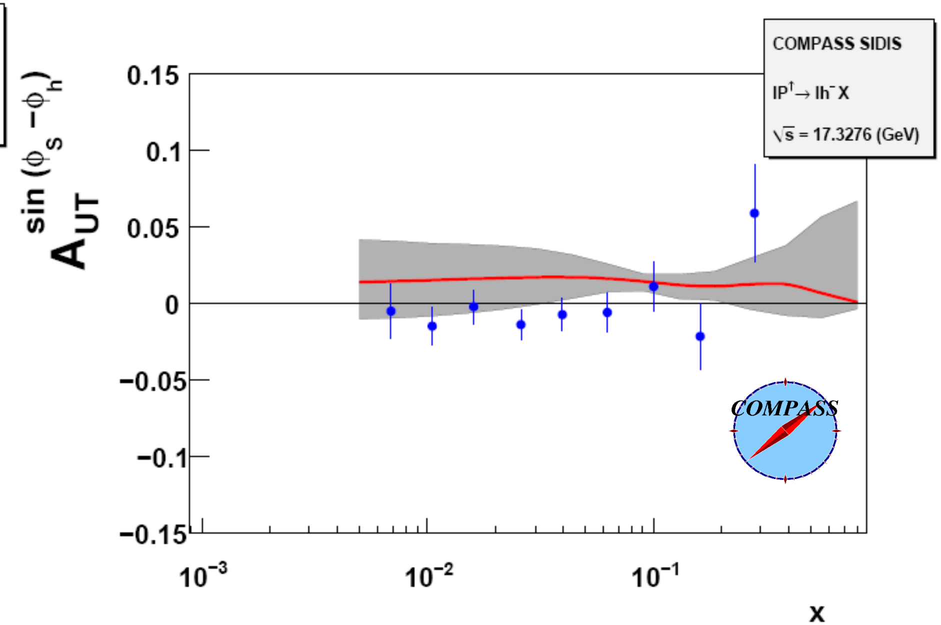
good agreements



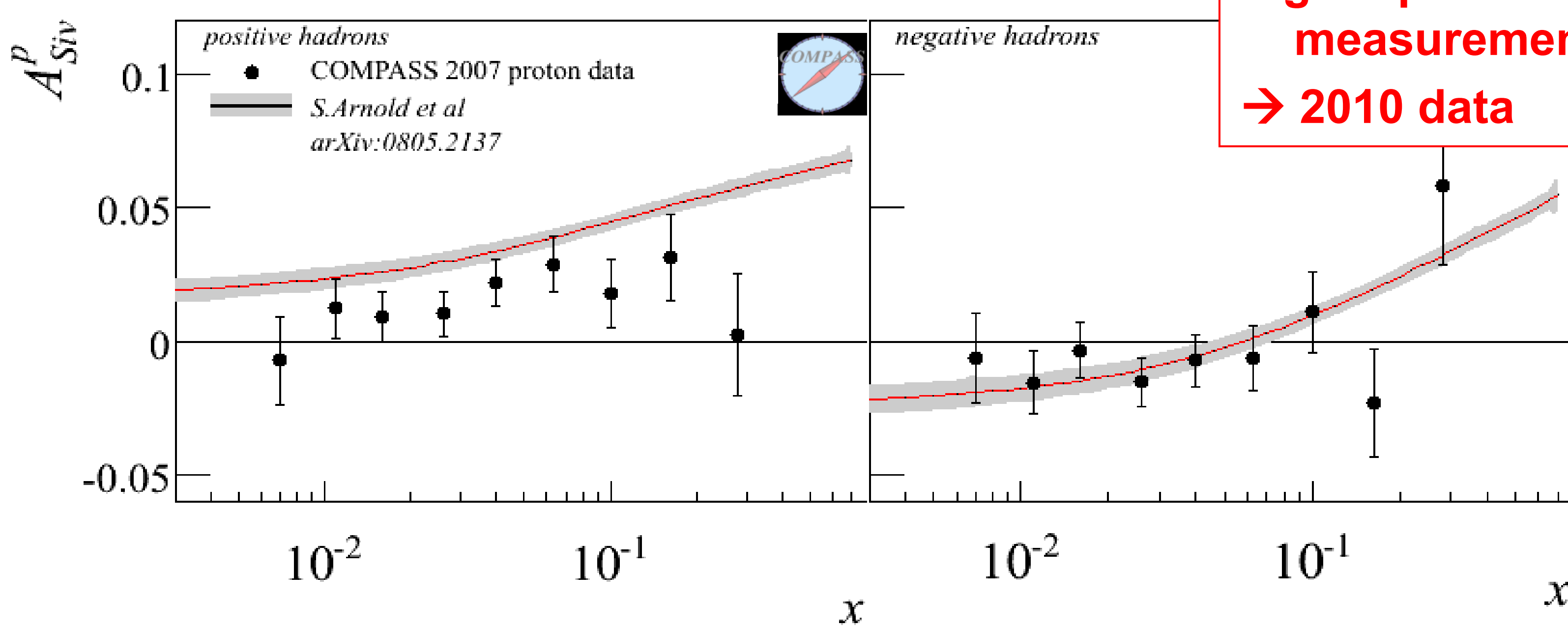
- same sign
- COMPASS results in the overlap region smaller by a factor ~ 2

Sivers asymmetry - proton





M. Boglione



higher precision measurements needed

→ 2010 data

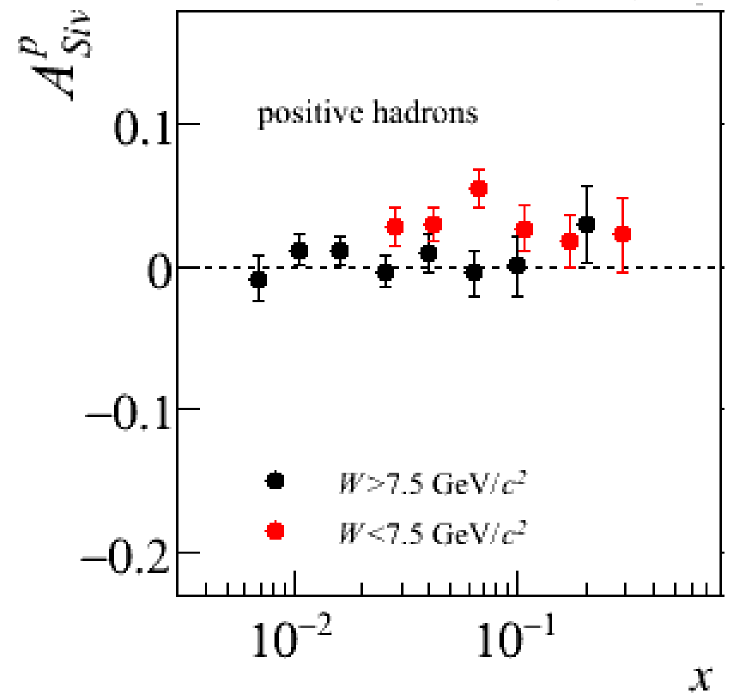
Sivers asymmetry - proton

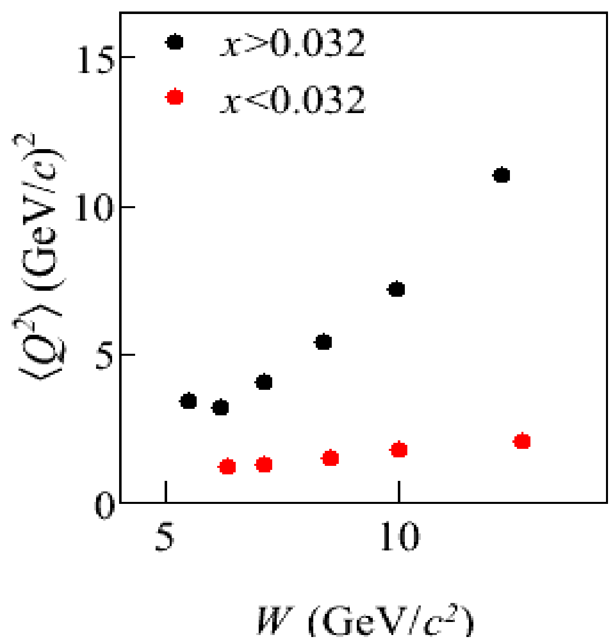
hints for a possible unexpected W dependence of the h^+ Sivers asymmetry

same effect in K^+ asymmetry (SPIN2010)

Q^2 dependence?

PLB 692 (2010) 240





no definite conclusion with the present accuracy:

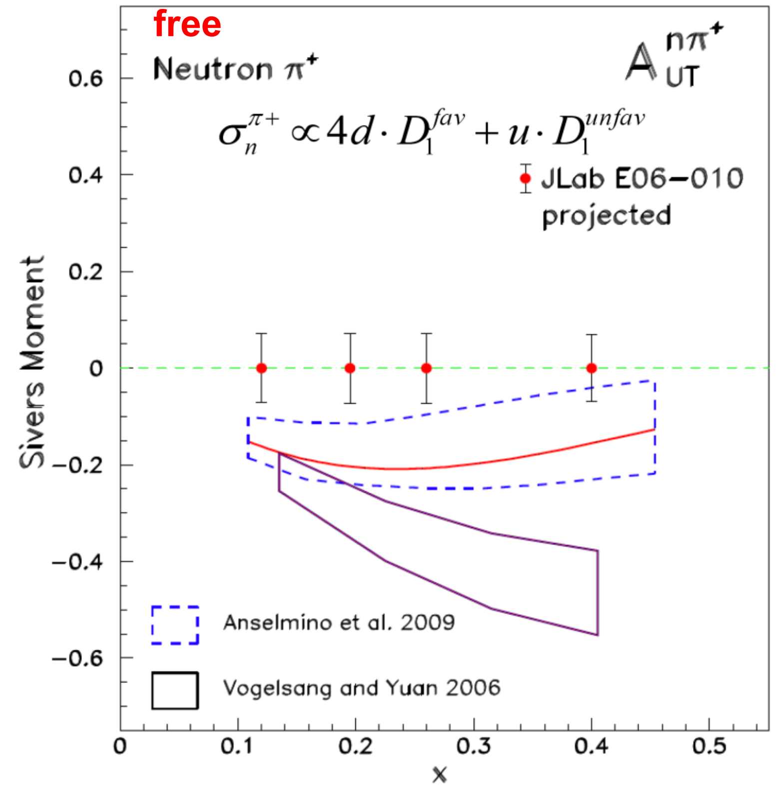
higher precision measurements are needed

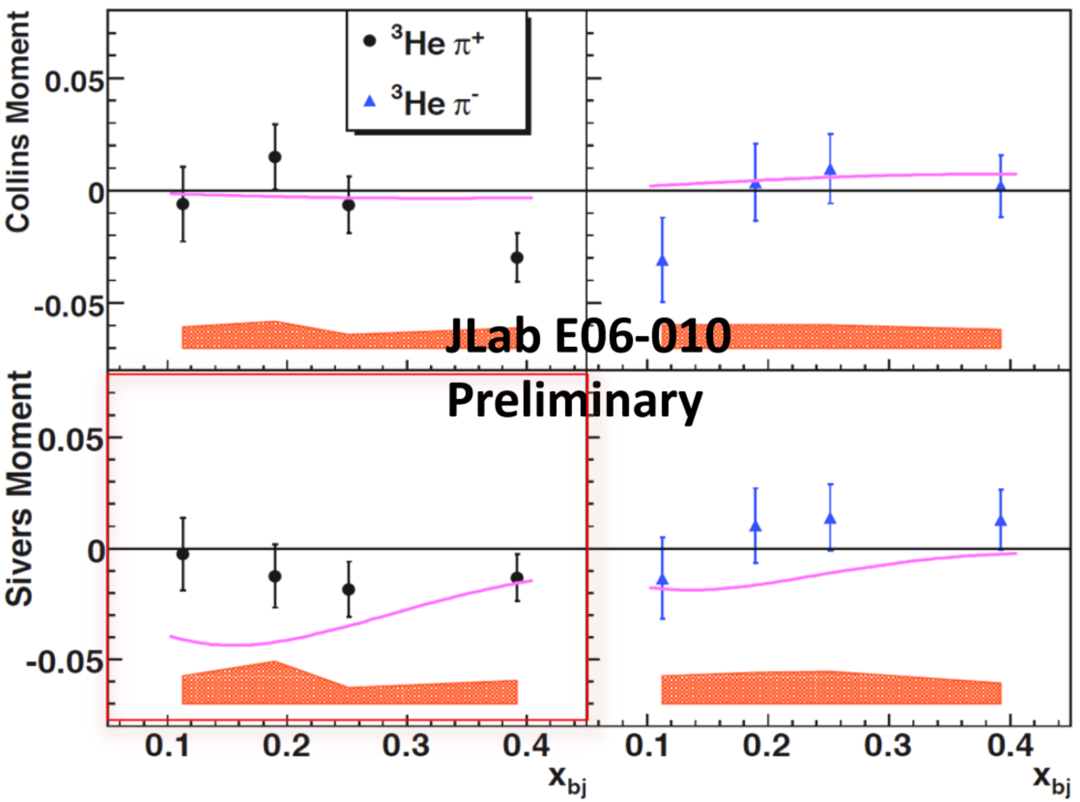
→ 2010 data

Sivers asymmetry

JLab E06-010 experiment

To extract information on neutron,
one would assume :
$$^{3}He^{\uparrow} = 0.865 \cdot n^{\uparrow} - 2 \times 0.028 \cdot p^{\uparrow}$$





^{3}He Collins SSA are not large (as expected).

^{3}He Sivers SSA are smaller than expected (vs Vogelsong and Yuan 2006), follow the trend of Anselmino et al. 2009.

azimuthal asymmetries
transverse target polarisation

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

Sivers asymmetry

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

Collins asymmetry

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

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

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

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

$g_{1T}\, D_1$

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

azimuthal asymmetries
transverse target polarisation

COMPASS

preliminary results

all the other 6 are small, compatible with zero both on p and d

$F_{LT}^{\cos(\phi_h-\phi_S)}$ **positive for π- on ^{3}He at JLab E06-010**

hermes

$F_{UT}^{\sin\phi_S}$ **different from zero**

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

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

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

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

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

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

$g_{1T} D_1$

azimuthal asymmetries

longitudinal target polarisation

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

twist 3

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

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

twist 3

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

worm-gear

COMPASS: no clear signal (on deuteron)	EPJC 70 (2010) 39
$F_{UL}^{\sin 2\phi_h}$ from CLAS	arXiv:1003.4549
$F_{UL}^{\sin\phi_h}$ from HERMES	... PLB 562(2003)182 PLB 622(2005)14

azimuthal asymmetries

unpolarised target

3 independent azimuthal modulations

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

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

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

twist-3

azimuthal asymmetries

unpolarised target

3 independent azimuthal modulations

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

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

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

twist-3

preliminary results

COMPASS: **positive for positive hadrons** (d)

hermes: **positive for positive pions** (p,d)

CLAS: positive for positive pions (p)

azimuthal asymmetries

unpolarised target

3 independent azimuthal modulations

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

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

Cahn effect — **Boer - Mulders × Collins FF**

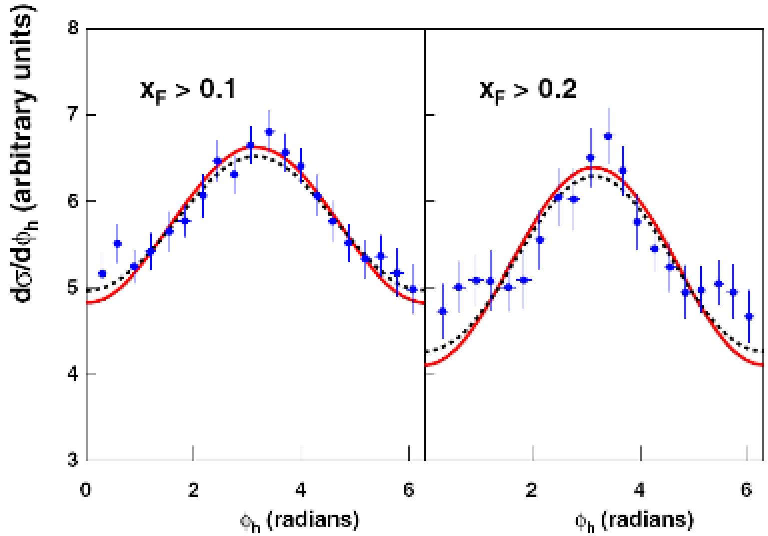
$$\propto \frac{1}{Q}\left(f_1\otimes D_1 + h_1^\perp\otimes H_1^\perp\right)$$

$$\propto h_1^\perp\otimes H_1^\perp + \frac{1}{Q^2} f_1\otimes D_1$$

Boer - Mulders × Collins FF — **Cahn effect**

cosϕ modulation

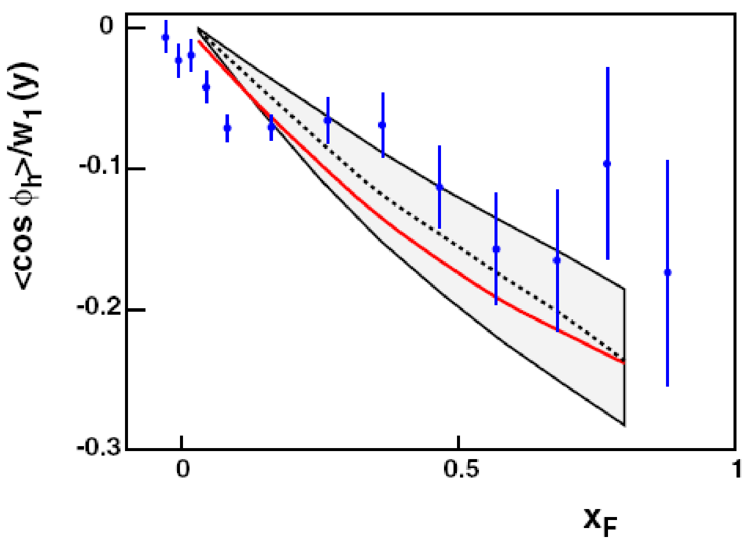
EMC 1987



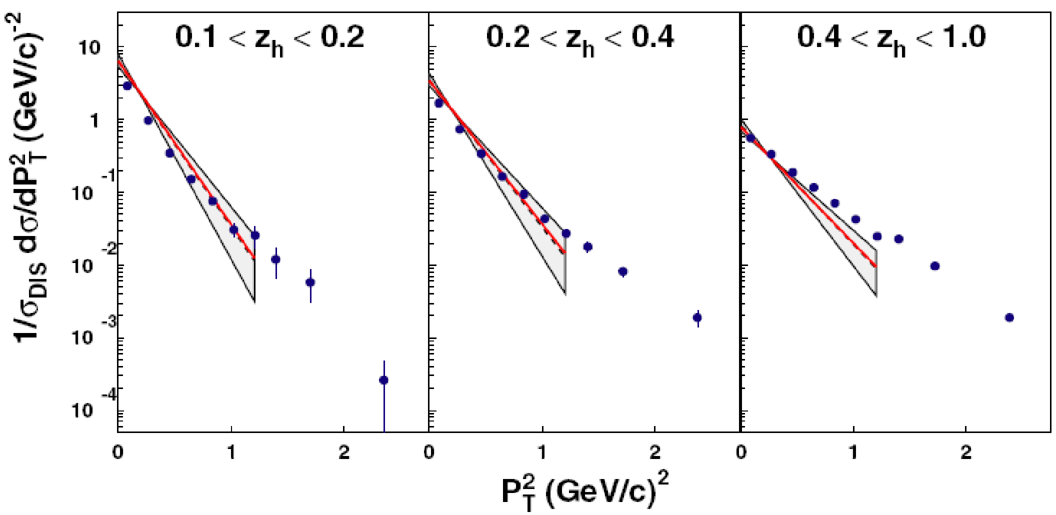
large effects
for $h^+ + h^-$ asymmetries

used to extract $\langle k_T^2 \rangle$

M. Anselmino et al., PRD 71 (2005) 074006

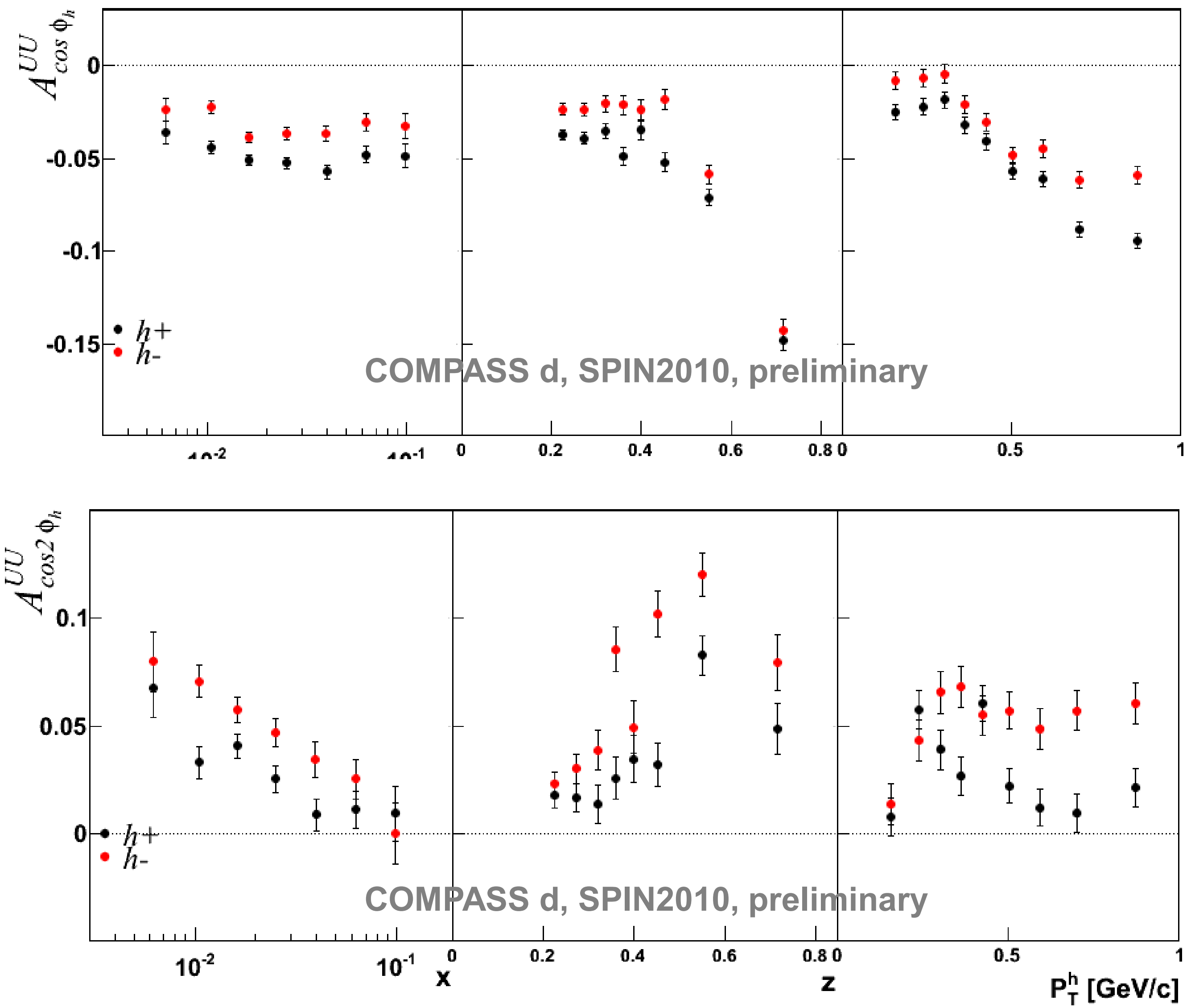


EMC 1991



cos ϕ and cos 2ϕ modulations

first results for h+ and h- from COMPASS in 2008



cos ϕ

large signals over all the x range

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

surprising, different for h^+ and h^-

Boer-Mulders contribution?

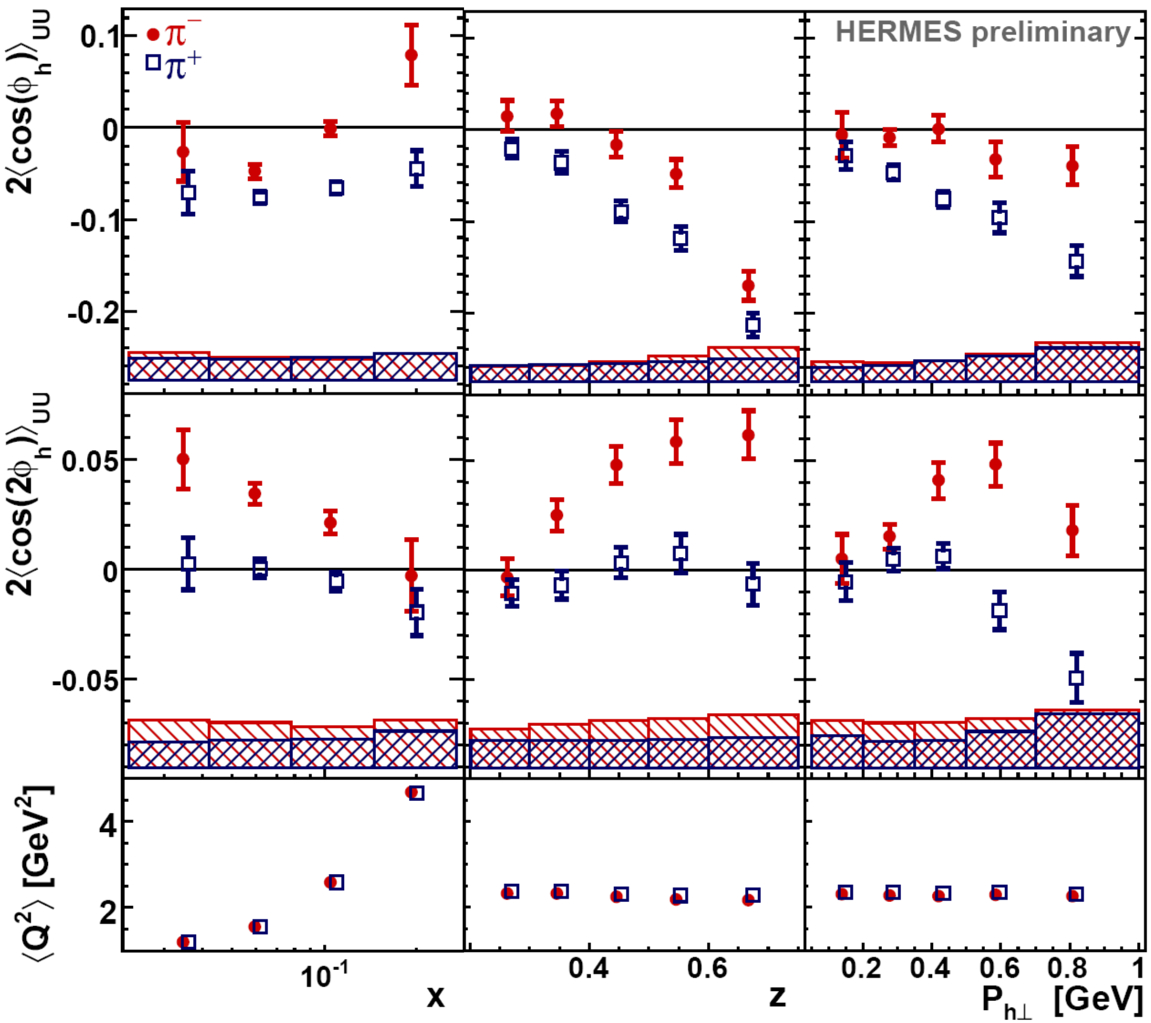
cos 2ϕ

large signals at small x

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

different for h^+ and h^-

cos ϕ and cos 2ϕ modulations



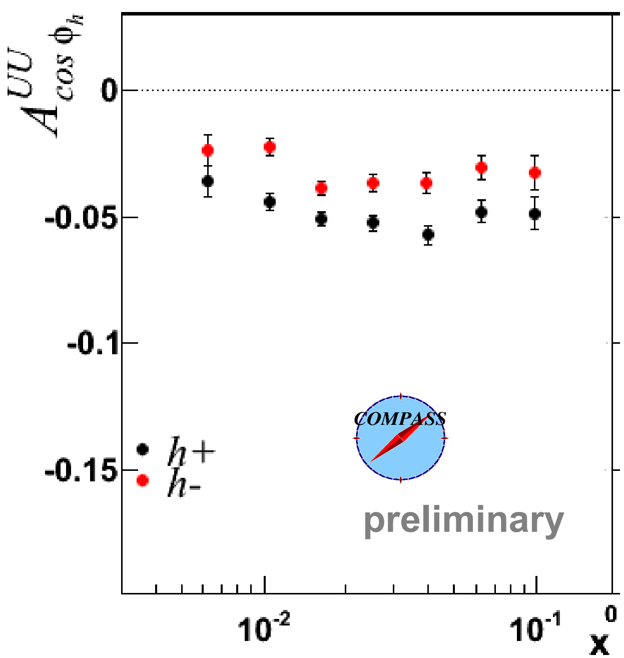
large signals

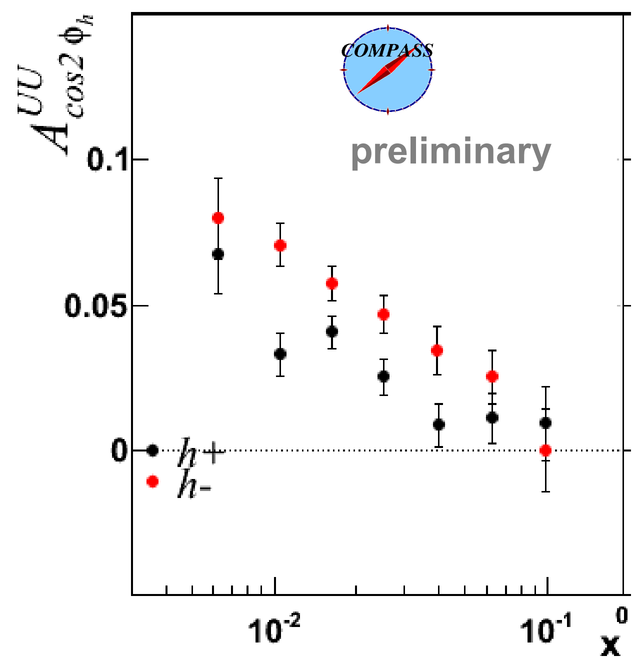
strong dependence on x, z, P_T^h

different values for π+ and π-

deuteron (very similar for proton)

cos ϕ and cos 2ϕ modulations

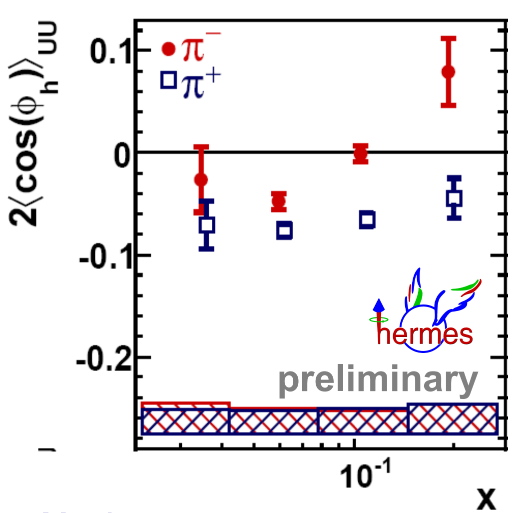


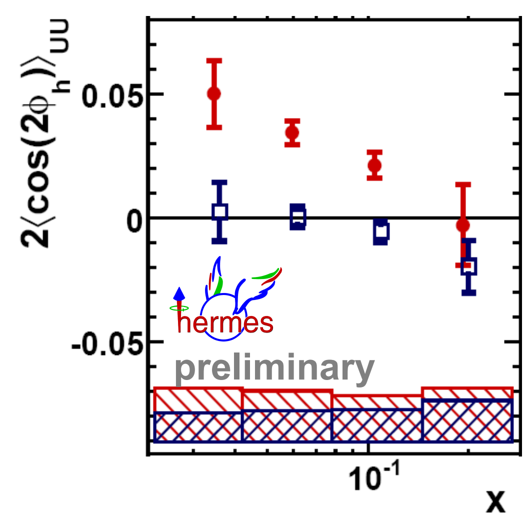


different contributions of the Boer-Mulders term at HERMES and COMPASS?

from first fits to extract the B-M function (Barone et al.)

- **difficult to fit all the data**
- **Cahn contribution not negligible**

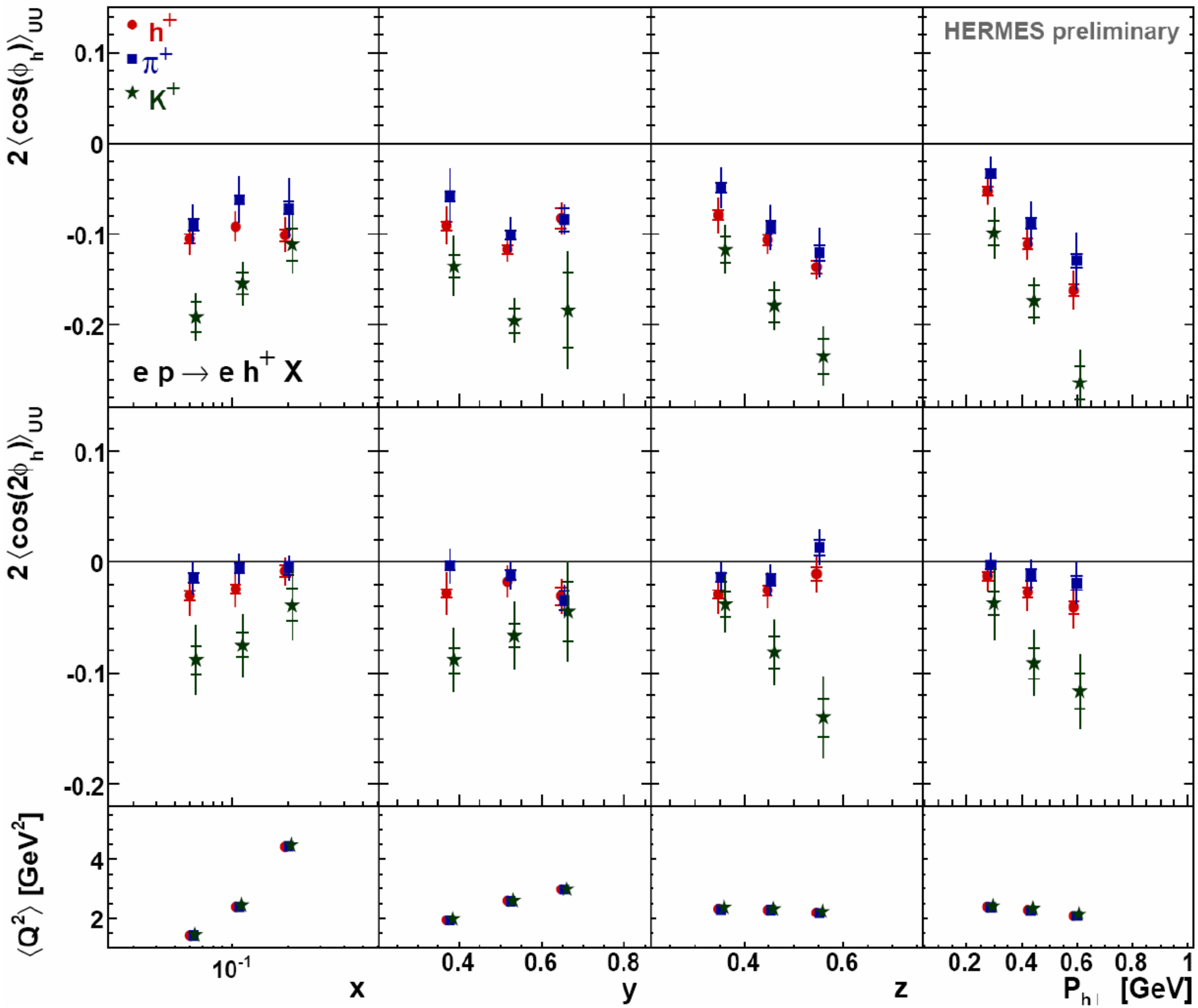




deuteron data

cos ϕ and cos 2ϕ modulations

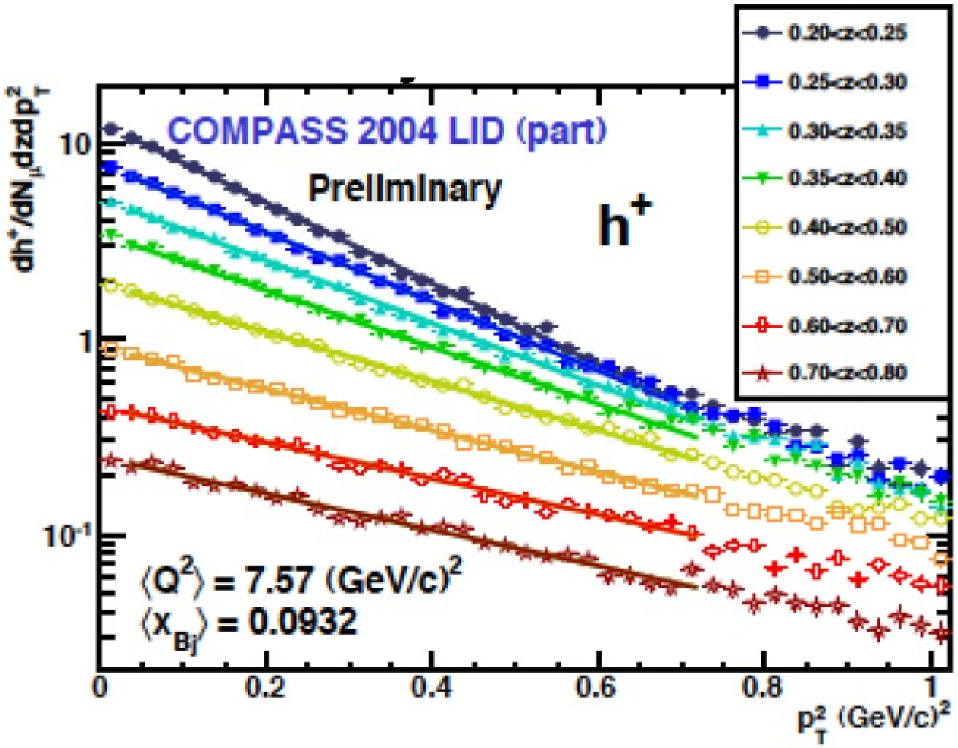
surprising ...!



unpolarised target
SIDIS differential cross-section

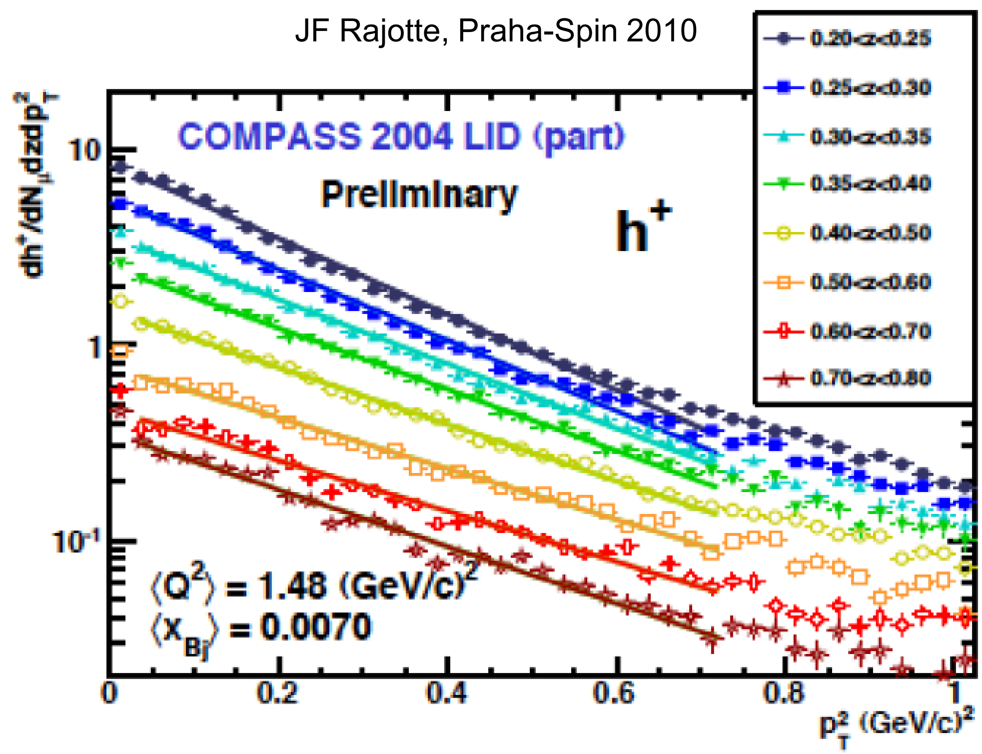
unpolarised target
SIDIS differential cross-section

deuteron



hadron multiplicity
vs transverse momentum of
the final state hadrons

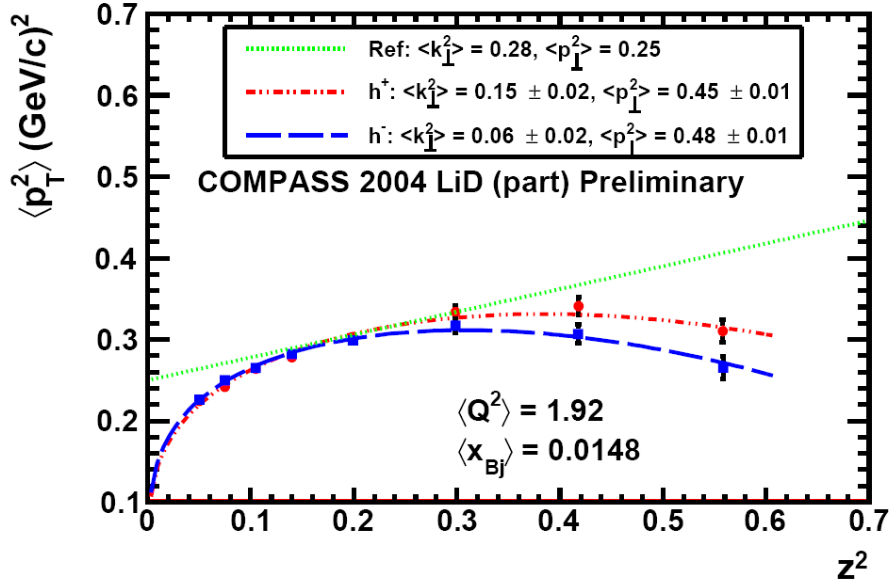
JF Rajotte, Praha-Spin 2010



as well as the cosϕ_h asymmetry,
these data can be used to extract
the intrinsic transverse momentum

unpolarised target
SIDIS differential cross-section

JF Rajotte, Praha-Spin 2010



the expected behaviour

$$\langle p_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$

final state hadron — FF — PDF

does not reproduce the data
as already known

using

$$\langle p_T^2 \rangle = z^\alpha (1-z)^\beta \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$

the extracted $\langle k_\perp^2 \rangle$ **is**

- **smaller than in previous extractions**
- **different for h+ and h-**
- **Q^2 dependent**

a lot of interpretation work on the transverse momenum is ongoing: news soon ?

summary

a lot of SIDIS results have been produced since 2005

very interesting, with some surprises

- solid evidence for: transversity PDF to be different from zero
  Sivers function to be different from zero

  still, important points to be clarified

  and the existing experiments will contribute
  new results will come soon from COMPASS 2010 data,
  and from JLab experiments

- several allowed TMD asymmetries seem not to be measurable in SIDIS

  global fits / calculations, using data from different experiments and all the measured SIDIS azimuthal asymmetries ?

SIDIS is an excellent tool to study the transverse structure of the nucleon

→ short term: high energy SIDIS off unpolarised p target at COMPASS II
JLab 12 GeV

→ longer time scale: ep collider

to know more: Transverity 2011
http://www.ecsac.ictp.it